4. Industrial Processes

Greenhouse gas emissions are produced as the byproducts of various non-energy-related industrial activities. That is, these emissions are produced from an industrial process itself and are not directly a result of energy consumed during the process. For example, raw materials can be chemically transformed from one state to another. This transformation can result in the release of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), or nitrous oxide (N_2O). The processes addressed in this chapter include iron and steel production, cement production, lime production, ammonia production and urea consumption, limestone and dolomite use (e.g., flux stone, flue gas desulfurization, and glass manufacturing), soda ash production and consumption, aluminum production, titanium dioxide production, CO_2 consumption, ferroalloy production, phosphoric acid production, zinc production, lead production, petrochemical production, silicon carbide production and consumption, nitric acid production, and adipic acid production (see Figure 4-1).

In addition to the three greenhouse gases listed above, there are also industrial sources of man-made fluorinated compounds called hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The present contribution of these gases to the radiative forcing effect of all anthropogenic greenhouse gases is small; however, because of their extremely long lifetimes, many of them will continue to accumulate in the atmosphere as long as emissions continue. In addition, many of these gases have high global warming potentials; SF_6 is the most potent greenhouse gas the Intergovernmental Panel on Climate Change (IPCC) has evaluated. Usage of HFCs for the substitution of ozone depleting substances is growing rapidly, as they are the primary substitutes for ozone depleting substances (ODSs), which are being phased-out under the *Montreal Protocol on Substances that Deplete the Ozone Layer*. In addition to their use as ODS substitutes, HFCs, PFCs, SF_6, and other fluorinated compounds are employed and emitted by a number of other industrial sources in the United States. These industries include aluminum production, HCFC-22 production, semiconductor manufacture, electric power transmission and distribution, and magnesium metal production and processing.

In 2006, industrial processes generated emissions of 320.9 teragrams of CO_2 equivalents (Tg CO_2 Eq.), or 5 percent of total U.S. greenhouse gas emissions. CO_2

Figure 4-1

2006 Industrial Processes Chapter Greenhouse Gas Emission Sources
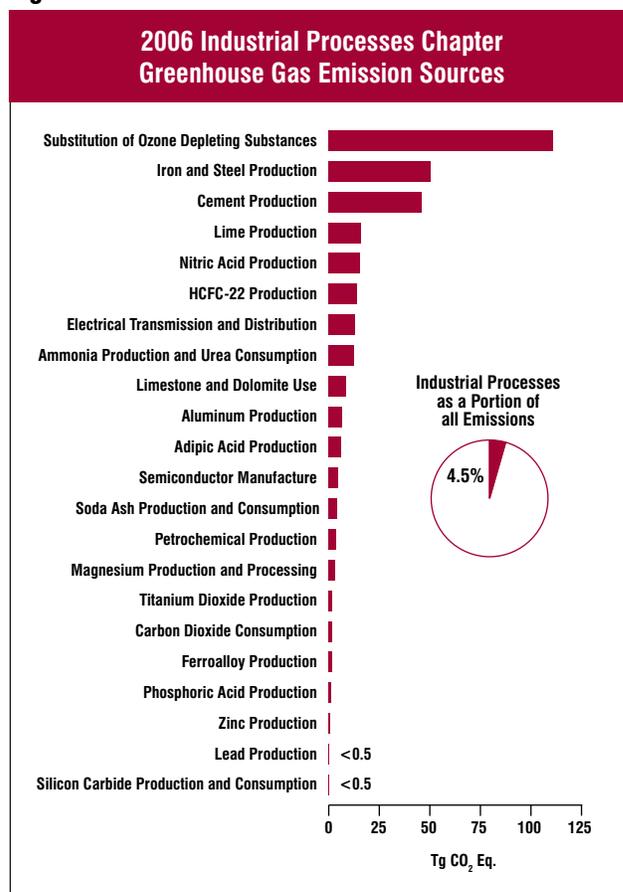
emissions from all industrial processes were 149.5 Tg CO_2 Eq. (149,465 Gg) in 2006, or 2 percent of total U.S. CO_2 emissions. CH_4 emissions from industrial processes resulted in emissions of approximately 2.0 Tg CO_2 Eq. (94 Gg) in 2006, which was less than 1 percent of U.S. CH_4 emissions. N_2O emissions from adipic acid and nitric acid production were 21.6 Tg CO_2 Eq. (70 Gg) in 2006, or 4 percent of total U.S. N_2O emissions. In 2006, combined emissions of HFCs, PFCs and SF_6 totaled 147.9 Tg CO_2 Eq. Overall, emissions from industrial processes increased by 7.0 percent from 1990 to 2006 despite decreases in emissions from several industrial processes, such as iron and steel, aluminum production, HCFC-22 production, and electrical transmission and distribution. The increase in overall emissions was driven by a rise in the emissions originating from cement production and, primarily, the emissions from the use of substitutes for ozone depleting substances.

Table 4-1 summarizes emissions for the Industrial Processes chapter in units of Tg CO_2 Eq., while unweighted native gas emissions in Gg are provided in Table 4-2. The source descriptions that follow in the chapter are presented in the order as reported to the UNFCCC in the common reporting format tables, corresponding generally to: mineral products, chemical production, metal production, and emissions from the uses of HFCs, PFCs, and SF_6.

Tier 1 quality assurance and quality control procedures have been performed for all industrial process sources. For industrial process sources of CO_2 and CH_4 emissions, a detailed plan was developed and implemented. This plan was based on U.S. strategy, but was tailored to include specific procedures recommended for these sources. Two types of checks were performed using this plan (1) general, or Tier 1, procedures that focus on annual procedures and checks to be used when gathering, maintaining, handling, documenting, checking and archiving the data, supporting documents, and files and (2) source-category specific, or Tier 2, procedures that focus on procedures and checks of the emission factors, activity data, and methodologies used for estimating emissions from the relevant Industrial Processes sources. Examples of these procedures include, among others, checks to ensure that activity data and emission estimates are consistent with historical trends; that, where possible, consistent and reputable data sources are used

across sources; that interpolation or extrapolation techniques are consistent across sources; and that common datasets and factors are used where applicable.

The general method employed to estimate emissions for industrial processes, as recommended by the IPCC, involves multiplying production data (or activity data) for each process by an emission factor per unit of production. The uncertainty in the emission estimates is therefore generally a function of a combination of the uncertainties surrounding the production and emission factor variables. Uncertainty of activity data and the associated probability density functions for industrial processes CO_2 sources were estimated based on expert assessment of available qualitative and quantitative information. Uncertainty estimates and probability density functions for the emission factors used to calculate emissions from this source were devised based on IPCC recommendations.

Activity data is obtained through a survey of manufacturers conducted by various organizations (specified within each source); the uncertainty of the activity data is a function of the reliability of plant-level production data and is influenced by the completeness of the survey response. The emission factors used were either derived using calculations that assume precise and efficient chemical reactions, or were based upon empirical data in published references. As a result, uncertainties in the emission coefficients can be attributed to, among other things, inefficiencies in the chemical reactions associated with each production process or to the use of empirically-derived emission factors that are biased; therefore, they may not represent U.S. national averages. Additional assumptions are described within each source.

The uncertainty analysis performed to quantify uncertainties associated with the 2006 inventory estimates from industrial processes continues a multi-year process for developing credible quantitative uncertainty estimates for these source categories using the IPCC Tier 2 approach. As the process continues, the type and the characteristics of the actual probability density functions underlying the input variables are identified and better characterized (resulting in development of more reliable inputs for the model, including accurate characterization of correlation between variables), based primarily on expert judgment.

Table 4-1: Emissions from Industrial Processes (Tg CO_2 Eq.)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	**175.0**	**171.6**	**166.5**	**151.9**	**151.0**	**147.8**	**151.8**	**145.9**	**149.5**
Iron and Steel Production	86.2	74.7	66.6	59.2	55.9	54.7	52.8	46.6	49.1
Cement Production	33.3	36.8	41.2	41.4	42.9	43.1	45.6	45.9	45.7
Lime Production	12.0	14.0	14.9	14.3	13.7	14.5	15.2	15.1	15.8
Ammonia Production & Urea Consumption	16.9	17.8	16.4	13.3	14.2	12.5	13.2	12.8	12.4
Limestone and Dolomite Use	5.5	7.4	6.0	5.7	5.9	4.8	6.7	7.4	8.6
Soda Ash Production and Consumption	4.1	4.3	4.2	4.1	4.1	4.1	4.2	4.2	4.2
Aluminum Production	6.8	5.7	6.1	4.4	4.5	4.5	4.2	4.2	3.9
Petrochemical Production	2.2	2.8	3.0	2.8	2.9	2.8	2.9	2.8	2.6
Titanium Dioxide Production	1.2	1.5	1.8	1.7	1.8	1.8	2.1	1.8	1.9
Carbon Dioxide Consumption	1.4	1.4	1.4	0.8	1.0	1.3	1.2	1.3	1.6
Ferroalloy Production	2.2	2.0	1.9	1.5	1.3	1.3	1.4	1.4	1.5
Phosphoric Acid Production	1.5	1.5	1.4	1.3	1.3	1.4	1.4	1.4	1.2
Zinc Production	0.9	1.0	1.1	1.0	0.9	0.5	0.5	0.5	0.5
Lead Production	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Silicon Carbide Production and Consumption	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
CH_4	**2.2**	**2.4**	**2.5**	**2.2**	**2.1**	**2.1**	**2.2**	**2.0**	**2.0**
Petrochemical Production	0.9	1.1	1.2	1.1	1.1	1.1	1.2	1.1	1.0
Iron and Steel Production	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.0	0.9
Ferroalloy Production	+	+	+	+	+	+	+	+	+
Silicon Carbide Production and Consumption	+	+	+	+	+	+	+	+	+
N_2O	**32.3**	**36.2**	**24.8**	**20.2**	**22.4**	**21.7**	**21.2**	**21.7**	**21.6**
Nitric Acid Production	17.0	18.9	18.6	15.1	16.4	15.4	15.2	15.8	15.6
Adipic Acid Production	15.3	17.3	6.2	5.1	6.1	6.3	5.9	5.9	5.9
HFCs	**36.9**	**61.8**	**100.1**	**97.9**	**106.3**	**104.4**	**116.6**	**121.4**	**124.5**
Substitution of Ozone Depleting Substances[a]	0.3	28.5	71.2	78.0	85.0	92.0	99.1	105.4	110.4
HCFC-22 Production	36.4	33.0	28.6	19.7	21.1	12.3	17.2	15.8	13.8
Semiconductor Manufacture	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.3
PFCs	**20.8**	**15.6**	**13.5**	**7.0**	**8.7**	**7.1**	**6.1**	**6.2**	**6.1**
Semiconductor Manufacture	2.2	3.8	4.9	3.5	3.5	3.3	3.3	3.2	3.6
Aluminum Production	18.5	11.8	8.6	3.5	5.2	3.8	2.8	3.0	2.5
SF_6	**32.7**	**28.0**	**19.1**	**18.7**	**18.0**	**18.1**	**18.0**	**18.2**	**17.3**
Electrical Transmission and Distribution	26.7	21.5	15.1	15.0	14.4	13.8	13.9	14.0	13.2
Magnesium Production and Processing	5.4	5.6	3.0	2.9	2.9	3.4	3.2	3.3	3.2
Semiconductor Manufacture	0.5	0.9	1.1	0.7	0.7	0.8	0.8	1.0	1.0
Total	**299.9**	**315.7**	**326.5**	**297.9**	**308.6**	**301.2**	**315.9**	**315.5**	**320.9**

+ Does not exceed 0.05 Tg CO_2 Eq.
Note: Totals may not sum due to independent rounding.
[a] Small amounts of PFC emissions also result from this source.

Accordingly, the quantitative uncertainty estimates reported in this section should be considered illustrative and as iterations of ongoing efforts to produce accurate uncertainty estimates. The correlation among data used for estimating emissions for different sources can influence the uncertainty analysis of each individual source. While the uncertainty analysis recognizes very significant connections among sources, a more comprehensive approach that accounts for all linkages will be identified as the uncertainty analysis moves forward.

Table 4-2: Emissions from Industrial Processes (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	175,018	171,600	166,452	151,944	150,960	147,752	151,841	145,926	149,465
Iron and Steel Production	86,220	74,729	66,609	59,249	55,938	54,744	52,771	46,627	49,119
Cement Production	33,278	36,847	41,190	41,357	42,898	43,082	45,603	45,910	45,739
Lime Production	12,004	14,019	14,872	14,261	13,652	14,458	15,154	15,131	15,825
Ammonia Production & Urea Consumption	16,889	17,796	16,402	13,305	14,194	12,488	13,241	12,817	12,376
Limestone and Dolomite Use	5,533	7,359	5,960	5,733	5,885	4,753	6,702	7,397	8,615
Soda Ash Production and Consumption	4,141	4,304	4,181	4,147	4,139	4,111	4,205	4,228	4,162
Aluminum Production	6,831	5,659	6,086	4,381	4,490	4,503	4,231	4,207	3,923
Petrochemical Production	2,221	2,750	3,004	2,787	2,857	2,777	2,895	2,804	2,573
Titanium Dioxide Production	1,195	1,526	1,752	1,697	1,824	1,839	2,064	1,755	1,876
Carbon Dioxide Consumption	1,416	1,422	1,421	829	989	1,311	1,198	1,321	1,579
Ferroalloy Production	2,152	2,036	1,893	1,459	1,349	1,305	1,419	1,392	1,505
Phosphoric Acid Production	1,529	1,513	1,382	1,264	1,338	1,382	1,395	1,386	1,167
Zinc Production	949	1,013	1,140	986	937	507	477	465	529
Lead Production	285	298	311	291	286	289	263	266	270
Silicon Carbide Production and Consumption	375	329	248	199	183	202	224	219	207
CH_4	106	116	117	103	101	101	106	97	94
Petrochemical Production	41	52	58	51	52	51	55	51	48
Iron and Steel Production	63	62	58	51	48	49	50	45	45
Ferroalloy Production	1	1	1	+	+	+	+	+	+
Silicon Carbide Production and Consumption	1	1	1	+	+	+	+	+	+
N_2O	104	117	80	65	72	70	68	70	70
Nitric Acid Production	55	61	60	49	53	50	49	51	50
Adipic Acid Production	49	56	20	16	20	20	19	19	19
HFCs	M	M	M	M	M	M	M	M	M
Substitution of Ozone Depleting Substances[a]	M	M	M	M	M	M	M	M	M
HCFC-22 Production	3	3	2	2	2	1	1	1	1
Semiconductor Manufacture	+	+	+	+	+	+	+	+	+
PFCs	M	M	M	M	M	M	M	M	M
Semiconductor Manufacture	M	M	M	M	M	M	M	M	M
Aluminum Production	M	M	M	M	M	M	M	M	M
SF_6	1	1	1	1	1	1	1	1	1
Electrical Transmission and Distribution	1	1	1	1	1	1	1	1	1
Magnesium Production and Processing	+	+	+	+	+	+	+	+	+
Semiconductor Manufacture	+	+	+	+	+	+	+	+	+

+ Does not exceed 0.5 Gg
M (Mixture of gases)
Note: Totals may not sum due to independent rounding.
[a] Small amounts of PFC emissions also result from this source.

4.1. Cement Production (IPCC Source Category 2A1)

Cement production is an energy- and raw-material-intensive process that results in the generation of CO_2 from both the energy consumed in making the cement and the chemical process itself.[1] Cement is produced in 37 states and Puerto Rico. CO_2 emitted from the chemical process of cement production is the second largest source of industrial CO_2 emissions in the United States.

---

[1] The CO_2 emissions related to the consumption of energy for cement production are accounted for under CO_2 from Fossil Fuel Combustion in the Energy chapter.

During the cement production process, calcium carbonate ($CaCO_3$) is heated in a cement kiln at a temperature of about 1,450°C (2,400°F) to form lime (i.e., calcium oxide or CaO) and CO_2 in a process known as calcination or calcining. A very small amount of carbonates other than $CaCO_3$ and non-carbonates are also present in the raw material; however, for calculation purposes all of the raw material is assumed to be $CaCO_3$. Next, the lime is combined with silica-containing materials to produce clinker (an intermediate product), with the earlier byproduct CO_2 being released to the atmosphere. The clinker is then allowed to cool, mixed with a small amount of gypsum, and potentially other materials (e.g., slag) and used to make portland cement.[2]

In 2006, U.S. clinker production—including Puerto Rico—totaled 88,453 thousand metric tons (van Oss 2007). The resulting emissions of CO_2 from 2006 cement production were estimated to be 45.7 Tg CO_2 Eq. (45,739 Gg) (see Table 4-3).

After falling in 1991 by two percent from 1990 levels, cement production emissions grew every year through 2005, and then decreased slightly from 2005 to 2006. Overall, from 1990 to 2006, emissions increased by 37 percent. Cement continues to be a critical component of the construction industry; therefore, the availability of public construction funding, as well as overall economic growth, have had considerable influence on cement production.

Table 4-3: CO$_2$ Emissions from Cement Production (Tg CO$_2$ Eq. and Gg)

Year	Tg CO$_2$ Eq.	Gg
1990	33.3	33,278
1995	36.8	36,847
2000	41.2	41,190
2001	41.4	41,357
2002	42.9	42,898
2003	43.1	43,082
2004	45.6	45,603
2005	45.9	45,910
2006	45.7	45,739

Methodology

CO_2 emissions from cement production are created by the chemical reaction of carbon-containing minerals (i.e., calcining limestone) in the cement kiln. While in the kiln, limestone is broken down into CO_2 and lime with the CO_2 released to the atmosphere. The quantity of CO_2 emitted during cement production is directly proportional to the lime content of the clinker. During calcination, each mole of $CaCO_3$ (i.e., limestone) heated in the clinker kiln forms one mole of lime (CaO) and one mole of CO_2:

$$CaCO_3 + heat \rightarrow CaO + CO_2$$

CO_2 emissions were estimated by applying an emission factor, in tons of CO_2 released per ton of clinker produced, to the total amount of clinker produced. The emission factor used in this analysis is the product of the average lime fraction for clinker of 65 percent (van Oss 2008) and a constant reflecting the mass of CO_2 released per unit of lime. This calculation yields an emission factor of 0.51 tons of CO_2 per ton of clinker produced, which was determined as follows:

$$EF_{Clinker} = 0.65 \, CaO \times \left[\frac{44.01 \text{ g/mole } CO_2}{56.08 \text{ g/mole } CaO} \right]$$
$$= 0.51 \text{ tons } CO_2/\text{ton clinker}$$

During clinker production, some of the clinker precursor materials remain in the kiln as non-calcinated, partially calcinated, or fully calcinated cement kiln dust (CKD). The emissions attributable to the calcinated portion of the CKD are not accounted for by the clinker emission factor. The IPCC recommends that these additional CKD CO_2 emissions should be estimated as two percent of the CO_2 emissions calculated from clinker production. Total cement production emissions were calculated by adding the emissions from clinker production to the emissions assigned to CKD (IPCC 2006).[3]

The 1990 through 2006 activity data for clinker production (see Table 4-4) were obtained through a personal communication with Hendrik van Oss (van Oss 2007) of the USGS and through the USGS *Mineral Yearbook: Cement* (USGS 1993 through 2006). The data were compiled by

---

[2] Approximately six percent of total clinker production is used to produce masonry cement, which is produced using plasticizers (e.g., ground limestone, lime) and portland cement. CO_2 emissions that result from the production of lime used to create masonry cement are included in the Lime Production source category (van Oss 2008).

[3] The 2 percent CO_2 addition associated with CKD is included in the emission estimate for completeness. The cement emission estimate also includes an assumption that all raw material is limestone ($CaCO_3$) when in fact a small percentage is likely composed of non-carbonate materials. Together these assumptions may result in a small emission overestimate (van Oss 2008).

Table 4-4: Clinker Production (Gg)

Year	Clinker
1990	64,355
1995	71,257
2000	79,656
2001	79,979
2002	82,959
2003	83,315
2004	88,190
2005	88,783
2006	88,453

USGS through questionnaires sent to domestic clinker and cement production plants.

Uncertainty

The uncertainties contained in these estimates are primarily due to uncertainties in the lime content of clinker and in the percentage of CKD recycled inside the cement kiln. Uncertainty is also associated with the assumption that all calcium-containing raw material is $CaCO_3$ when a small percentage likely consists of other carbonate and non-carbonate raw materials. The lime content of clinker varies from 60 to 67 percent (van Oss 2008). CKD loss can range from 1.5 to 8 percent depending upon plant specifications. Additionally, some amount of CO_2 is reabsorbed when the cement is used for construction. As cement reacts with water, alkaline substances such as calcium hydroxide are formed. During this curing process, these compounds may react with CO_2 in the atmosphere to create calcium carbonate. This reaction only occurs in roughly the outer 0.2 inches of surface area. Because the amount of CO_2 reabsorbed is thought to be minimal, it was not estimated.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-5. Cement production CO_2 emissions were estimated to be between 39.8 and 52.0 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 13 percent below and 14 percent above the emission estimate of 45.7 Tg CO_2 Eq.

4.2. Lime Production (IPCC Source Category 2A2)

Lime is an important manufactured product with many industrial, chemical, and environmental applications. Its major uses are in steel making, flue gas desulfurization (FGD) systems at coal-fired electric power plants, construction, and water purification. For U.S. operations, the term "lime" actually refers to a variety of chemical compounds. These include calcium oxide (CaO), or high-calcium quicklime; calcium hydroxide ($Ca(OH)_2$), or hydrated lime; dolomitic quicklime ([CaO•MgO]); and dolomitic hydrate ([$Ca(OH)_2$•MgO] or [$Ca(OH)_2$•$Mg(OH)_2$]).

Lime production involves three main processes: stone preparation, calcination, and hydration. CO_2 is generated during the calcination stage, when limestone—mostly calcium carbonate ($CaCO_3$)—is roasted at high temperatures in a kiln to produce CaO and CO_2. The CO_2 is given off as a gas and is normally emitted to the atmosphere. In certain applications, lime reabsorbs CO_2 during use.

Lime production in the United States—including Puerto Rico—was reported to be 20,929 thousand metric tons in 2006 (USGS 2007). This resulted in estimated CO_2 emissions of 15.8 Tg CO_2 Eq. (or 15,825 Gg) (see Table 4-6).

The contemporary lime market is distributed across five end-use categories as follows: metallurgical uses, 36 percent; environmental uses, 29 percent; chemical and industrial uses, 21 percent; construction uses, 13 percent; and refractory dolomite, 1 percent. In the construction sector, lime is used to improve durability in plaster, stucco, and mortars, as well as to stabilize soils. In 2006, the amount of lime used for

Table 4-5: Tier 2 Quantitative Uncertainty Estimates for CO$_2$ Emissions from Cement Production (Tg CO$_2$ Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO$_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a]			
			(Tg CO$_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Cement Production	CO$_2$	45.7	39.8	52.0	-13%	+14%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Table 4-6: CO$_2$ Emissions from Lime Production (Tg CO$_2$ Eq. and Gg)

Year	Tg CO$_2$ Eq.	Gg
1990	12.0	12,004
1995	14.0	14,019
2000	14.9	14,872
2001	14.3	14,261
2002	13.7	13,652
2003	14.5	14,458
2004	15.2	15,154
2005	15.1	15,131
2006	15.8	15,825

construction decreased slightly from 2005 levels, most likely as a result of increased prices for lime and the downturn in new home construction (USGS 2007).

Lime production in 2006 slightly increased over 2005, the fourth annual increase in production after four years of decline. Overall, from 1990 to 2006, lime production has increased by 32 percent. Annual consumption for industrial and chemical, and environmental lime consumption increased by 8 percent and 7 percent, respectively (USGS 2007). The increase in environmental production for environmental uses is attributed in part to growth in demand for flue gas desulfurization technologies, particularly at incineration plants, and wastewater treatment (USGS 2007).

Methodology

During the calcination stage of lime production, CO$_2$ is given off as a gas and normally exits the system with the stack gas. To calculate emissions, the amounts of high-calcium and dolomitic lime produced were multiplied by their respective emission factors. The emission factor is the product of a constant reflecting the mass of CO$_2$ released per unit of lime and the average calcium plus magnesium oxide (CaO + MgO) content for lime (95 percent for both types of lime) (IPCC 2006). The emission factors were calculated as follows:

For high-calcium lime:

$$[(44.01 \text{ g/mole CO}_2) \div (56.08 \text{ g/mole CaO})] \times (0.95 \text{ CaO/lime}) = 0.75 \text{ g CO}_2/\text{g lime}$$

For dolomitic lime:

$$[(88.02 \text{ g/mole CO}_2) \div (96.39 \text{ g/mole CaO})] \times (0.95 \text{ CaO/lime}) = 0.87 \text{ g CO}_2/\text{g lime}$$

Production was adjusted to remove the mass of chemically combined water found in hydrated lime, determined according to the molecular weight ratios of H$_2$O to (Ca(OH)$_2$ and [Ca(OH)$_2$•Mg(OH)$_2$]) (IPCC 2000). These factors set the chemically combined water content to 24.3 percent for high-calcium hydrated lime, and 27.3 percent for dolomitic hydrated lime.

Lime emission estimates were multiplied by a factor of 1.02 to account for lime kiln dust (LKD), which is produced as a byproduct during the production of lime (IPCC 2006).

Lime production data (high-calcium- and dolomitic-quicklime, high-calcium- and dolomitic-hydrated, and dead-burned dolomite) for 1990 through 2006 (see Table 4-7) were obtained from USGS (1992 through 2007). Natural hydraulic lime, which is produced from CaO and hydraulic calcium silicates, is not produced in the United States (USGS 2006).

Table 4-7: High-Calcium- and Dolomitic-Quicklime, High-Calcium- and Dolomitic-Hydrated, and Dead-Burned-Dolomite Lime Production (Gg)

Year	High-Calcium Quicklime	Dolomitic Quicklime	High-Calcium Hydrated	Dolomitic Hydrated	Dead-Burned Dolomite
1990	11,166	2,234	1,781	319	342
1995	13,165	2,635	2,027	363	308
2000	14,300	3,000	1,550	421	200
2001	13,600	2,580	2,030	447	200
2002	13,400	2,420	1,500	431	200
2003	13,900	2,460	2,140	464	200
2004	14,200	3,020	2,140	421	200
2005	14,100	2,990	2,220	474	200
2006	15,000	2,950	2,370	409	200

Table 4-8: Adjusted Lime Production[a] (Gg)

Year	High-Calcium	Dolomitic
1990	12,514	2,809
1995	14,700	3,207
2000	15,473	3,506
2001	15,137	3,105
2002	14,536	2,934
2003	15,520	2,998
2004	15,820	3,526
2005	15,781	3,535
2006	16,794	3,448

[a] Minus water content of hydrated lime

Total lime production was adjusted to account for the water content of hydrated lime by converting hydrate to oxide equivalent, based on recommendations from the IPCC *Good Practice Guidance* and is presented in Table 4-8 (USGS 1992 through 2007, IPCC 2000). The CaO and CaO•MgO contents of lime were obtained from the IPCC (IPCC 2006). Since data for the individual lime types (high calcium and dolomitic) was not provided prior to 1997, total lime production for 1990 through 1996 was calculated according to the three year distribution from 1997 to 1999.

Uncertainty

The uncertainties contained in these estimates can be attributed to slight differences in the chemical composition of these products. Although the methodology accounts for various formulations of lime, it does not account for the trace impurities found in lime, such as iron oxide, alumina, and silica. Due to differences in the limestone used as a raw material, a rigid specification of lime material is impossible. As a result, few plants manufacture lime with exactly the same properties.

In addition, a portion of the CO_2 emitted during lime production will actually be reabsorbed when the lime is consumed. As noted above, lime has many different chemical, industrial, environmental, and construction applications. In many processes, CO_2 reacts with the lime to create calcium carbonate (e.g., water softening). CO_2 reabsorption rates vary, however, depending on the application. For example, 100 percent of the lime used to produce precipitated calcium carbonate reacts with CO_2; whereas most of the lime used

in steel making reacts with impurities such as silica, sulfur, and aluminum compounds. A detailed accounting of lime use in the United States and further research into the associated processes are required to quantify the amount of CO_2 that is reabsorbed.[4]

In some cases, lime is generated from calcium carbonate byproducts at pulp mills and water treatment plants.[5] The lime generated by these processes is not included in the USGS data for commercial lime consumption. In the pulping industry, mostly using the Kraft (sulfate) pulping process, lime is consumed in order to causticize a process liquor (green liquor) composed of sodium carbonate and sodium sulfide. The green liquor results from the dilution of the smelt created by combustion of the black liquor where biogenic C is present from the wood. Kraft mills recover the calcium carbonate "mud" after the causticizing operation and calcine it back into lime—thereby generating CO_2—for reuse in the pulping process. Although this re-generation of lime could be considered a lime production process, the CO_2 emitted during this process is mostly biogenic in origin, and therefore is not included in inventory totals.[6]

In the case of water treatment plants, lime is used in the softening process. Some large water treatment plants may recover their waste calcium carbonate and calcine it into quicklime for reuse in the softening process. Further research is necessary to determine the degree to which lime recycling is practiced by water treatment plants in the United States.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-9. Lime CO_2 emissions were estimated to be between 14.6 and 17.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below and 8 percent above the emission estimate of 15.8 Tg CO_2 Eq.

---

[4] Representatives of the National Lime Association estimate that CO_2 reabsorption that occurs from the use of lime may offset as much as a quarter of the CO_2 emissions from calcination (Males 2003).

[5] Some carbide producers may also regenerate lime from their calcium hydroxide byproducts, which does not result in emissions of CO_2. In making calcium carbide, quicklime is mixed with coke and heated in electric furnaces. The regeneration of lime in this process is done using a waste calcium hydroxide (hydrated lime) [$CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$], not calcium carbonate [$CaCO_3$]. Thus, the calcium hydroxide is heated in the kiln to simply expel the water [$Ca(OH)_2 + heat$ ($CaO + H_2O$] and no CO_2 is released.

[6] Based on comments submitted by and personal communication with Dr. Sergio F. Galeano, Georgia-Pacific Corporation.

Table 4-9: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Lime Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lime Production	CO_2	15.8	14.6	17.1	-8%	+8%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Recalculations Discussion

Estimates of CO_2 emissions from lime production were revised for all years in the time series to remove estimates of CO_2 recovery associated with lime use during sugar refining and precipitate calcium carbonate (PCC) production. Currently, research does not indicate that CO_2 used in these processes stems from CO_2 captured during lime production. Additional research is needed to determine if lime production plants in the US capture CO_2 as well as to determine the fates of precipitates formed during the sugar refining process. This change resulted in an average annual emission increase of 9.5 percent.

4.3. Limestone and Dolomite Use (IPCC Source Category 2A3)

Limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$)[7] are basic raw materials used by a wide variety of industries, including construction, agriculture, chemical, metallurgy, glass production, and environmental pollution control.

Limestone is widely distributed throughout the world in deposits of varying sizes and degrees of purity. Large deposits of limestone occur in nearly every state in the United States, and significant quantities are extracted for industrial applications. For some of these applications, limestone is sufficiently heated during the process and generates CO_2 as a byproduct. Examples of such applications include limestone used as a flux or purifier in metallurgical furnaces, as a sorbent in flue gas desulfurization systems for utility and industrial plants, or as a raw material in glass manufacturing and magnesium production.

In 2006, approximately 13,192 thousand metric tons of limestone and 5,886 thousand metric tons of dolomite were consumed during production for these applications. Overall, usage of limestone and dolomite resulted in aggregate CO_2 emissions of 8.6 Tg CO_2 Eq. (8,615 Gg) (see Table 4-10 and Table 4-11). Emissions in 2006 increased 17 percent from the previous year and have increased 56 percent overall from 1990 through 2006.

Table 4-10: CO_2 Emissions from Limestone & Dolomite Use (Tg CO_2 Eq.)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Flux Stone	3.0	4.0	2.8	2.5	2.4	2.1	4.1	3.3	5.1
Glass Making	0.2	0.5	0.4	0.1	0.1	0.3	0.4	0.4	0.7
FGD	1.4	1.7	1.8	2.6	2.8	1.9	1.9	3.0	2.1
Magnesium Production	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Other Miscellaneous Uses	0.8	1.1	0.9	0.5	0.7	0.4	0.4	0.7	0.7
Total	**5.5**	**7.4**	**6.0**	**5.7**	**5.9**	**4.8**	**6.7**	**7.4**	**8.6**

Notes: Totals may not sum due to independent rounding. "Other miscellaneous uses" include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

---

[7] Limestone and dolomite are collectively referred to as limestone by the industry, and intermediate varieties are seldom distinguished.

Table 4-11: CO$_2$ Emissions from Limestone & Dolomite Use (Gg)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Flux Stone	2,999	4,004	2,830	2,514	2,405	2,081	4,112	3,265	5,072
Limestone	2,554	3,077	1,810	1,640	1,330	913	2,023	1,398	2,291
Dolomite	446	927	1,020	874	1,075	1,168	2,088	1,867	2,781
Glass Making	217	533	368	113	61	339	350	427	747
Limestone	189	410	368	113	61	339	350	406	717
Dolomite	28	122	0	0	0	0	0	21	31
FGD	1,433	1,663	1,774	2,551	2,766	1,950	1,871	2,985	2,061
Magnesium Production	64	41	73	53	0	0	0	0	0
Other Miscellaneous Uses	819	1,119	916	501	652	383	369	721	735
Total	**5,533**	**7,359**	**5,960**	**5,733**	**5,885**	**4,753**	**6,702**	**7,397**	**8,615**

Notes: Totals may not sum due to independent rounding. Other miscellaneous uses include chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

Methodology

CO$_2$ emissions were calculated by multiplying the quantity of limestone or dolomite consumed by the average C content, approximately 12.0 percent for limestone and 13.2 percent for dolomite (based on stoichiometry), and converting this value to CO$_2$. This methodology was used for flux stone, glass manufacturing, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining and then converting to CO$_2$ using a molecular weight ratio.

Traditionally, the production of magnesium metal was the only other significant use of limestone and dolomite that produced CO$_2$ emissions. At the start of 2001, there were two magnesium production plants operating in the United States and they used different production methods. One plant produced magnesium metal using a dolomitic process that resulted in the release of CO$_2$ emissions, while the other plant produced magnesium from magnesium chloride using a CO$_2$-emissions-free process called electrolytic reduction. However, the plant utilizing the dolomitic process ceased its operations prior to the end of 2001, so beginning in 2002 there were no emissions from this particular sub-use.

Consumption data for 1990 through 2006 of limestone and dolomite used for flux stone, glass manufacturing, flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining (see Table 4-12) were obtained from the USGS *Minerals Yearbook: Crushed Stone Annual Report* (USGS 1993, 1995a, 1996a through 2007a). The production capacity data for 1990 through 2006 of dolomitic magnesium metal (see Table 4-13) also came from the USGS (1995b, 1996b through 2007b). The last plant in the United States that used the dolomitic production process for magnesium metal closed in 2001. The USGS does not mention this process in the 2006 *Minerals Yearbook: Magnesium*; therefore, it is assumed that this process continues to be non-existent in the United States (USGS 2007b). During 1990 and 1992, the USGS did not conduct a detailed survey of limestone and dolomite consumption by end-use. Consumption for 1990 was estimated by applying the 1991 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to 1990 total use. Similarly, the 1992 consumption figures were approximated by applying an average of the 1991 and 1993 percentages of total limestone and dolomite use constituted by the individual limestone and dolomite uses to the 1992 total.

Additionally, each year the USGS withholds data on certain limestone and dolomite end-uses due to confidentiality agreements regarding company proprietary data. For the purposes of this analysis, emissive end-uses that contained withheld data were estimated using one of the following techniques: (1) the value for all the withheld data points for limestone or dolomite use was distributed evenly to all withheld end-uses, (2) the average percent of total limestone or dolomite for the withheld end-use in the preceding and succeeding years, or (3) the average fraction of total limestone or dolomite for the end-use over the entire time period.

Finally, there is a large quantity of crushed stone reported to the USGS under the category "unspecified uses."

Table 4-12: Limestone and Dolomite Consumption (Thousand Metric Tons)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Flux Stone	6,738	8,935	6,249	5,558	5,275	4,521	8,971	7,086	11,030
Limestone	5,804	6,995	4,114	3,727	3,023	2,075	4,599	3,176	5,208
Dolomite	933	1,941	2,135	1,831	2,252	2,446	4,373	3,910	5,822
Glass Making	489	1,189	836	258	139	771	796	966	1,693
Limestone	430	933	836	258	139	771	796	923	1,629
Dolomite	59	256	0	0	0	0	0	43	64
FGD	3,258	3,779	4,031	5,798	6,286	4,432	4,253	6,785	4,683
Other Miscellaneous Uses	1,835	2,543	2,081	1,138	1,483	870	840	1,638	1,671
Total	**12,319**	**16,445**	**13,197**	**12,751**	**13,183**	**10,594**	**14,859**	**16,475**	**19,078**

Notes: "Other miscellaneous uses" includes chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining. Zero values for limestone and dolomite consumption for glass making result during years when the USGS reports that no limestone or dolomite are consumed for this use.

Table 4-13: Dolomitic Magnesium Metal Production Capacity (Metric Tons)

Year	Production Capacity
1990	35,000
1995	22,222
2000	40,000
2001	29,167
2002	0
2003	0
2004	0
2005	0
2006	0

Note: Production capacity for 2002, 2003, 2004, 2005, and 2006 amounts to zero because the last U.S. production plant employing the dolomitic process shut down mid-2001 (USGS 2002b through 2007b).

A portion of this consumption is believed to be limestone or dolomite used for emissive end uses. The quantity listed for "unspecified uses" was, therefore, allocated to each reported end-use according to each end uses fraction of total consumption in that year.[8]

Uncertainty

The uncertainty levels presented in this section arise in part due to variations in the chemical composition of limestone. In addition to calcium carbonate, limestone may contain smaller amounts of magnesia, silica, and sulfur, among other minerals. The exact specifications for limestone or dolomite used as flux stone vary with the pyrometallurgical process and the kind of ore processed. Similarly, the quality of the limestone used for glass manufacturing will depend on the type of glass being manufactured.

The estimates below also account for uncertainty associated with activity data. Large fluctuations in reported consumption exist, reflecting year-to-year changes in the number of survey responders. The uncertainty resulting from a shifting survey population is exacerbated by the gaps in the time series of reports. The accuracy of distribution by end use is also uncertain because this value is reported by the manufacturer and not the end user. Additionally, there is significant inherent uncertainty associated with estimating withheld data points for specific end uses of limestone and dolomite. The uncertainty of the estimates for limestone used in glass making is especially high; however, since glass making accounts for a small percent of consumption, its contribution to the overall emissions estimate is low. Lastly, much of the limestone consumed in the United States is reported as "other unspecified uses;" therefore, it is difficult to accurately allocate this unspecified quantity to the correct end-uses.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-14. Limestone and Dolomite Use CO_2 emissions were estimated to be between 8.0 and 9.2 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 7 percent above the emission estimate of 8.6 Tg CO_2 Eq.

---

[8] This approach was recommended by USGS.

Table 4-14: Tier 2 Quantitative Uncertainty Estimates for CO$_2$ Emissions from Limestone and Dolomite Use (Tg CO$_2$ Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO$_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO$_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Limestone and Dolomite Use	CO$_2$	8.6	8.0	9.2	-7%	+7%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Recalculations Discussion

Emission estimates for 2003 were revised to reflect updated limestone production data. This change resulted in a less than one percent increase in 2003 emissions.

Planned Improvements

Future improvements to the limestone and dolomite source category involve research into the availability of limestone and dolomite end-use data. If sufficient data are available, limestone and dolomite used as process materials in source categories to be included in future inventories (e.g., glass production, other process use of carbonates) may be removed and the emission estimates included there.

4.4. Soda Ash Production and Consumption (IPCC Source Category 2A4)

Soda ash (sodium carbonate, Na$_2$CO$_3$) is a white crystalline solid that is readily soluble in water and strongly alkaline. Commercial soda ash is used as a raw material in a variety of industrial processes and in many familiar consumer products such as glass, soap and detergents, paper, textiles, and food. It is used primarily as an alkali, either in glass manufacturing or simply as a material that reacts with and neutralizes acids or acidic substances. Internationally, two types of soda ash are produced—natural and synthetic. The United States produces only natural soda ash and is second only to China in total soda ash-production. Trona is the principal ore from which natural soda ash is made.

Only two states produce natural soda ash: Wyoming and California. Of these two states, only net emissions of CO$_2$ from Wyoming were calculated due to specifics regarding the production processes employed in the state.[9] During the production process used in Wyoming, trona ore is treated to produce soda ash. CO$_2$ is generated as a byproduct of this reaction, and is eventually emitted into the atmosphere. In addition, CO$_2$ may also be released when soda ash is consumed.

In 2006, CO$_2$ emissions from the production of soda ash from trona were approximately 1.6 Tg CO$_2$ Eq. (1,626 Gg). Soda ash consumption in the United States generated 2.5 Tg CO$_2$ Eq. (2,536 Gg) in 2006. Total emissions from soda

Table 4-15: CO$_2$ Emissions from Soda Ash Production and Consumption (Tg CO$_2$ Eq.)

Year	Production	Consumption	Total
1990	1.4	2.7	4.1
1995	1.6	2.7	4.3
2000	1.5	2.7	4.2
2001	1.5	2.6	4.1
2002	1.5	2.7	4.1
2003	1.5	2.6	4.1
2004	1.6	2.6	4.2
2005	1.7	2.6	4.2
2006	1.6	2.5	4.2

Note: Totals may not sum due to independent rounding.

[9] In California, soda ash is produced using sodium carbonate-bearing brines instead of trona ore. To extract the sodium carbonate, the complex brines are first treated with CO$_2$ in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which then precipitates from the brine solution. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO$_2$ is generated as a byproduct, the CO$_2$ is recovered and recycled for use in the carbonation stage and is not emitted.

A third state, Colorado, produced soda ash until the plant was idled in 2004. The lone producer of sodium bicarbonate no longer mines trona in the state. For a brief time, NaHCO$_3$ was produced using soda ash feedstocks mined in Wyoming and shipped to Colorado. Because the trona is mined in Wyoming, the production numbers given by the USGS included the feedstocks mined in Wyoming and shipped to Colorado. In this way, the sodium bicarbonate production that took place in Colorado was accounted for in the Wyoming numbers.

Table 4-16: CO$_2$ Emissions from Soda Ash Production and Consumption (Gg)

Year	Production	Consumption	Total
1990	1,431	2,710	4,141
1995	1,607	2,698	4,304
2000	1,529	2,652	4,181
2001	1,500	2,648	4,147
2002	1,470	2,668	4,139
2003	1,509	2,602	4,111
2004	1,607	2,598	4,205
2005	1,655	2,573	4,228
2006	1,626	2,536	4,162

Note: Totals may not sum due to independent rounding.

Table 4-17: Soda Ash Production and Consumption (Gg)

Year	Production*	Consumption
1990	14,700	6,530
1995	16,500	6,500
2000	15,700	6,390
2001	15,400	6,380
2002	15,100	6,430
2003	15,500	6,270
2004	16,500	6,260
2005	17,000	6,200
2006	16,700	6,110

* Soda ash produced from trona ore only.

ash production and consumption in 2006 were 4.2 Tg CO$_2$ Eq. (4,162 Gg) (see Table 4-15 and Table 4-16). Emissions have fluctuated since 1990. These fluctuations were strongly related to the behavior of the export market and the U.S. economy. Emissions in 2006 decreased by approximately 1.6 percent from the previous year, and have increased overall by approximately 0.5 percent since 1990.

The United States represents about one-fourth of total world soda ash output. The approximate distribution of soda ash by end-use in 2006 was glass making, 50 percent; chemical production, 29 percent; soap and detergent manufacturing, 9 percent; distributors, 4 percent; flue gas desulfurization, 2 percent; water treatment, 2 percent; pulp and paper production, 1 percent; and miscellaneous, 3 percent (USGS 2007).

Although the United States continues to be a major supplier of world soda ash, China, which surpassed the United States in soda ash production in 2003, is the world's leading producer. While Chinese soda ash production appears to be stabilizing, U.S. competition in Asian markets is expected to continue. Despite this competition, U.S. soda ash production is expected to increase by about 0.5 percent annually over the next five years (USGS 2006).

Methodology

During the production process, trona ore is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. CO$_2$ and water are generated as byproducts of the calcination process. CO$_2$ emissions

from the calcination of trona can be estimated based on the following chemical reaction:

$$2(Na_3(CO_3)(HCO_3) \bullet 2H_2O) \rightarrow 3Na_2CO_3 + 5H_2O + CO_2$$

[trona]   [soda ash]
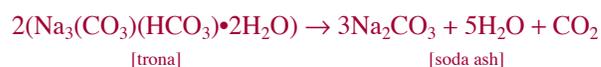
Based on this formula, approximately 10.27 metric tons of trona are required to generate one metric ton of CO$_2$, or an emission factor of 0.097 metric tons CO$_2$ per metric ton trona (IPCC 2006). Thus, the 16.7 million metric tons of trona mined in 2006 for soda ash production (USGS 2007) resulted in CO$_2$ emissions of approximately 1.6 Tg CO$_2$ Eq. (1,626 Gg).

Once manufactured, most soda ash is consumed in glass and chemical production, with minor amounts in soap and detergents, pulp and paper, flue gas desulfurization and water treatment. As soda ash is consumed for these purposes, additional CO$_2$ is usually emitted. In these applications, it is assumed that one mole of C is released for every mole of soda ash used. Thus, approximately 0.113 metric tons of C (or 0.415 metric tons of CO$_2$) are released for every metric ton of soda ash consumed.

The activity data for trona production and soda ash consumption (see Table 4-17) were taken from USGS (1994 through 2007). Soda ash production and consumption data were collected by the USGS from voluntary surveys of the U.S. soda ash industry.

Uncertainty

Emission estimates from soda ash production have relatively low associated uncertainty levels in that reliable and accurate data sources are available for the

Table 4-18: Tier 2 Quantitative Uncertainty Estimates for CO$_2$ Emissions from Soda Ash Production and Consumption (Tg CO$_2$ Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO$_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO$_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Soda Ash Production and Consumption	CO$_2$	4.2	3.9	4.5	-7%	+7%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

emission factor and activity data. The primary source of uncertainty, however, results from the fact that emissions from soda ash consumption are dependent upon the type of processing employed by each end-use. Specific information characterizing the emissions from each end-use is limited. Therefore, there is uncertainty surrounding the emission factors from the consumption of soda ash.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-18. Soda Ash Production and Consumption CO$_2$ emissions were estimated to be between 3.9 and 4.5 Tg CO$_2$ Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 7 percent above the emission estimate of 4.2 Tg CO$_2$ Eq.

Planned Improvements

Future Inventories may include estimates of emissions from glass production and other use of carbonates. These Inventories will extract soda ash consumed for glass production and other use of carbonates from the current soda ash consumption emission estimates and include them under those sources.

4.5. Ammonia Production (IPCC Source Category 2B1) and Urea Consumption

Emissions of CO$_2$ occur during the production of synthetic ammonia, primarily through the use of natural gas as a feedstock. The natural-gas-based, naphtha-based, and petroleum-coke-based processes produce CO$_2$ and hydrogen (H$_2$), the latter of which is used in the production of ammonia. One nitrogen production plant located in Kansas is producing ammonia from petroleum coke feedstock. In some plants the CO$_2$ produced is captured and used to produce urea. The

brine electrolysis process for production of ammonia does not lead to process-based CO$_2$ emissions.

There are five principal process steps in synthetic ammonia production from natural gas feedstock. The primary reforming step converts CH$_4$ to CO$_2$, carbon monoxide (CO), and H$_2$ in the presence of a catalyst. Only 30 to 40 percent of the CH$_4$ feedstock to the primary reformer is converted to CO and CO$_2$. The secondary reforming step converts the remaining CH$_4$ feedstock to CO and CO$_2$. The CO in the process gas from the secondary reforming step (representing approximately 15 percent of the process gas) is converted to CO$_2$ in the presence of a catalyst, water, and air in the shift conversion step. CO$_2$ is removed from the process gas by the shift conversion process, and the hydrogen gas is combined with the nitrogen (N$_2$) gas in the process gas during the ammonia synthesis step to produce ammonia. The CO$_2$ is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO$_2$ is released.

The conversion process for conventional steam reforming of CH$_4$, including primary and secondary reforming and the shift conversion processes, is approximately as follows:

$$0.88\,CH_4 + 1.26\,Air + 1.24\,H_2O \xrightarrow{\text{(catalyst)}} 0.88\,CO_2 + N_2 + 3\,H_2$$

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3$$
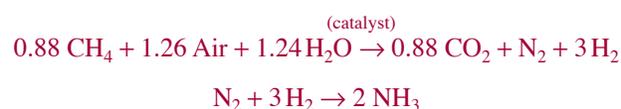
To produce synthetic ammonia from petroleum coke, the petroleum coke is gasified and converted to CO$_2$ and H$_2$. These gases are separated, and the H$_2$ is used as a feedstock to the ammonia production process, where it is reacted with N$_2$ to form ammonia.

Not all of the CO$_2$ produced in the production of ammonia is emitted directly to the atmosphere. Both ammonia and CO$_2$ are used as raw materials in the production of urea [CO(NH$_2$)$_2$], which is another type of nitrogenous

fertilizer that contains C as well as N. The chemical reaction that produces urea is:

$$2\,NH_3 + CO_2 \rightarrow NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

Urea is consumed in a variety of uses, including as a nitrogenous fertilizer, in urea-formaldehyde resins, and as a deicing agent (TIG 2002). The C in the consumed urea is assumed to be released into the environment as CO_2 during use. Therefore, the CO_2 produced by ammonia production that is subsequently used in the production of urea is still emitted during urea consumption. The majority of CO_2 emissions associated with urea consumption are those that result from its use as a fertilizer. These emissions are accounted for in the Cropland Remaining Cropland section of the Land Use, Land-Use Change, and Forestry chapter. CO_2 emissions associated with other uses of urea are accounted for in this chapter. Net emissions of CO_2 from ammonia production in 2006 were 11.8 Tg CO_2 Eq. (11,832 Gg), and are summarized in Table 4-19 and Table 4-20. Emissions of CO_2 from urea consumed for non-fertilizer purposes in 2006 totaled 0.5 Tg CO_2 Eq. (543 Gg), and are summarized in Table 4-19 and Table 4-20. The decrease in ammonia production in recent years is due to several factors, including market fluctuations and high natural gas prices. Ammonia production relies on natural gas as both a feedstock and a fuel, and as such, domestic producers are competing with imports from countries with lower gas prices. If natural gas prices remain high, it is likely that domestically produced ammonia will continue to decrease with increasing ammonia imports (EEA 2004).

Methodology

The calculation methodology for non-combustion CO_2 emissions from production of nitrogenous fertilizers from natural gas feedstock is based on a CO_2 emission factor published by the European Fertilizer Manufacturers Association (EFMA). The selected EFMA factor is based on ammonia production technologies that are similar to those employed in the United States. The CO_2 emission factor (1.2 metric tons CO_2/metric ton NH_3) is applied to the percent of total annual domestic ammonia production from natural gas feedstock. Emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter. Emissions of CO_2 from ammonia production are then adjusted to account for the use of some of the CO_2 produced from ammonia production as a raw material in the production of urea. For each ton of urea produced, 8.8 of every 12 tons of CO_2 are consumed and 6.8 of every 12 tons of ammonia are consumed. The CO_2 emissions reported for ammonia production are therefore reduced by a factor of 0.73 multiplied by total annual domestic urea production. Total CO_2 emissions resulting from nitrogenous fertilizer production do not change as a result of this calculation, but some of the CO_2 emissions are attributed to ammonia production and some of the CO_2 emissions are attributed to urea consumption. Those CO_2 emissions that result from the use of urea as a fertilizer are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

Approximately 87 percent (TIG 2002) of urea consumed in the United States is consumed as a nitrogenous fertilizer

Table 4-19: CO$_2$ Emissions from Ammonia Production and Urea Consumption (Tg CO$_2$ Eq.)

Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
Ammonia Production	16.5	17.4	15.9	12.8	13.7	11.9	12.7	12.3	11.8
Urea Consumption[a]	0.4	0.4	0.5	0.5	0.5	0.6	0.5	0.5	0.5
Total	**16.9**	**17.8**	**16.4**	**13.3**	**14.2**	**12.5**	**13.2**	**12.8**	**12.4**

Note: Totals may not sum due to independent rounding.
[a] Urea Consumption is for non-fertilizer purposes only. Urea consumed as a fertilizer is accounted for in the Land Use, Land-Use Change, and Forestry chapter.

Table 4-20: CO$_2$ Emissions from Ammonia Production and Urea Consumption (Gg)

Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
Ammonia Production	16,528	17,399	15,922	12,795	13,660	11,937	12,695	12,293	11,832
Urea Consumption[a]	361	397	480	510	534	551	546	524	543
Total	**16,889**	**17,796**	**16,402**	**13,305**	**14,194**	**12,488**	**13,241**	**12,817**	**12,376**

Note: Totals may not sum due to independent rounding.
[a] Urea Consumption is for non-fertilizer purposes only. Urea consumed as a fertilizer is accounted for in the Land Use, Land-Use Change, and Forestry chapter.

on agricultural lands. The total amount of urea consumed is estimated based on this percent and the quantity of urea fertilizer applied to agricultural lands, which is obtained directly from the Land Use, Land-Use Change, and Forestry Chapter, and is reported in Table 4-21. CO_2 emissions associated with the remaining urea are estimated using a factor of 0.73 tons of CO_2 per ton of urea consumed. Total urea production is estimated based on the amount of urea applied plus the sum of net urea imports and exports.

All ammonia production and subsequent urea production are assumed to be from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of ammonia production from petroleum coke feedstock at one plant located in Kansas. The CO_2 emission factor for production of ammonia from petroleum coke is based on plant-specific data, wherein all C contained in the petroleum coke feedstock that is not used for urea production is assumed to be emitted to the atmosphere as CO_2 (Bark 2004). Ammonia and urea are assumed to be produced in the same manufacturing complex, as both the raw materials needed for urea production are produced by the ammonia production process. The CO_2 emission factor (3.57 metric tons CO_2/metric ton NH_3) is applied to the percent of total annual domestic ammonia production from petroleum coke feedstock.

The emission factor of 1.2 metric ton CO_2/metric ton NH_3 for production of ammonia from natural gas feedstock was taken from the EFMA Best Available Techniques publication, *Production of Ammonia* (EFMA 1995). The EFMA reported an emission factor range of 1.15 to 1.30 metric ton CO_2/metric ton NH_3, with 1.2 metric ton CO_2/metric ton NH_3 as a typical value. Technologies (e.g., catalytic

reforming process) associated with this factor are found to closely resemble those employed in the United States for use of natural gas as a feedstock. The EFMA reference also indicates that more than 99 percent of the CH_4 feedstock to the catalytic reforming process is ultimately converted to CO_2. The emission factor of 3.57 metric ton CO_2/metric ton NH_3 for production of ammonia from petroleum coke feedstock was developed from plant-specific ammonia production data and petroleum coke feedstock utilization data for the ammonia plant located in Kansas (Bark 2004). As noted earlier, emissions from fuels consumed for energy purposes during the production of ammonia are accounted for in the Energy chapter. Ammonia production data (see Table 4-21) was obtained from Coffeyville Resources (Coffeyville 2005, 2006, 2007) and the Census Bureau of the U.S. Department of Commerce (U.S. Census Bureau 1991 through 1994, 1998 through 2007) as reported in *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports. Urea-ammonia nitrate production was obtained from Coffeyville Resources (Coffeyville 2005 through 2007). With the exception of 2006 urea export data, import and export data for urea were obtained from the U.S. Census Bureau *Current Industrial Reports Fertilizer Materials and Related Products* annual and quarterly reports for 1997 through 2006 (U.S. Census Bureau 1998 through 2007), The Fertilizer Institute (TFI 2002) for 1993 through 1996, and the United States International Trade Commission Interactive Tariff and Trade DataWeb (U.S. ITC 2002) for 1990 through 1992 (see Table 4-21). Because the U.S. Census Bureau did not report urea export data for 2006, 2005 data were proxied.

Table 4-21: Ammonia Production, Urea Production, Urea Net Imports, and Urea Exports (Gg)

Year	Ammonia Production	Urea Applied as Fertilizer	Urea Imports	Urea Exports
1990	15,425	3,296	1,860	774
1995	15,788	3,623	2,936	881
2000	14,342	4,382	3,904	663
2001	11,092	4,655	4,800	792
2002	12,577	4,871	3,840	970
2003	10,279	5,025	4,973	723
2004	10,939	4,982	4,935	704
2005	10,143	4,779	5,026	579
2006	9,962	4,958	5,029	579

Uncertainty

The uncertainties presented in this section are primarily due to how accurately the emission factor used represents an average across all ammonia plants using natural gas feedstock, and the assumption that 87 percent of urea consumed is as fertilizer. Uncertainties are also associated with natural gas feedstock consumption data for the U.S. ammonia industry as a whole, the assumption that all ammonia production and subsequent urea production was from the same process—conventional catalytic reforming of natural gas feedstock, with the exception of one ammonia production plant located in Kansas that is manufacturing ammonia from petroleum coke feedstock. It is also assumed that ammonia and urea are produced at collocated plants from the same natural gas raw material.

Such recovery may or may not affect the overall estimate of CO_2 emissions depending upon the end use to which the recovered CO_2 is applied. Further research is required to determine whether byproduct CO_2 is being recovered from other ammonia production plants for application to end uses that are not accounted for elsewhere.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-22. Ammonia Production and Urea Consumption CO_2 emissions were estimated to be between 11.1 and 13.8 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 10 percent below and 12 percent above the emission estimate of 12.4 Tg CO_2 Eq.

Recalculations Discussion

Estimates of CO_2 emissions from ammonia production and urea consumption were revised for all years to allocate CO_2 emissions associated with urea applied as fertilizer to the Land Use, Land-Use Change, and Forestry chapter. Revised estimates reflect a new methodology that estimates urea production and consumption based on urea consumed as fertilizer. Previous estimates of urea production are believed to have overestimated actual urea production. On average, this change resulted in a 19 percent decrease in emissions for each year in the time series 1990 through 2005; however, because CO_2 captured during ammonia production to produce urea is estimated based on the amount of urea produced, emissions from ammonia production have increased.

Planned Improvements

Plans for improvements to the ammonia production and urea consumption source category include updating emission factors to include both fuel and feedstock CO_2 emissions and incorporating CO_2 capture and storage. Methodologies will also be updated if additional ammonia-production plants are found to hydrocarbons other than natural gas for ammonia production.

Table 4-22: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ammonia Production and Urea Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ammonia Production and Urea Consumption	CO_2	12.4	11.1	13.8	-10%	+12%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

4.6. Nitric Acid Production (IPCC Source Category 2B2)

Nitric acid (HNO_3) is an inorganic compound used primarily to make synthetic commercial fertilizers. It is also a major component in the production of adipic acid—a feedstock for nylon—and explosives. Virtually all of the nitric acid produced in the United States is produced by the catalytic oxidation of ammonia (EPA 1997). During this reaction, N_2O is formed as a byproduct and is released from reactor vents into the atmosphere.

Currently, the nitric acid industry controls for emissions of NO and NO_2 (i.e., NO_x). As such, the industry uses a combination of non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) technologies. In the process of destroying NO_x, NSCR systems are also very effective at destroying N_2O. However, NSCR units are generally not preferred in modern plants because of high energy costs and associated high gas temperatures. NSCRs were widely installed in nitric plants built between 1971 and 1977. Approximately 20 percent of nitric acid plants use NSCR (Choe et al. 1993). The remaining 80 percent use SCR or extended absorption, neither of which is known to reduce N_2O emissions.

N_2O emissions from this source were estimated to be 15.6 Tg CO_2 Eq. (50 Gg) in 2006 (see Table 4-23). Emissions from nitric acid production have decreased by 7.8 percent since 1990, with the trend in the time series closely tracking the changes in production.

Methodology

N_2O emissions were calculated by multiplying nitric acid production by the amount of N_2O emitted per unit of nitric acid produced. The emission factor was determined as a weighted average of 2 kg N_2O/metric ton HNO_3 for plants using non-selective catalytic reduction (NSCR) systems and 9 kg N_2O/metric ton HNO_3 for plants not equipped with NSCR (IPCC 2006). In the process of destroying NO_x, NSCR systems destroy 80 to 90 percent of the N_2O, which is accounted for in the emission factor of 2 kg N_2O/metric ton HNO_3. An estimated 20 percent of HNO_3 plants in the United States are equipped with NSCR (Choe et al. 1993). Hence, the emission factor is equal to $(9 \times 0.80) + (2 \times 0.20)$ = 7.6 kg N_2O per metric ton HNO_3.

Nitric acid production data for 1990 through 2004 was obtained from the U.S. Census Bureau, *Current Industrial Reports* (2006) and for 2005 through 2006, from the U.S. Census Bureau, *Current Industrial Reports* (2007) (see Table 4-24).

Uncertainty

The overall uncertainty associated with the 2006 N_2O emissions estimate from nitric acid production was calculated using the IPCC Guidelines for National Greenhouse Gas Inventories (2006) Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions included that of production data, the share of U.S. nitric acid production attributable to each emission abatement technology, and the emission factors applied to each abatement technology type.

Table 4-23: N_2O Emissions from Nitric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	17.0	55
1995	18.9	61
2000	18.6	60
2001	15.1	49
2002	16.4	53
2003	15.4	50
2004	15.2	49
2005	15.8	51
2006	15.6	50

Table 4-24: Nitric Acid Production (Gg)

Year	Gg
1990	7,195
1995	8,019
2000	7,900
2001	6,417
2002	6,941
2003	6,522
2004	6,467
2005	6,711
2006	6,637

Table 4-25: Tier 2 Quantitative Uncertainty Estimates for N$_2$O Emissions From Nitric Acid Production (Tg CO$_2$ Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO$_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO$_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Nitric Acid Production	N$_2$O	15.6	9.4	22.1	-40%	+41%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-25. N$_2$O emissions from nitric acid production were estimated to be between 9.4 and 22.1 Tg CO$_2$ Eq. at the 95 percent confidence level. This indicates a range of approximately 40 percent below to 41 percent above the 2006 emissions estimate of 15.6 Tg CO$_2$ Eq.

Recalculations Discussion

The nitric acid production values for 2003 and 2005 have been updated relative to the previous Inventory based on revised production data published by the U.S. Census Bureau (2006, 2007). The updated production data for 2003 resulted in a decrease of 0.6 Tg CO$_2$ Eq. (3.3 percent) in N$_2$O emissions relative to the previous Inventory. The updated production data for 2005 resulted in an increase of 1.0 Tg CO$_2$ Eq. (6.1 percent) in N$_2$O emissions relative to the previous Inventory. Minor changes in production data due to directly citing U.S. Census Bureau reports in this Inventory resulted in negligible changes in N$_2$O emissions relative to the previous Inventory (less than one-tenth of one percent) for all other years in the time series, respectively. Additionally, the N$_2$O emission factor for plants not equipped with NSCR systems has been updated based on IPCC Guidelines (2006), which resulted in a slight decrease in emissions in each year of the time series relative to the previous Inventory. Overall, these changes resulted in an average annual decrease in N$_2$O emissions of 0.9 Tg CO$_2$ Eq. (4.8 percent) for the period 1990 through 2005 relative to the previous Inventory.

Planned Improvements

Planned improvements are focused on assessing the plant-by-plant implementation of NO$_x$ abatement technologies to more accurately match plant production capacities to appropriate emission factors, instead of using a national profiling of abatement implementation.

4.7. Adipic Acid Production (IPCC Source Category 2B3)

Adipic acid production is an anthropogenic source of N$_2$O emissions. Worldwide, few adipic acid plants exist. The United States and Europe are the major producers. The United States has three companies in four locations accounting for 34 percent of world production, and eight European producers account for a combined 38 percent of world production (CW 2007). Adipic acid is a white crystalline solid used in the manufacture of synthetic fibers, plastics, coatings, urethane foams, elastomers, and synthetic lubricants. Commercially, it is the most important of the aliphatic dicarboxylic acids, which are used to manufacture polyesters. Eighty-four percent of all adipic acid produced in the United States is used in the production of nylon 6,6, 9 percent is used in the production of polyester polyols, 4 percent is used in the production of plasticizers, and the remaining 4 percent is accounted for by other uses, including unsaturated polyester resins and food applications (ICIS 2007). Food-grade adipic acid is used to provide some foods with a "tangy" flavor (Thiemens and Trogler 1991).

Adipic acid is produced through a two-stage process during which N$_2$O is generated in the second stage. The first stage of production usually involves the oxidation of cyclohexane to form a cyclohexanone/cyclohexanol mixture. The second stage involves oxidizing this mixture with nitric acid to produce adipic acid. N$_2$O is generated as a byproduct of the nitric acid oxidation stage and is emitted in the waste gas stream (Thiemens and Trogler 1991). Process emissions from the production of adipic acid vary with the types of technologies and level of emission controls employed by a facility. In 1990, two of the three major adipic acid-producing plants had N$_2$O abatement technologies in place and, as of 1998, the three major adipic acid production facilities had

Table 4-26: N$_2$O Emissions from Adipic Acid Production (Tg CO$_2$ Eq. and Gg)

Year	Tg CO$_2$ Eq.	Gg
1990	15.3	49
1995	17.3	56
2000	6.2	20
2001	5.1	16
2002	6.1	20
2003	6.3	20
2004	5.9	19
2005	5.9	19
2006	5.9	19

control systems in place.[10] Only one small plant, representing approximately two percent of production, does not control for N$_2$O (Reimer 1999).

N$_2$O emissions from adipic acid production were estimated to be 5.9 Tg CO$_2$ Eq. (19 Gg) in 2006 (see Table 4-26). National adipic acid production has increased by approximately 36 percent over the period of 1990 through 2006, to approximately one million metric tons. At the same time, emissions have been reduced by 61 percent due to the widespread installation of pollution control measures in the late 1990s.

Methodology

For two production plants, 1990 to 2002 emission estimates were obtained directly from the plant engineer and account for reductions due to control systems in place at these plants during the time series (Childs 2002, 2003). These estimates were based on continuous emissions monitoring equipment installed at the two facilities. Reported emission estimates for 2003 to 2006 were unavailable and, thus, were calculated by applying 4.4, 4.2, 0.0, and 0.0 percent national production growth rates, respectively. 2003 national production was calculated through linear interpolation between 2002 and 2004 reported national production data. 2005 national production was calculated through linear interpolation between 2004 and 2006 reported national production. Subsequently, the growth rates for 2004, 2005, and 2006 were based on the change between the estimated

2003 production data and the reported 2004 production data, the change between 2004 reported production data and the estimated 2005 production data, and between the estimated 2005 production data and the reported 2006 production data, respectively (see discussion below on sources of production data). For the other two plants, N$_2$O emissions were calculated by multiplying adipic acid production by an emission factor (i.e., N$_2$O emitted per unit of adipic acid produced) and adjusting for the percentage of N$_2$O released as a result of plant-specific emission controls. On the basis of experiments, the overall reaction stoichiometry for N$_2$O production in the preparation of adipic acid was estimated at approximately 0.3 metric tons of N$_2$O per metric ton of product (IPCC 2006). Emissions are estimated using the following equation:

N$_2$O emissions = production of adipic acid (MT) ×
(0.3 MT N$_2$O/MT adipic acid) ×
(1-[N$_2$O destruction factor × abatement system utility factor])

The "N$_2$O destruction factor" represents the percentage of N$_2$O emissions that are destroyed by the installed abatement technology. The "abatement system utility factor" represents the percentage of time that the abatement equipment operates during the annual production period. Overall, in the United States, two of the plants employ catalytic destruction, one plant employs thermal destruction, and the smallest plant uses no N$_2$O abatement equipment. For the one plant that uses thermal destruction and for which no reported plant-specific emissions are available, the N$_2$O abatement system destruction factor is assumed to be 98.5 percent, and the abatement system utility factor is assumed to be 97 percent (IPCC 2006).

For 1990 to 2003, plant-specific production data was estimated where direct emission measurements were not available. In order to calculate plant-specific production for the two plants, national adipic acid production was allocated to the plant level using the ratio of their known plant capacities to total national capacity for all U.S. plants. The estimated plant production for the two plants was then used for calculating emissions as described above. For 2004 and 2006, actual plant production data were obtained for these two plants and used for emission calculations. For 2005, interpolated national production was used for calculating emissions as described above.

---

[10] During 1997, the N$_2$O emission controls installed by the third plant operated for approximately a quarter of the year.

Table 4-27: Adipic Acid Production (Gg)

Year	Gg
1990	735
1995	830
2000	925
2001	835
2002	921
2003	961
2004	1,002
2005	1,002
2006	1,002

National adipic acid production data (see Table 4-27) for 1990 through 2002 were obtained from the American Chemistry Council (ACC 2003). Production for 2003 was estimated based on linear interpolation of 2002 and 2004 reported production. Production for 2004 and 2006 were obtained from *Chemical Week*, Product Focus: Adipic Acid (CW 2005, 2007). Plant capacities for 1990 through 1994 were obtained from *Chemical and Engineering News*, "Facts and Figures" and "Production of Top 50 Chemicals" (C&EN 1992 through 1995). Plant capacities for 1995 and 1996 were kept the same as 1994 data. The 1997 plant capacities were taken from *Chemical Market Reporter* "Chemical Profile: Adipic Acid" (CMR 1998). The 1998 plant capacities for all four plants and 1999 plant capacities for three of the plants were obtained from *Chemical Week*, Product Focus: Adipic Acid/Adiponitrile (CW 1999). Plant capacities for 2000 for three of the plants were updated using *Chemical Market Reporter*, "Chemical Profile: Adipic Acid" (CMR 2001). For 2001 through 2005, the plant capacities for these three plants were kept the same as the year 2000 capacities. Plant capacity for 1999 to 2005 for the one remaining plant was kept the same as 1998. For 2004 to 2006, although plant capacity data are available (CW 1999, CMR 2001, ICIS 2007), they are not used to calculate plant-specific production for these years because plant-specific production data for 2004 and 2006 are also available and are used in our calculations instead (CW 2005, CW 2007).

Uncertainty

The overall uncertainty associated with the 2006 N_2O emission estimate from adipic acid production was calculated using the IPCC Guidelines for National Greenhouse Gas Inventories (2006) Tier 2 methodology. Uncertainty associated with the parameters used to estimate N_2O emissions included that of company specific production data, industry wide estimated production growth rates, emission factors for abated and unabated emissions, and company specific historical emissions estimates.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-28. N_2O emissions from adipic acid production were estimated to be between 5.0 and 6.9 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 15 percent below to 16 percent above the 2006 emission estimate of 5.9 Tg CO_2 Eq.

Recalculations Discussion

The adipic acid production value for 2005 was recalculated. In the 1990–2005 Inventory, 2005 production was calculated by applying the annual production growth rate from 2003 to 2004 of 4 percent to 2004 production. In this Inventory, 2005 production was recalculated because 2006 production data is now available (CW 2007). 2005 production was estimated through linear interpolation between 2004 and 2006 reported production data. The updated production value for 2005 resulted in a decrease of 0.3 Tg CO_2 Eq. (4.1 percent) in N_2O emissions relative to the previous inventory. Additionally, changes based on IPCC Guidelines (2006) to the N_2O destruction factor and abatement system utilization factor for one plant resulted in an increase of between 0.1 and 0.2 Tg CO_2 Eq. (0.8 to 3.2 percent) in N_2O emissions in each year of the historical time series, respectively.

Table 4-28: Tier 2 Quantitative Uncertainty Estimates for N_2O Emissions from Adipic Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Adipic Acid Production	N_2O	5.9	5.0	6.9	-15%	+16%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Planned Improvements

Improvement efforts will be focused on obtaining direct measurement data from facilities. If they become available, cross verification with top-down approaches will provide a useful Tier 2 level QC check. Also, additional information on the actual performance of the latest catalytic and thermal abatement equipment at plants with continuous emission monitoring may support the re-evaluation of current default abatement values.

4.8. Silicon Carbide Production (IPCC Source Category 2B4) and Consumption

CO_2 and CH_4 are emitted from the production of silicon carbide (SiC), a material used as an industrial abrasive. To make SiC, quartz (SiO_2) is reacted with C in the form of petroleum coke. A portion (about 35 percent) of the C contained in the petroleum coke is retained in the SiC. The remaining C is emitted as CO_2, CH_4, or CO.

CO_2 is also emitted from the consumption of SiC for metallurgical and other non-abrasive applications. The USGS reports that a portion (approximately 50 percent) of SiC is used in metallurgical and other non-abrasive applications, primarily in iron and steel production (USGS 2005a).

CO_2 from SiC production and consumption in 2006 were 0.2 Tg CO_2 Eq. (207 Gg). Approximately 44 percent of these emissions resulted from SiC production while the remainder result from SiC consumption. CH_4 emissions from SiC production in 2006 were 0.01 Tg CO_2 Eq. CH_4 (0.4 Gg) (see Table 4-29 and Table 4-30).

Methodology

Emissions of CO_2 and CH_4 from the production of SiC were calculated by multiplying annual SiC production by the emission factors (2.62 metric tons CO_2/metric ton SiC for CO_2 and 11.6 kg CH_4/metric ton SiC for CH_4) provided by the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

Emissions of CO_2 from silicon carbide consumption were calculated by multiplying the annual SiC consumption (production plus net imports) by the percent used in metallurgical and other non-abrasive uses (50 percent) (USGS 2005a). The total SiC consumed in metallurgical and other non-abrasive uses was multiplied by the C content of SiC (31.5 percent), which was determined according to the molecular weight ratio of SiC.

Production data for 1990 through 2005 were obtained from the *Minerals Yearbook: Manufactured Abrasives* (USGS 1991a through 2005a, 2006). Production data for 2006 were obtained from a personal communication with the USGS Minerals Commodity Specialist (Corathers 2007). Silicon carbide consumption by major end use was obtained from the *Minerals Yearbook: Silicon* (USGS 1991b through 2005b) (see Table 4-31) for years 1990 through 2004 and from the USGS Minerals Commodity Specialist for 2005 and 2006 (Corathers 2006, 2007). Net imports for the entire time series were obtained from the U.S. Census Bureau (2005 through 2007).

Table 4-29: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (Tg CO_2 Eq.)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
CH_4	+	+	+	+	+	+	+	+	+
Total	**0.4**	**0.3**	**0.3**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**

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

Table 4-30: CO_2 and CH_4 Emissions from Silicon Carbide Production and Consumption (Gg)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	375	329	248	199	183	202	224	219	207
CH_4	1	1	1	+	+	+	+	+	+

+ Does not exceed 0.5 Gg.

Table 4-31: Production and Consumption of Silicon Carbide (Metric Tons)

Year	Production	Consumption
1990	105,000	172,464
1995	75,400	227,397
2000	45,000	225,280
2001	40,000	162,142
2002	30,000	180,956
2003	35,000	191,289
2004	35,000	229,692
2005	35,000	220,150
2006	35,000	199,938

Uncertainty

There is uncertainty associated with the emission factors used because they are based on stoichiometry as opposed to monitoring of actual SiC production plants. An alternative would be to calculate emissions based on the quantity of petroleum coke used during the production process rather than on the amount of silicon carbide produced. However, these data were not available. For CH_4, there is also uncertainty associated with the hydrogen-containing volatile compounds in the petroleum coke (IPCC 2006). There is also some uncertainty associated with production, net imports, and consumption data as well as the percent of total consumption that is attributed to metallurgical and other non-abrasive uses.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-32. Silicon carbide production and consumption CO_2 emissions were estimated to be between 10 percent below and 10 percent above the emission estimate of 0.2 Tg CO_2 Eq. at the 95 percent confidence level. Silicon carbide production CH_4 emissions were estimated to be between 9 percent below and 10 percent above the emission estimate of 0.01 Tg CO_2 Eq. at the 95 percent confidence level.

Planned Improvements

Future improvements to the carbide production source category include continued research to determine if calcium carbide production and consumption data are available for the United States. If these data are available, calcium carbide emission estimates will be included in this source category.

4.9. Petrochemical Production (IPCC Source Category 2B5)

The production of some petrochemicals results in the release of small amounts of CH_4 and CO_2 emissions. Petrochemicals are chemicals isolated or derived from petroleum or natural gas. CH_4 emissions are presented here from the production of C black, ethylene, ethylene dichloride, and methanol, while CO_2 emissions are presented here for only C black production. The CO_2 emissions from petrochemical processes other than C black are currently included in the Carbon Stored in Products from Non-Energy Uses of Fossil Fuels section of the Energy chapter. The CO_2 from C black production is included here to allow for the direct reporting of CO_2 emissions from the process and direct accounting of the feedstocks used in the process.

C black is an intensely black powder generated by the incomplete combustion of an aromatic petroleum or coal-based feedstock. Most C black produced in the United States is added to rubber to impart strength and abrasion resistance, and the tire industry is by far the largest consumer. Ethylene is consumed in the production processes of the plastics industry including polymers such as high, low, and

Table 4-32: Tier 2 Quantitative Uncertainty Estimates for CH_4 and CO_2 Emissions from Silicon Carbide Production and Consumption (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Silicon Carbide Production and Consumption	CO_2	0.2	0.2	0.2	-10%	+10%
Silicon Carbide Production and Consumption	CH_4	+	+	+	-9%	+10%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
+ Does not exceed 0.05 Tg CO_2 Eq. or 0.5 Gg.

linear low density polyethylene (HDPE, LDPE, LLDPE), polyvinyl chloride (PVC), ethylene dichloride, ethylene oxide, and ethylbenzene. Ethylene dichloride is one of the first manufactured chlorinated hydrocarbons with reported production as early as 1795. In addition to being an important intermediate in the synthesis of chlorinated hydrocarbons, ethylene dichloride is used as an industrial solvent and as a fuel additive. Methanol is an alternative transportation fuel as well as a principle ingredient in windshield wiper fluid, paints, solvents, refrigerants, and disinfectants. In addition, methanol-based acetic acid is used in making PET plastics and polyester fibers.

Emissions of CO_2 and CH_4 from petrochemical production in 2006 were 2.6 Tg CO_2 Eq. (2,573 Gg) and 1.0 Tg CO_2 Eq. (48 Gg), respectively (see Table 4-33 and Table 4-34), totaling 3.6 Tg CO_2 Eq. Emissions of CO_2 from C black production decreased from 2.8 Tg CO_2 Eq. (2,805 Gg) in 2005 to 2.6 Tg CO_2 Eq. (2,573 Gg) in 2006 . There has been an overall increase in CO_2 emissions from C black production of 16 percent since 1990. CH_4 emissions from petrochemical production decreased by less than 1 percent from the previous year and increased 16 percent since 1990.

Methodology

Emissions of CH_4 were calculated by multiplying annual estimates of chemical production by the appropriate emission factor, as follows: 11 kg CH_4/metric ton C black, 1 kg CH_4/metric ton ethylene, 0.4 kg CH_4/metric ton ethylene dichloride,[11] and 2 kg CH_4/metric ton methanol. Although the production of other chemicals may also result in CH_4

emissions, there were not sufficient data available to estimate their emissions.

Emission factors were taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Annual production data for 1990 (see Table 4-35) were obtained from the Chemical Manufacturer's Association *Statistical Handbook* (CMA 1999). Production data for 1991 through 2006 were obtained from the American Chemistry Council's *Guide to the Business of Chemistry* (ACC 2002, 2003, 2005 through 2007) and the International Carbon Black Association (Johnson 2003, 2005 through 2007).

Almost all C black in the United States is produced from petroleum-based or coal-based feedstocks using the "furnace black" process (European IPPC Bureau 2004). The furnace black process is a partial combustion process in which a portion of the C black feedstock is combusted to provide energy to the process. C black is also produced in the United States by the thermal cracking of acetylene-containing feedstocks ("acetylene black process") and by the thermal cracking of other hydrocarbons ("thermal black process"). One U.S. C black plant produces C black using the thermal black process, and one U.S. C black plant produces C black using the acetylene black process (The Innovation Group 2004).

The furnace black process produces C black from "C black feedstock" (also referred to as "C black oil"), which is a heavy aromatic oil that may be derived as a byproduct of either the petroleum refining process or the metallurgical (coal) coke production process. For the production of both

Table 4-33: CO_2 and CH_4 Emissions from Petrochemical Production (Tg CO_2 Eq.)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	2.2	2.8	3.0	2.8	2.9	2.8	2.9	2.8	2.6
CH_4	0.9	1.1	1.2	1.1	1.1	1.1	1.2	1.1	1.0
Total	**3.1**	**3.8**	**4.2**	**3.9**	**4.0**	**3.9**	**4.1**	**4.0**	**3.6**

Table 4-34: CO_2 and CH_4 Emissions from Petrochemical Production (Gg)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	2,221	2,750	3,004	2,787	2,857	2,777	2,895	2,804	2,573
CH_4	41	52	58	51	52	51	55	51	48

---

[11] The emission factor obtained from IPCC/UNEP/OECD/IEA (1997), page 2.23 is assumed to have a misprint; the chemical identified should be ethylene dichloride ($C_2H_4Cl_2$) rather than dichloroethylene ($C_2H_2Cl_2$).

Table 4-35: Production of Selected Petrochemicals (Thousand Metric Tons)

Chemical	1990	1995	2000	2001	2002	2003	2004	2005	2006
Carbon Black	1,307	1,619	1,769	1,641	1,682	1,635	1,705	1,651	1,515
Ethylene	16,542	21,215	24,971	22,521	23,623	22,957	25,660	23,954	25,000
Ethylene Dichloride	6,282	7,829	9,866	9,294	9,288	9,952	12,111	11,261	9,737
Methanol	3,785	4,992	4,876	3,402	3,289	3,166	2,937	2,336	1,123

Table 4-36: Carbon Black Feedstock (Primary Feedstock) and Natural Gas Feedstock (Secondary Feedstock) Consumption (Thousand Metric Tons)

Activity	1990	1995	2000	2001	2002	2003	2004	2005	2006
Primary Feedstock	1,864	2,308	2,521	2,339	2,398	2,331	2,430	2,353	2,159
Secondary Feedstock	302	374	408	379	388	377	393	381	350

petroleum-derived and coal-derived C black, the "primary feedstock" (i.e., C black feedstock) is injected into a furnace that is heated by a "secondary feedstock" (generally natural gas). Both the natural gas secondary feedstock and a portion of the C black feedstock are oxidized to provide heat to the production process and pyrolyze the remaining C black feedstock to C black. The "tail gas" from the furnace black process contains CO_2, carbon monoxide, sulfur compounds, CH_4, and non-CH_4 volatile organic compounds. A portion of the tail gas is generally burned for energy recovery to heat the downstream C black product dryers. The remaining tail gas may also be burned for energy recovery, flared, or vented uncontrolled to the atmosphere.

The calculation of the C lost during the production process is the basis for determining the amount of CO_2 released during the process. The C content of national C black production is subtracted from the total amount of C contained in primary and secondary C black feedstock to find the amount of C lost during the production process. It is assumed that the C lost in this process is emitted to the atmosphere as either CH_4 or CO_2. The C content of the CH_4 emissions, estimated as described above, is subtracted from the total C lost in the process to calculate the amount of C emitted as CO_2. The total amount of primary and secondary C black feedstock consumed in the process (see Table 4-36) is estimated using a primary feedstock consumption factor and a secondary feedstock consumption factor estimated from U.S. Census Bureau (1999 and 2004) data. The average C black feedstock consumption factor for U.S. C black production is 1.43 metric tons of C black feedstock consumed per metric ton of C black produced. The average

natural gas consumption factor for U.S. C black production is 341 normal cubic meters of natural gas consumed per metric ton of C black produced. The amount of C contained in the primary and secondary feedstocks is calculated by applying the respective C contents of the feedstocks to the respective levels of feedstock consumption (EIA 2003, 2004).

For the purposes of emissions estimation, 100 percent of the primary C black feedstock is assumed to be derived from petroleum refining byproducts. C black feedstock derived from metallurgical (coal) coke production (e.g., creosote oil) is also used for C black production; however, no data are available concerning the annual consumption of coal-derived C black feedstock. C black feedstock derived from petroleum refining byproducts is assumed to be 89 percent elemental C (Srivastava et al. 1999). It is assumed that 100 percent of the tail gas produced from the C black production process is combusted and that none of the tail gas is vented to the atmosphere uncontrolled. The furnace black process is assumed to be the only process used for the production of C black because of the lack of data concerning the relatively small amount of C black produced using the acetylene black and thermal black processes. The C black produced from the furnace black process is assumed to be 97 percent elemental C (Othmer et al. 1992).

Uncertainty

The CH_4 emission factors used for petrochemical production are based on a limited number of studies. Using plant-specific factors instead of average factors could increase the accuracy of the emission estimates; however, such data were not available. There may also be other significant

Table 4-37: Tier 2 Quantitative Uncertainty Estimates for CH$_4$ Emissions from Petrochemical Production and CO$_2$ Emissions from Carbon Black Production (Tg CO$_2$ Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO$_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO$_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Petrochemical Production	CO$_2$	2.6	1.7	3.6	-35%	+39%
Petrochemical Production	CH$_4$	1.0	0.9	1.1	-9%	+9%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

sources of CH$_4$ arising from petrochemical production activities that have not been included in these estimates.

The results of the quantitative uncertainty analysis for the CO$_2$ emissions from C black production calculation are based on feedstock consumption, import and export data, and C black production data. The composition of C black feedstock varies depending upon the specific refinery production process, and therefore the assumption that C black feedstock is 89 percent C gives rise to uncertainty. Also, no data are available concerning the consumption of coal-derived C black feedstock, so CO$_2$ emissions from the utilization of coal-based feedstock are not included in the emission estimate. In addition, other data sources indicate that the amount of petroleum-based feedstock used in C black production may be underreported by the U.S. Census Bureau. Finally, the amount of C black produced from the thermal black process and acetylene black process, although estimated to be a small percentage of the total production, is not known. Therefore, there is some uncertainty associated with the assumption that all of the C black is produced using the furnace black process.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-37. Petrochemical production CO$_2$ emissions were estimated to be between 1.7 and 3.6 Tg CO$_2$ Eq. at the 95 percent confidence level. This indicates a range of approximately 35 percent below to 39 percent above the emission estimate of 2.6 Tg CO$_2$ Eq. Petrochemical production CH$_4$ emissions were estimated to be between 0.9 and 1.1 Tg CO$_2$ Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below to 9 percent above the emission estimate of 1.0 Tg CO$_2$ Eq.

Recalculations Discussion

Estimates of CO$_2$ from carbon black have been revised for 2005 to reflect new production data. The revision resulted in a decrease in emissions of less than one percent.

Planned Improvements

Future improvements to the petrochemicals source category include research into the use of acrylonitrile in the United States, revisions to the C black CH$_4$ and CO$_2$ emission factors, and research into process and feedstock data to obtain Tier 2 emission estimates from the production of methanol, ethylene, propylene, ethylene dichloride, and ethylene oxide.

4.10. Titanium Dioxide Production (IPCC Source Category 2B5)

Titanium dioxide (TiO$_2$) is a metal oxide produced from titanium ore, and is principally used as a pigment. Titanium dioxide is a principal ingredient in white paint, and is also used as a pigment in the manufacture of white paper, foods, and other products. There are two processes for making TiO$_2$: the chloride process and the sulfate process. The chloride process uses petroleum coke and chlorine as raw materials and emits process-related CO$_2$. The sulfate process does not use petroleum coke or other forms of C as a raw material and does not emit CO$_2$.

The chloride process is based on the following chemical reactions:

$$2 \, FeTiO_3 + 7 \, Cl_2 + 3 \, C \rightarrow 2 \, TiCl_4 + 2 \, FeCl_3 + 3 \, CO_2$$

$$2 \, TiCl_4 + 2 \, O_2 \rightarrow 2 \, TiO_2 + 4 \, Cl_2$$
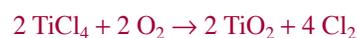
The C in the first chemical reaction is provided by petroleum coke, which is oxidized in the presence of the chlorine and FeTiO$_3$ (the Ti-containing ore) to form CO$_2$. The majority of U.S. TiO$_2$ was produced in the United States through the chloride process, and a special grade of petroleum coke is manufactured specifically for this purpose.

Emissions of CO$_2$ in 2006 were 1.9 Tg CO$_2$ Eq. (1,876 Gg), an increase of 7 percent from the previous year and an increase of 57 percent since 1990 (Table 4-38).

Table 4-38: CO₂ Emissions from Titanium Dioxide Production (Tg CO₂ Eq. and Gg)

Year	Tg CO$_2$ Eq.	Gg
1990	1.2	1,195
1995	1.5	1,526
2000	1.8	1,752
2001	1.7	1,697
2002	1.8	1,824
2003	1.8	1,839
2004	2.1	2,064
2005	1.8	1,755
2006	1.9	1,876

Table 4-39: Titanium Dioxide Production (Gg)

Year	Gg
1990	979
1995	1,250
2000	1,400
2001	1,330
2002	1,410
2003	1,420
2004	1,540
2005	1,310
2006	1,400

Methodology

Emissions of CO_2 from TiO_2 production were calculated by multiplying annual TiO_2 production by chloride-process-specific emission factors.

Data were obtained for the total amount of TiO_2 produced each year. For years previous to 2004, it was assumed that TiO_2 was produced using the chloride process and the sulfate process in the same ratio as the ratio of the total U.S. production capacity for each process. As of 2004, the last remaining sulfate-process plant in the United States had closed. As a result, all U.S. current TiO_2 production results from the chloride process (USGS 2005). An emission factor of 0.4 metric tons C/metric ton TiO_2 was applied to the estimated chloride-process production. It was assumed that all TiO_2 produced using the chloride process was produced using petroleum coke, although some TiO_2 may have been produced with graphite or other C inputs. The amount of petroleum coke consumed annually in TiO_2 production was calculated based on the assumption that petroleum coke used in the process is 90 percent C and 10 percent inert materials.

The emission factor for the TiO_2 chloride process was taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Titanium dioxide production data and the percentage of total TiO_2 production capacity that is chloride process for 1990 through 2006 (see Table 4-39) were obtained from a personal communication with Joe Gambogi, USGS Commodity Specialist, of the USGS (Gambogi 2007) and through the *Minerals Yearbook: Titanium Annual Report* (USGS 1991 through 2005). Percentage chloride-process data were not available for

1990 through 1993, and data from the 1994 USGS *Minerals Yearbook* were used for these years. Because a sulfate-process plant closed in September 2001, the chloride-process percentage for 2001 was estimated based on a discussion with Joseph Gambogi (2002). By 2002, only one sulfate plant remained online in the United States and this plant closed in 2004 (USGS 2005). The composition data for petroleum coke were obtained from Onder and Bagdoyan (1993).

Uncertainty

Although some TiO_2 may be produced using graphite or other C inputs, information and data regarding these practices were not available. Titanium dioxide produced using graphite inputs, for example, may generate differing amounts of CO_2 per unit of TiO_2 produced as compared to that generated through the use of petroleum coke in production. While the most accurate method to estimate emissions would be to base calculations on the amount of reducing agent used in each process rather than on the amount of TiO_2 produced, sufficient data were not available to do so.

Also, annual TiO_2 is not reported by USGS by the type of production process used (chloride or sulfate). Only the percentage of total production capacity by process is reported. The percent of total TiO_2 production capacity that was attributed to the chloride process was multiplied by total TiO_2 production to estimate the amount of TiO_2 produced using the chloride process (since, as of 2004, the last remaining sulfate-process plant in the United States closed). This assumes that the chloride-process plants and sulfate-process plants operate at the same level of utilization. Finally, the emission factor was applied uniformly to all chloride-

Table 4-40: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Titanium Dioxide Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Titanium Dioxide Production	CO_2	1.9	1.7	2.1	-12%	+13%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

process production, and no data were available to account for differences in production efficiency among chloride-process plants. In calculating the amount of petroleum coke consumed in chloride-process TiO_2 production, literature data were used for petroleum coke composition. Certain grades of petroleum coke are manufactured specifically for use in the TiO_2 chloride process; however, this composition information was not available.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-40. Titanium dioxide consumption CO_2 emissions were estimated to be between 1.7 and 2.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 13 percent above the emission estimate of 1.9 Tg CO_2 Eq.

Recalculations Discussion

Estimates of CO_2 emissions from titanium dioxide production were updated to reflect a revised chloride-process emission factor provided by the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). The change in emission factor resulted in a decrease in emissions of 8.6 percent for each year in the time series.

Planned Improvements

Future improvements to TiO_2 production methodology include researching the significance of titanium-slag production in electric furnaces and synthetic-rutile production using the Becher process in the United States. Significant use of these production processes will be included in future estimates.

4.11. Carbon Dioxide Consumption (IPCC Source Category 2B5)

CO_2 is used for a variety of commercial applications, including food processing, chemical production, carbonated beverage production, and refrigeration, and is also used in petroleum production for enhanced oil recovery (EOR). CO_2 used for EOR is injected into the underground reservoirs to increase the reservoir pressure to enable additional petroleum to be produced.

For the most part, CO_2 used in non-EOR applications will eventually be released to the atmosphere, and for the purposes of this analysis CO_2 used in commercial applications other than EOR is assumed to be emitted to the atmosphere. CO_2 used in EOR applications is discussed in the Energy Chapter under "Carbon Capture and Storage, including Enhanced Oil Recovery" and is not discussed in this section.

CO_2 is produced from naturally occurring CO_2 reservoirs, as a byproduct from the energy and industrial production processes (e.g., ammonia production, fossil fuel combustion, ethanol production), and as a byproduct from the production of crude oil and natural gas, which contain naturally occurring CO_2 as a component. Only CO_2 produced from naturally occurring CO_2 reservoirs and used in industrial applications other than EOR is included in this analysis. Neither byproduct CO_2 generated from energy nor industrial production processes nor CO_2 separated from crude oil and natural gas are included in this analysis for a number of reasons. CO_2 captured from biogenic sources (e.g., ethanol production plants) is not included in the inventory. CO_2 captured from crude oil and gas production is used in EOR applications and is therefore reported in the Energy Chapter. Any CO_2 captured from industrial or energy production processes (e.g., ammonia plants, fossil fuel combustion) and used in non-EOR applications is assumed to be emitted to the atmosphere. The CO_2 emissions from such capture and use are therefore accounted for under Ammonia Production, Fossil Fuel Combustion, or other appropriate source category.

CO_2 is produced as a byproduct of crude oil and natural gas production. This CO_2 is separated from the crude oil and

natural gas using gas processing equipment, and may be emitted directly to the atmosphere, or captured and reinjected into underground formations, used for EOR, or sold for other commercial uses. A further discussion of CO_2 used in EOR is described in the Energy Chapter under "Box 3-3 Carbon Dioxide Transport, Injection, and Geological Storage." The only CO_2 consumption that is accounted for in this analysis is CO_2 produced from naturally-occurring CO_2 reservoirs that is used in commercial applications other than EOR.

There are currently two facilities, one in Mississippi and one in New Mexico, producing CO_2 from naturally occurring CO_2 reservoirs for use in both EOR and in other commercial applications (e.g., chemical manufacturing, food production). There are other naturally occurring CO_2 reservoirs, mostly located in the western U.S. facilities are producing CO_2 from these natural reservoirs, but they are only producing CO_2 for EOR applications, not for other commercial applications

Table 4-41: CO_2 Emissions from CO_2 Consumption (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.4	1,416
1995	1.4	1,422
2000	1.4	1,421
2001	0.8	829
2002	1.0	989
2003	1.3	1,311
2004	1.2	1,198
2005	1.3	1,321
2006	1.6	1,579

(Allis et al. 2000). CO_2 production from these facilities is discussed in the Energy Chapter.

In 2006, the amount of CO_2 produced by the Mississippi and New Mexico facilities for commercial applications and subsequently emitted to the atmosphere were 1.6 Tg CO_2 Eq. (1,579 Gg) (see Table 4-41). This amount represents an increase of 17.9 percent from the previous year and an increase of 9.9 percent from emissions in 1990. This increase was due to an in increase in production at the Mississippi facility, despite the decrease in the percent of the facility's total reported production that was used for commercial applications.

Methodology

CO_2 emission estimates for 1990 through 2006 were based on production data for the two facilities currently producing CO_2 from naturally-occurring CO_2 reservoirs for use in non-EOR applications. Some of the CO_2 produced by these facilities is used for EOR and some is used in other commercial applications (e.g., chemical manufacturing, food production). It is assumed that 100 percent of the CO_2 production used in commercial applications other than EOR is eventually released into the atmosphere.

CO_2 production data for the Jackson Dome, Mississippi facility and the percentage of total production that was used for EOR and in non-EOR applications were obtained from the Advanced Resources Institute (ARI 2006, 2007) for 1990 to 2000 and from the Annual Reports for Denbury Resources (Denbury Resources 2002 through 2007) for 2001 to 2006 (see Table 4-42). Denbury Resources reported the average CO_2 production in units of MMCF CO_2 per day

Table 4-42: CO_2 Production (Gg CO_2) and the Percent Used for Non-EOR Applications for Jackson Dome and Bravo Dome

Year	Jackson Dome CO_2 Production (Gg)	Jackson Dome % Used for Non-EOR	Bravo Dome CO_2 Production (Gg)	Bravo Dome % Used for Non-EOR
1990	1,353	100%	6,301	1%
1995	1,353	100%	6,862	1%
2000	1,353	100%	6,834	1%
2001	1,624	47%	6,627	1%
2002	2,010	46%	6,420	1%
2003	3,286	38%	6,213	1%
2004	4,214	27%	6,006	1%
2005	4,678	27%	5,799	1%
2006	7,615	20%	5,613	1%

Table 4-43: Tier 2 Quantitative Uncertainty Estimates for CO₂ Emissions from CO₂ Consumption (Tg CO₂ Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO₂ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO₂ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
CO₂ Consumption	CO₂	1.6	1.3	2.0	-21%	+26%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

for 2001 through 2006 and reported the percentage of the total average annual production that was used for EOR. CO_2 production data for the Bravo Dome, New Mexico facility were obtained from the Advanced Resources International, Inc. (ARI 2006, 2007).

Uncertainty

Uncertainty is associated with the number of facilities that are currently producing CO_2 from naturally occurring CO_2 reservoirs for commercial uses other than EOR, and for which the CO_2 emissions are not accounted for elsewhere. Research indicates that there are only two such facilities, which are in New Mexico and Mississippi; however, additional facilities may exist that have not been identified. In addition, it is possible that CO_2 recovery exists in particular production and end-use sectors that are not accounted for elsewhere. Such recovery may or may not affect the overall estimate of CO_2 emissions from that sector depending upon the end use to which the recovered CO_2 is applied. Further research is required to determine whether CO_2 is being recovered from other facilities for application to end uses that are not accounted for elsewhere.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-43. CO_2 consumption CO_2 emissions were estimated to be between 1.3 and 2.0 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 21 percent below to 26 percent above the emission estimate of 1.6 Tg CO_2 Eq.

Recalculations Discussion

Data for total Bravo Dome CO_2 production were updated for the entire time series based on new production data from the facility. These changes resulted in an average annual emission increase of less than one percent for 1990 through 2005.

4.12. Phosphoric Acid Production (IPCC Source Category 2B5)

Phosphoric acid (H_3PO_4) is a basic raw material in the production of phosphate-based fertilizers. Phosphate rock is mined in Florida, North Carolina, Idaho, Utah, and other areas of the United States and is used primarily as a raw material for phosphoric acid production. The production of phosphoric acid from phosphate rock produces byproduct gypsum ($CaSO_4.2H_2O$), referred to as phosphogypsum.

The composition of natural phosphate rock varies depending upon the location where it is mined. Natural phosphate rock mined in the United States generally contains inorganic C in the form of calcium carbonate (limestone) and also may contain organic C. The chemical composition of phosphate rock (francolite) mined in Florida is:

$$Ca_{10-x-y} Na_x Mg_y (PO_4)_{6-x}(CO_3)_x F_{2+0.4x}$$

The calcium carbonate component of the phosphate rock is integral to the phosphate rock chemistry. Phosphate rock can also contain organic C that is physically incorporated into the mined rock but is not an integral component of the phosphate rock chemistry. Phosphoric acid production from natural phosphate rock is a source of CO_2 emissions, due to the chemical reaction of the inorganic C (calcium carbonate) component of the phosphate rock.

The phosphoric acid production process involves chemical reaction of the calcium phosphate ($Ca_3(PO_4)_2$) component of the phosphate rock with sulfuric acid (H_2SO_4) and recirculated phosphoric acid (H_3PO_4) (EFMA 2000). The primary chemical reactions for the production of phosphoric acid from phosphate rock are:

$$Ca_3(PO_4)_2 + 4H_3PO_4 \rightarrow 3Ca(H_2PO_4)_2$$

$$3Ca(H_2PO_4)_2 + 3H_2SO_4 + 6H_2O \rightarrow$$
$$3CaSO_4 \bullet 6H_2O + 6H_3PO_4$$
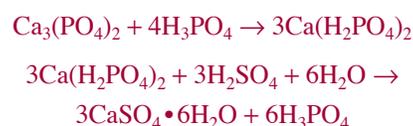
The limestone ($CaCO_3$) component of the phosphate rock reacts with the sulfuric acid in the phosphoric acid production process to produce calcium sulfate (phosphogypsum) and CO_2. The chemical reaction for the limestone-sulfuric acid reaction is:

$$CaCO_3 + H_2SO_4 + H_2O \rightarrow CaSO_4 \bullet 2H_2O + CO_2$$

Total marketable phosphate rock production in 2006 was 30.1 million metric tons. Approximately 87 percent of domestic phosphate rock production was mined in Florida and North Carolina, while approximately 13 percent of production was mined in Idaho and Utah. In addition, 2.4 million metric tons of crude phosphate rock was imported for consumption in 2006. Marketable phosphate rock production, including domestic production and imports for consumption, decreased by approximately 16 percent between 2005 and 2006. However, over the 1990 to 2006 period, production has decreased by 26 percent. Total CO_2 emissions from phosphoric acid production were 1.2 Tg CO_2 Eq. (1,167 Gg) in 2006 (see Table 4-44).

Table 4-44: CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	1.5	1,529
1995	1.5	1,513
2000	1.4	1,382
2001	1.3	1,264
2002	1.3	1,338
2003	1.4	1,382
2004	1.4	1,395
2005	1.4	1,383
2006	1.2	1,167

Methodology

CO_2 emissions from production of phosphoric acid from phosphate rock are calculated by multiplying the average amount of calcium carbonate contained in the natural phosphate rock by the amount of phosphate rock that is used annually to produce phosphoric acid, accounting for domestic production and net imports for consumption.

The CO_2 emissions calculation methodology is based on the assumption that all of the inorganic C (calcium carbonate) content of the phosphate rock reacts to CO_2 in the phosphoric acid production process and is emitted with the stack gas. The methodology also assumes that none of the organic C content of the phosphate rock is converted to CO_2 and that all of the organic C content remains in the phosphoric acid product.

From 1993 to 2004, the *USGS Mineral Yearbook: Phosphate Rock* disaggregated phosphate rock mined annually in Florida and North Carolina from phosphate rock mined annually in Idaho and Utah, and reported the annual amounts of phosphate rock exported and imported for consumption (see Table 4-45). For the years 1990, 1991, 1992, 2005, and 2006 only nationally aggregated mining data was reported by USGS. For these years, the breakdown of phosphate rock mined in Florida and North Carolina, and the amount mined in Idaho and Utah, are approximated using 1993 to 2004 data. Data for domestic production of phosphate rock, exports of phosphate rock, and imports of phosphate rock for consumption for 1990 through 2006 were obtained from *USGS Mineral Yearbook: Phosphate Rock* (USGS 1994 through 2007. From 2004–2006, the USGS reported no exports of phosphate rock from U.S. producers (USGS 2005 through 2007).

Table 4-45: Phosphate Rock Domestic Production, Exports, and Imports (Gg)

Location/Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
U.S. Production[a]	49,800	43,720	37,370	32,830	34,720	36,410	36,530	36,000	30,100
FL & NC	42,494	38,100	31,900	28,100	29,800	31,300	31,600	31,140	26,037
ID & UT	7,306	5,620	5,470	4,730	4,920	5,110	4,930	4,860	4,064
Exports—FL & NC	6,240	2,760	299	9	62	64	-	-	-
Imports—Morocco	451	1,800	1,930	2,500	2,700	2,400	2,500	2,630	2,420
Total U.S. Consumption	**44,011**	**42,760**	**39,001**	**35,321**	**37,358**	**38,746**	**39,030**	**38,630**	**32,520**

[a] USGS does not disaggregate production data regionally (FL & NC and ID & UT) for 1990 and 2006. Data for those years are estimated based on the remaining time series distribution.
- Assumed equal to zero.

The carbonate content of phosphate rock varies depending upon where the material is mined. Composition data for domestically mined and imported phosphate rock were provided by the Florida Institute of Phosphate Research (FIPR 2003). Phosphate rock mined in Florida contains approximately 1 percent inorganic C, and phosphate rock imported from Morocco contains approximately 1.46 percent inorganic C. Calcined phosphate rock mined in North Carolina and Idaho contains approximately 0.41 percent and 0.27 percent inorganic C, respectively (see Table 4-46).

Carbonate content data for phosphate rock mined in Florida are used to calculate the CO_2 emissions from consumption of phosphate rock mined in Florida and North Carolina (87 percent of domestic production) and carbonate content data for phosphate rock mined in Morocco are used to calculate CO_2 emissions from consumption of imported phosphate rock. The CO_2 emissions calculation is based on the assumption that all of the domestic production of phosphate rock is used in uncalcined form. At last reporting, the USGS noted that one phosphate rock producer in Idaho produces calcined phosphate rock; however, no production data were available for this single producer (USGS 2006). Carbonate content data for uncalcined phosphate rock mined in Idaho and Utah (13 percent of domestic production) were not available, and carbonate content was therefore estimated from the carbonate content data for calcined phosphate rock mined in Idaho.

Uncertainty

Phosphate rock production data used in the emission calculations were developed by the USGS through monthly and semiannual voluntary surveys of the active phosphate rock mines during 2006. For previous years in the time series, USGS provided the data disaggregated regionally; however, for 2006 only total U.S. phosphate rock production were reported. Regional production for 2006 was estimated based on regional production data from previous years and multiplied by regionally-specific emission factors. There is uncertainty associated with the degree to which the estimated 2006 regional production data represents actual production in those regions. Total U.S. phosphate rock production data are not considered to be a significant source of uncertainty because all the domestic phosphate rock producers report their annual production to the USGS. Data for imports for consumption and exports of phosphate rock used in the emission calculation are based on international trade data collected by the U.S. Census Bureau. These U.S. government economic data are not considered to be a significant source of uncertainty.

An additional source of uncertainty in the calculation of CO_2 emissions from phosphoric acid production is the carbonate composition of phosphate rock; the composition of phosphate rock varies depending upon where the material is mined, and may also vary over time. Another source of uncertainty is the disposition of the organic C content of the phosphate rock. A representative of the FIPR indicated that in the phosphoric acid production process, the organic C content of the mined phosphate rock generally remains in the phosphoric acid product, which is what produces the color of the phosphoric acid product (FIPR 2003a). Organic C is therefore not included in the calculation of CO_2 emissions from phosphoric acid production.

Table 4-46: Chemical Composition of Phosphate Rock (percent by weight)

Composition	Central Florida	North Florida	North Carolina (calcined)	Idaho (calcined)	Morocco
Total Carbon (as C)	1.60	1.76	0.76	0.60	1.56
Inorganic Carbon (as C)	1.00	0.93	0.41	0.27	1.46
Organic Carbon (as C)	0.60	0.83	0.35	-	0.10
Inorganic Carbon (as CO_2)	3.67	3.43	1.50	1.00	5.00

Source: FIPR 2003
- Assumed equal to zero.

A third source of uncertainty is the assumption that all domestically-produced phosphate rock is used in phosphoric acid production and used without first being calcined. Calcination of the phosphate rock would result in conversion of some of the organic C in the phosphate rock into CO_2. However, according to the USGS, only one producer in Idaho is currently calcining phosphate rock, and no data were available concerning the annual production of this single producer (USGS 2005). For available years, total production of phosphate rock in Utah and Idaho combined amounts to approximately 13 percent of total domestic production on average (USGS 1994 through 2005).

Finally, USGS indicated that approximately 7 percent of domestically-produced phosphate rock is used to produce elemental phosphorus and other phosphorus-based chemicals, rather than phosphoric acid (USGS 2006). According to USGS, there is only one domestic producer of elemental phosphorus, in Idaho, and no data were available concerning the annual production of this single producer. Elemental phosphorus is produced by reducing phosphate rock with coal coke, and it is therefore assumed that 100 percent of the carbonate content of the phosphate rock will be converted to CO_2 in the elemental phosphorus production process. The calculation for CO_2 emissions is based on the assumption that phosphate rock consumption, for purposes other than phosphoric acid production, results in CO_2 emissions from 100 percent of the inorganic C content in phosphate rock, but none from the organic C content.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-47. Phosphoric acid production CO_2 emissions were estimated to be between 1.0 and 1.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 19 percent above the emission estimate of 1.2 Tg CO_2 Eq.

Planned Improvements

Currently, data sources for the carbonate content of the phosphate rock are limited. If additional data sources are found, this information will be incorporated into future estimates.

4.13. Iron and Steel Production (IPCC Source Category 2C1)

In addition to being an energy intensive process, the production of iron and steel also generates process-related emissions of CO_2 and CH_4. Iron is produced by first reducing iron oxide (iron ore) with metallurgical coke in a blast furnace to produce pig iron (impure or crude iron containing about 3 to 5 percent C by weight). Metallurgical coke is manufactured using coking coal as a raw material. Iron may be introduced into the blast furnace in the form of raw iron ore, pellets, briquettes, or sinter. Pig iron is used as a raw material in the production of steel, which contains about 4 percent C by weight. Pig iron is also used as a raw material in the production of iron products in foundries. The pig iron production process produces CO_2 emissions and fugitive CH_4 emissions.

The production of metallurgical coke from coking coal and the consumption of the metallurgical coke used as a reducing agent in the blast furnace are considered in the inventory to be non-energy (industrial) processes, not energy (combustion) processes. Metallurgical coke is produced by heating coking coal in a coke oven in a low-oxygen environment. The process drives off the volatile components of the coking coal and produces coal (metallurgical) coke. Coke oven gas and coal tar are C containing byproducts of the coke manufacturing process. Coke oven gas is generally burned as a fuel within the steel mill. Coal tar is used as a raw material to produce

Table 4-47: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Phosphoric Acid Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Phosphoric Acid Production	CO_2	1.2	1.0	1.4	-18%	+19%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

anodes used for primary aluminum production and other electrolytic processes, and also used in the production of other coal tar products. The coke production process produces CO_2 emissions and fugitive CH_4 emissions.

Sintering is a thermal process by which fine iron-bearing particles, such as air emission control system dust, are baked, which causes the material to agglomerate into roughly one-inch pellets that are then recharged into the blast furnace for pig iron production. Iron ore particles may also be formed into larger pellets or briquettes by mechanical means, and then agglomerated by heating prior to being charged into the blast furnace. The sintering process produces CO_2 emissions and fugitive CH_4 emissions.

The metallurgical coke is a reducing agent in the blast furnace. CO_2 is produced as the metallurgical coke used in the blast furnace process is oxidized and the iron ore is reduced. Steel is produced from pig iron in a variety of specialized steel-making furnaces. The majority of CO_2 emissions from the iron and steel process come from the use of coke in the production of pig iron, with smaller amounts evolving from the removal of C from pig iron used to produce steel. Some C is also stored in the finished iron and steel products.

Emissions of CO_2 and CH_4 from iron and steel production in 2006 were 49.1 Tg CO_2 Eq. (49,119 Gg) and 0.9 Tg CO_2 Eq. (45 Gg), respectively (see Table 4-48 and Table 4-49), totaling 50.1 Tg CO_2 Eq. Emissions increased in 2006 after declining steadily from 1990 to 2005 due to restructuring of the industry, technological improvements, and increased scrap utilization. Interannual fluctuations in CO_2 emissions per unit of steel produced result, in part, because iron and steel emission estimates include emissions associated with producing metallurgical coke. Metallurgical

coke emissions are included here because metallurgical coke is primarily used to produce iron and steel; however, some amounts are also used to produce other metals (e.g., lead, zinc). In 2006, domestic production of pig iron increased by 1.8 percent and coal coke production decreased by 1.9 percent. Overall, domestic pig iron and coke production have declined since the 1990s. Pig iron production in 2006 was 21 percent lower than in 2000 and 23 percent below 1990 levels. Coke production in 2006 was 21 percent lower than in 2000 and 41 percent below 1990 levels. Overall, emissions from iron and steel productions have declined by 43 percent (37.4 Tg CO_2 Eq.) from 1990 to 2006.

Methodology

Coking coal is used to manufacture metallurgical (coal) coke that is used primarily as a reducing agent in the production of iron and steel, but is also used in the production of other metals including lead and zinc (see Lead Production and Zinc Production in this chapter). Emissions associated with producing metallurgical coke from coking coal are estimated, and then attributed to the iron and steel sector. To estimate emission from coke produced from coking coal the amount of C contained in coke (calculated by multiplying the amount of C contained in coke by the amount of coke produced) is deducted from the amount of C contained in the coking coal (calculated by multiplying the C content of coking coal by the amount of coking coal consumed). The amount of coking coal needed for these production processes is deducted from coking coal amounts provided in the Energy chapter to avoid double counting. Emissions associated with the consumption of coke to produce pig iron are also estimated. The C content of the coking coal and coke consumed in these processes were estimated by

Table 4-48: CO_2 and CH_4 Emissions from Iron and Steel Production (Tg CO_2 Eq.)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	86.2	74.7	66.6	59.2	55.9	54.7	52.8	46.6	49.1
CH_4	1.3	1.3	1.2	1.1	1.0	1.0	1.0	1.0	0.9
Total	**87.5**	**76.0**	**67.8**	**60.3**	**57.0**	**55.8**	**53.8**	**47.6**	**50.1**

Table 4-49: CO_2 and CH_4 Emissions from Iron and Steel Production (Gg)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	86,220	74,729	66,609	59,249	55,938	54,744	52,771	46,627	49,119
CH_4	63	62	58	51	48	49	50	45	45

multiplying the energy consumption by material specific C-content coefficients. The C content coefficients used are presented in Annex 2.1.

Emissions from the reuse of scrap steel were also estimated by assuming that all the associated C content of the scrap steel, which has an associated C content of approximately 0.5 percent, are released during the scrap re-use process.

Lastly, emissions from C anodes, used during the production of steel in electric arc furnaces (EAFs), were also estimated. Emissions of CO_2 were calculated by multiplying the annual production of steel in EAFs by an emission factor (4.4 kg CO_2/ton steel$_{EAF}$). It was assumed that the C anodes used in the production of steel in EAFs are composed of 80 percent petroleum coke and 20 percent coal tar pitch (DOE 1997). Since coal tar pitch is a byproduct of the coke production process and its C-related emissions have already been accounted for earlier in the iron and steel emissions calculation as part of the process, the emissions were reduced by the amount of C in the coal tar pitch used in the anodes to avoid double counting.

Emissions associated with the production of coke from coking coal, pig iron production, the re-use of scrap steel, and the consumption of C anodes during the production of steel were summed.

Additionally, the coal tar pitch component of C anodes consumed during the production of aluminum is accounted for in the aluminum production section of this chapter. The emissions were reduced by the amount of coal tar pitch used in aluminum production to avoid double counting. The amount of coal tar pitch consumed for processes other than the aluminum production and as EAF anodes and net imports of coal tar were also estimated. A storage factor was applied to estimate emissions associated with other coal tar pitch consumption and net imports.

C storage was accounted for by assuming that all domestically produced steel had a C content of 0.1 percent. Furthermore, any pig iron that was not consumed during steel production, but fabricated into finished iron products, was assumed to have a C content of 4 percent.

The potential CO_2 emissions associated with C contained in pig iron used for purposes other than iron and steel production, stored in the steel product, stored as coal tar, and attributed to C anode consumption during aluminum

Table 4-50: CH$_4$ Emission Factors for Coal Coke, Sinter, and Pig Iron Production (g/kg)

Material Produced	g CH$_4$/kg produced
Coal Coke	0.5
Pig Iron	0.9
Sinter	0.5

Source: IPCC/UNEP/OECD/IEA 1997.

production were summed and subtracted from the total emissions estimated above.

The production processes for coal coke, sinter, and pig iron result in fugitive emissions of CH_4, which are emitted via leaks in the production equipment rather than through the emission stacks or vents of the production plants. The fugitive emissions were calculated by applying emission factors taken from the 1995 IPCC Guidelines (IPCC/UNEP/OECD/IEA 1995) (see Table 4-50) to annual domestic production data for coal coke, sinter, and pig iron.

Data relating to the amount of coal consumed at coke plants, and for the production of coke for domestic consumption in blast furnaces, were taken from the Energy Information Administration (EIA), *Quarterly Coal Report* October through December (EIA 1998 through 2004a) and January through March (EIA 2006a, 2007). Data on total coke consumed for pig iron production were taken from the American Iron and Steel Institute (AISI), *Annual Statistical Report* (AISI 2001 through 2007). Scrap steel consumption data for 1990 through 2005 were obtained from *Annual Statistical Report* (AISI 1995, 2001 through 2006) (see Table 4-51). Because scrap steel consumption data were unavailable for 2006, 2005 data were used. Crude steel production, as well as pig iron use for purposes other than steel production, was also obtained from *Annual Statistical Report* (AISI 1996, 2001 through 2007). C content percentages for pig iron and the CO_2 emission factor for C anode emissions from steel production were obtained from IPCC *Good Practice Guidance* (IPCC 2000). C content percentages for crude steel were taken from USGS (2005a). Data on the non-energy use of coking coal were obtained from EIA's *Emissions of Greenhouse Gases in the United States* (EIA 2004b, 2006b). Information on coal tar net imports was determined using data from the U.S. Bureau of the Census's U.S. International Trade Commission's Trade Dataweb (U.S. Bureau of the Census 2007). Coal tar

Table 4-51: Production and Consumption Data for the Calculation of CO$_2$ and CH$_4$ Emissions from Iron and Steel Production (Thousand Metric Tons)

Gas/Activity Data	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO$_2$									
Coal Consumption at Coke Plants	35,269	29,948	26,254	23,655	21,461	21,998	21,473	21,259	20,827
Coke Consumption for Pig Iron	25,043	22,288	19,307	17,236	15,959	15,482	15,068	13,848	14,729
Basic Oxygen Furnace Steel Production	56,216	56,721	53,965	47,359	45,463	45,874	47,714	42,705	42,119
Electric Arc Furnace Steel Production	33,510	38,472	47,860	42,774	46,125	47,804	51,969	52,194	56,071
CH$_4$									
Coke Production	25,054	21,545	18,877	17,191	15,221	15,579	15,340	15,167	14,882
Iron Ore Consumption for Sinter	12,239	12,575	10,784	9,234	9,018	8,984	8,047	8,313	7,085
Domestic Pig Iron Production for Steel	49,062	50,233	47,888	42,134	40,226	40,644	42,292	37,222	37,903

consumption for aluminum production data was estimated based on information gathered by EPA's Voluntary Aluminum Industrial Partnership (VAIP) program and data from USAA Primary Aluminum Statistics (USAA 2004, 2005, 2006) (see Aluminum Production in this chapter). Annual consumption of iron ore used in sinter production for 1990 through 2005 was obtained from the USGS Iron Ore Yearbook (USGS 1994 through 2005b). Iron ore consumption for 2006 was obtained from the USGS Minerals Commodity Specialist (Jorgenson 2007). The CO$_2$ emission factor for C anode emissions from aluminum production was taken from the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997). Estimates for the composition of C anodes used during EAF steel and aluminum production were obtained from Energy and *Environmental Profile of the U.S. Aluminum Industry* (DOE 1997).

Uncertainty

The time series data sources for production of coal coke, sinter, pig iron, steel, and aluminum upon which the calculations are based are assumed to be consistent for the entire time series. The estimates of CO$_2$ emissions from the production and utilization of coke are based on consumption data, average C contents, and the fraction of C oxidized. Uncertainty is associated with the total U.S. coke consumption and coke consumed for pig iron production. These data are provided by different data sources (EIA and AISI) and comparisons between the two datasets for net imports, production, and consumption identified discrepancies; however, the data chosen are considered the best available. These data and factors produce a relatively accurate estimate of CO$_2$ emissions. However, there are uncertainties associated with each of these factors. For example, C oxidation factors may vary depending on inefficiencies in the combustion process, where varying degrees of ash or soot can remain unoxidized.

Simplifying assumptions were made concerning the composition of C anodes and the C contents of all pig iron and crude steel. It was also assumed that all coal tar used during anode production originates as a byproduct of the domestic coking process. There is also uncertainty associated with the total amount of coal tar products produced and with the storage factor for coal tar. Uncertainty surrounding the CO$_2$ emission factor for C anode consumption in aluminum production was also estimated.

For the purposes of the CH$_4$ calculation it is assumed that none of the CH$_4$ is captured in stacks or vents and that all of the CH$_4$ escapes as fugitive emissions. Additionally, the CO$_2$ emissions calculation is not corrected by subtracting the C content of the CH$_4$, which means there may be a slight double counting of C as both CO$_2$ and CH$_4$.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-52. Iron and Steel CO$_2$ emissions were estimated to be between 40.3 and 56.5 Tg CO$_2$ Eq. at the 95 percent confidence level. This indicates a range of approximately 18 percent below and 15 percent above the emission estimate of 49.1 Tg CO$_2$ Eq. Iron and Steel CH$_4$ emissions were estimated to be between 0.9 Tg CO$_2$ Eq. and 1.0 Tg CO$_2$ Eq. at the 95 percent confidence level. This indicates a range of approximately 8 percent below and 9 percent above the emission estimate of 0.9 Tg CO$_2$ Eq.

Table 4-52: Tier 2 Quantitative Uncertainty Estimates for CO_2 and CH_4 Emissions from Iron and Steel Production (Tg. CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Iron and Steel Production	CO_2	49.1	40.3	56.5	-18%	+15%
Iron and Steel Production	CH_4	0.9	0.9	1.0	-8%	+9%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Recalculations Discussion

Estimates of CO_2 from iron and steel production have been revised for the entire time series to reflect a revised carbon content for crude steel. This revision resulted in an average annual increase in emissions of 2 percent throughout the time series.

Planned Improvements

Plans for improvements to the Iron and Steel source category are to include methodologies outlined in the 2006 *IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). These methodologies involve the inclusion of energy- and flux-related emissions in the iron and steel emission estimates as well as emissions associated with metallurgical coke production, sinter production, pellet production, and direct reduced iron ore production in addition to iron and steel production.

4.14. Ferroalloy Production (IPCC Source Category 2C2)

CO_2 and CH_4 are emitted from the production of several ferroalloys. Ferroalloys are composites of iron and other elements such as silicon, manganese, and chromium. When incorporated in alloy steels, ferroalloys are used to alter the material properties of the steel. Estimates from two types of ferrosilicon (25 to 55 percent and 56 to 95 percent silicon), silicon metal (about 98 percent silicon), and miscellaneous alloys (36 to 65 percent silicon) have been calculated. Emissions from the production of ferrochromium and ferromanganese are not included here because of the small number of manufacturers of these materials in the United States. Subsequently, government information disclosure rules prevent the publication of production data for these production facilities.

Similar to emissions from the production of iron and steel, CO_2 is emitted when metallurgical coke is oxidized during a high-temperature reaction with iron and the selected alloying element. Due to the strong reducing environment, CO is initially produced, and eventually oxidized to CO_2. A representative reaction equation for the production of 50 percent ferrosilicon is given below:

$$Fe_2O_3 + 2\ SiO_2 + 7C \rightarrow 2FeSi + 7CO$$

While most of the C contained in the process materials is released to the atmosphere as CO_2, a percentage is also released as CH_4 and other volatiles. The amount of CH_4 that is released is dependent on furnace efficiency, operation technique, and control technology.

Emissions of CO_2 from ferroalloy production in 2006 were 1.5 Tg CO_2 Eq. (1,505 Gg) (see Table 4-53 and Table 4-54), which is an eight percent increase from the previous year and a 30 percent reduction since 1990. Emissions of CH_4 from ferroalloy production in 2006 were 0.01 Tg CO_2 Eq. (0.4 Gg), which is an 11 percent increase from the previous year and a 37 percent decrease since 1990.

Table 4-53: CO_2 and CH_4 Emissions from Ferroalloy Production (Tg CO_2 Eq.)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	2.2	2.0	1.9	1.5	1.3	1.3	1.4	1.4	1.5
CH_4	+	+	+	+	+	+	+	+	+
Total	2.2	2.0	1.9	1.5	1.4	1.3	1.4	1.4	1.5

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

Table 4-54: CO_2 and CH_4 Emissions from Ferroalloy Production (Gg)

Year	1990	1995	2000	2001	2002	2003	2004	2005	2006
CO_2	2,152	2,036	1,893	1,459	1,349	1,305	1,419	1,392	1,505
CH_4	0.7	0.6	0.5	0.4	0.4	0.4	0.4	0.4	0.4

Methodology

Emissions of CO_2 and CH_4 from ferroalloy production were calculated by multiplying annual ferroalloy production by material-specific emission factors. Emission factors taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) were applied to ferroalloy production. For ferrosilicon alloys containing 25 to 55 percent silicon and miscellaneous alloys (including primarily magnesium-ferrosilicon, but also including other silicon alloys) containing 32 to 65 percent silicon, an emission factor for 45 percent silicon was applied for CO_2 (2.5 metric tons CO_2/metric ton of alloy produced) and an emission factor for 65 percent silicon was applied for CH_4 (1 kg CH_4/metric ton of alloy produced). Additionally, for ferrosilicon alloys containing 56 to 95 percent silicon, an emission factor for 75 percent silicon ferrosilicon was applied for both CO_2 and CH_4 (4 metric tons CO_2/metric ton alloy produced and 1 kg CH_4/metric ton of alloy produced, respectively). The emission factors for silicon metal equaled 5 metric tons CO_2/metric ton metal produced and 1.2 kg CH_4/metric ton metal produced. It was assumed that 100 percent of the ferroalloy production was produced using petroleum coke using an electric arc furnace process (IPCC 2006), although some ferroalloys may have been produced with coking coal, wood, other biomass, or graphite C inputs. The amount of petroleum coke consumed in ferroalloy production was calculated assuming that the petroleum coke used is 90 percent C and 10 percent inert material.

Ferroalloy production data for 1990 through 2006 (see Table 4-55) were obtained from the USGS through personal communications with the USGS Silicon Commodity Specialist (Corathers 2007) and through the *Minerals Yearbook: Silicon Annual Report* (USGS 1991 through 2006). Because USGS does not provide estimates of silicon metal production for 2006, 2005 production data are used. Until 1999, the USGS reported production of ferrosilicon containing 25 to 55 percent silicon separately from production of miscellaneous alloys containing 32 to 65 percent silicon; beginning in 1999, the USGS reported these as a single category (see Table 4-55). The composition data for petroleum coke was obtained from Onder and Bagdoyan (1993).

Uncertainty

Although some ferroalloys may be produced using wood or other biomass as a C source, information and data regarding these practices were not available. Emissions from ferroalloys produced with wood or other biomass would not

Table 4-55: Production of Ferroalloys (Metric Tons)

Year	Ferrosilicon 25%–55%	Ferrosilicon 56%–95%	Silicon Metal	Misc. Alloys 32%–65%
1990	321,385	109,566	145,744	72,442
1995	184,000	128,000	163,000	99,500
2000	229,000	100,000	184,000	NA
2001	167,000	89,000	137,000	NA
2002	156,000	98,600	113,000	NA
2003	115,000	80,500	139,000	NA
2004	120,000	92,300	150,000	NA
2005	123,000	86,100	148,000	NA
2006	164,000	88,700	148,000	NA

NA (Not Available)

Table 4-56: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Ferroalloy Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Ferroalloy Production	CO_2	1.5	1.3	1.7	-12%	+12%
Ferroalloy Production	CH_4	+	+	+	-12%	+12%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
+ Does not exceed 0.05 Tg CO_2 Eq.

be counted under this source because wood-based C is of biogenic origin.[12] Even though emissions from ferroalloys produced with coking coal or graphite inputs would be counted in national trends, they may be generated with varying amounts of CO_2 per unit of ferroalloy produced. The most accurate method for these estimates would be to base calculations on the amount of reducing agent used in the process, rather than the amount of ferroalloys produced. These data, however, were not available.

Emissions of CH_4 from ferroalloy production will vary depending on furnace specifics, such as type, operation technique, and control technology. Higher heating temperatures and techniques such as sprinkle charging will reduce CH_4 emissions; however, specific furnace information was not available or included in the CH_4 emission estimates.

Also, annual ferroalloy production is now reported by the USGS in three broad categories: ferroalloys containing 25 to 55 percent silicon (including miscellaneous alloys), ferroalloys containing 56 to 95 percent silicon, and silicon metal. It was assumed that the IPCC emission factors apply to all of the ferroalloy production processes, including miscellaneous alloys. Finally, production data for silvery pig iron (alloys containing less than 25 percent silicon) are not reported by the USGS to avoid disclosing company proprietary data. Emissions from this production category, therefore, were not estimated.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-56. Ferroalloy production CO_2 emissions were estimated to be between 1.3 and 1.7 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 12 percent below and 12 percent above the emission estimate of 1.5 Tg CO_2 Eq. Ferroalloy production

CH_4 emissions were estimated to be between a range of approximately 12 percent below and 12 percent above the emission estimate of 0.01 Tg CO_2 Eq.

Planned Improvements

Future improvements to the ferroalloy production source category include research into the data availability for ferroalloys other than ferrosilicon and silicon metal. If data are available, emissions will be estimated for those ferroalloys. Additionally, research will be conducted to determine whether data are available concerning raw material consumption (e.g., coal coke, limestone and dolomite flux, etc.) for inclusion in ferroalloy production emission estimates.

4.15. Aluminum Production (IPCC Source Category 2C3)

Aluminum is a light-weight, malleable, and corrosion-resistant metal that is used in many manufactured products, including aircraft, automobiles, bicycles, and kitchen utensils. As of last reporting, the United States was the fourth largest producer of primary aluminum, with approximately eight percent of the world total (USGS 2006). The United States was also a major importer of primary aluminum. The production of primary aluminum—in addition to consuming large quantities of electricity—results in process-related emissions of CO_2 and two perfluorocarbons (PFCs): perfluoromethane (CF_4) and perfluoroethane (C_2F_6).

CO_2 is emitted during the aluminum smelting process when alumina (aluminum oxide, Al_2O_3) is reduced to aluminum using the Hall-Heroult reduction process. The reduction of the alumina occurs through electrolysis in a

---

[12] Emissions and sinks of biogenic carbon are accounted for in the Land Use, Land-Use Change, and Forestry chapter.

molten bath of natural or synthetic cryolite (Na_3AlF_6). The reduction cells contain a C lining that serves as the cathode. C is also contained in the anode, which can be a C mass of paste, coke briquettes, or prebaked C blocks from petroleum coke. During reduction, most of this C is oxidized and released to the atmosphere as CO_2.

Process emissions of CO_2 from aluminum production were estimated to be 3.9 Tg CO_2 Eq. (3,923 Gg) in 2006 (see Table 4-57). The C anodes consumed during aluminum production consist of petroleum coke and, to a minor extent, coal tar pitch. The petroleum coke portion of the total CO_2 process emissions from aluminum production is considered to be a non-energy use of petroleum coke, and is accounted for here and not under the CO_2 from Fossil Fuel Combustion source category of the Energy sector. Similarly, the coal tar pitch portion of these CO_2 process emissions is accounted for here rather than in the Iron and Steel source category of the Industrial Processes sector.

In addition to CO_2 emissions, the aluminum production industry is also a source of PFC emissions. During the smelting process, when the alumina ore content of the electrolytic bath falls below critical levels required for electrolysis, rapid voltage increases occur, which are termed "anode effects." These anode effects cause carbon from the anode and fluorine from the dissociated molten cryolite bath to combine, thereby producing fugitive emissions of CF_4 and C_2F_6. In general, the magnitude of emissions for a given level of production depends on the frequency and duration of these anode effects. As the frequency and duration of the anode effects increase, emissions increase.

Since 1990, emissions of CF_4 and C_2F_6 have both declined by 87 percent to 2.1 Tg CO_2 Eq. of CF_4 (0.4 Gg) and 0.4 Tg CO_2 Eq. of C_2F_6 (0.04 Gg) in 2006, as shown in Table 4-58 and Table 4-59. This decline is due both to reductions in domestic aluminum production and to actions taken by aluminum smelting companies to reduce the frequency and duration of anode effects. Since 1990, aluminum production has declined by 44 percent, while the average CF_4 and C_2F_6 emission rates (per metric ton of aluminum produced) have each been reduced by 76 percent.

In 2006, U.S. primary aluminum production totaled approximately 2.3 million metric tons, a slight decrease from 2005 production levels. Due to high electric power costs in various regions of the country, aluminum production has been curtailed at several U.S. smelters, which resulted in 2006 production levels that were approximately 40 percent lower

Table 4-58: PFC Emissions from Aluminum Production (Tg CO_2 Eq.)

Year	CF_4	C_2F_6	Total
1990	15.9	2.7	18.5
1995	10.2	1.7	11.8
2000	7.8	0.8	8.6
2001	3.0	0.4	3.5
2002	4.6	0.7	5.2
2003	3.3	0.5	3.8
2004	2.4	0.4	2.8
2005	2.5	0.4	3.0
2006	2.1	0.4	2.5

Note: Totals may not sum due to independent rounding.

Table 4-57: CO_2 Emissions from Aluminum Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	6.8	6,831
1995	5.7	5,659
2000	6.1	6,086
2001	4.4	4,381
2002	4.5	4,490
2003	4.5	4,503
2004	4.2	4,231
2005	4.2	4,207
2006	3.9	3,923

Table 4-59: PFC Emissions from Aluminum Production (Gg)

Year	CF_4	C_2F_6
1990	2.4	0.3
1995	1.6	0.2
2000	1.2	0.1
2001	0.5	+
2002	0.7	0.1
2003	0.5	0.1
2004	0.4	+
2005	0.4	+
2006	0.3	+

+ Does not exceed 0.05 Gg

than the levels in 1999, the year with the highest production since 1995.

Methodology

CO_2 emissions released during aluminum production were estimated using the combined application of process-specific emissions estimates modeling with individual partner reported data. These estimates are achieved through information gathered by EPA's Voluntary Aluminum Industrial Partnership (VAIP) program.

Most of the CO_2 emissions released during aluminum production occur during the electrolysis reaction of the C anode, as described by the following reaction.

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

For prebake smelter technologies, CO_2 is also emitted during the anode baking process. These emissions can account for approximately 10 percent of total process CO_2 emissions from prebake smelters. The CO_2 emission factor employed was estimated from the production of primary aluminum metal and the C consumed by the process. Emissions vary depending on the specific technology used by each plant (e.g., prebake or Søderberg). CO_2 process emissions were estimated using the methodology recommended by IPCC (2006).

The prebake process specific formula recommended by IPCC (2006) accounts for various parameters, including net C consumption, and the sulfur, ash, and impurity content of the baked anode. For anode baking emissions, process formulas account for packing coke consumption, the sulfur and ash content of the packing coke, as well as the pitch content and weight of baked anodes produced. The Søderberg process formula accounts for the weight of paste consumed per metric ton of aluminum produced, and pitch properties, including sulfur, hydrogen, and ash content.

Through the VAIP, process data have been reported for 1990, 2000, 2003, 2004, 2005, and 2006. Where available, smelter-specific process data reported under the VAIP were used; however, if the data were incomplete or unavailable, information was supplemented using industry average values recommended by IPCC (2006). Smelter-specific CO_2 process data were provided by 18 of the 23 operating smelters in 1990 and 2000, by 14 out of 16 operating smelters in 2003

and 2004, 14 out of 15 operating smelters in 2005, and 12 out of 13 operating smelters in 2006. For years where CO_2 process data were not reported by these companies, estimates were developed through linear interpolation, and/or assuming industry default values.

In the absence of any smelter specific process data (i.e., 1 out of 13 in 2006, 1 out of 15 smelters in 2005, and 5 out of 23 between 1990 and 2003), CO_2 emission estimates were estimated using Tier 1 Søderberg and/or Prebake emission factors (metric ton of CO_2 per metric ton of aluminum produced) from IPCC (2006).

Aluminum production data for 12 out of 13 operating smelters were reported under the VAIP in 2006. Between 1990 and 2005, production data were provided by 21 of the 23 U.S. smelters that operated during at least part of that period. For the non-reporting smelters, production was estimated based on the difference between reporting smelters and national aluminum production levels (USAA 2006), with allocation to specific smelters based on reported production capacities (USGS 2002).

PFC emissions from aluminum production were estimated using a per-unit production emission factor that is expressed as a function of operating parameters (anode effect frequency and duration), as follows:

$$PFC \ (CF_4 \ or \ C_2F_6) \ kg/metric \ ton \ Al =$$
$$S \times Anode \ Effect \ Minutes/Cell-Day$$

where,

S	=	Slope coefficient (kg PFC/metric ton Al)/(Anode Effect Minute/Cell-Day)
Anode Effect Minutes/ Cell-Day	=	Anode Effect Frequency/Cell-Day × Anode Effect Duration (Minutes)

This approach corresponds to either the Tier 3 or the Tier 2 approach in the 2006 IPCC Guidelines, depending upon whether the slope-coefficient is smelter-specific (Tier 3) or technology-specific (Tier 2). For 1990 through 2006, smelter-specific slope coefficients were available and were used for smelters representing between 30 and 55 percent of U.S. primary aluminum production. The percentage changed from year to year as some smelters closed or changed hands and as the production at remaining smelters fluctuated. For smelters that did not report smelter-specific slope coefficients, IPCC

technology-specific slope coefficients were applied (IPCC 2001, 2006). The slope coefficients were combined with smelter-specific anode effect data collected by aluminum companies and reported under the VAIP, to estimate emission factors over time. For 1990 through 2006, smelter-specific anode effect data were available for smelters representing between 80 and 100 percent of U.S. primary aluminum production. Where smelter-specific anode effect data were not available, industry averages were used.

For all smelters, emission factors were multiplied by annual production to estimate annual emissions at the smelter level. For 1990 through 2006, smelter-specific production data were available for smelters representing between 30 and 100 percent of U.S. primary aluminum production. (For the years after 2000, this percentage was near the high end of the range.) Production at non-reporting smelters was estimated by calculating the difference between the production reported under VAIP and the total U.S. production supplied by USGS and then by allocating this difference to non-reporting smelters in proportion to their production capacity. Emissions were then aggregated across smelters to estimate national emissions.

National primary aluminum production data for 2006 were obtained via communication with USGS (USGS, 2007). For 1990 through 2001 (see Table 4-60) data were obtained from USGS, *Mineral Industry Surveys: Aluminum Annual Report* (USGS 1995, 1998, 2000, 2001, 2002). For 2002 through 2005, national aluminum production data were obtained from the United States Aluminum Association's *Primary Aluminum Statistics* (USAA 2004, 2005, 2006).

Table 4-60: Production of Primary Aluminum (Gg)

Year	Gg
1990	4,048
1995	3,375
2000	3,668
2001	2,637
2002	2,705
2003	2,704
2004	2,517
2005	2,478
2006	2,284

Uncertainty

The overall uncertainties associated with the 2006 CO_2, CF_4, and C_2F_6 emission estimates were calculated using a Tier 2 approach, as defined by IPCC (2006). For CO_2, uncertainty was assigned to each of the parameters used to estimate CO_2 emissions. Uncertainty surrounding reported production data was assumed to be 2 percent (IPCC 2006). For additional variables, such as net C consumption, and sulfur and ash content in baked anodes, estimates for uncertainties associated with reported and default data were obtained from IPCC (2006). A Monte Carlo analysis was applied to estimate the overall uncertainty of the CO_2 emission estimate for the U.S. aluminum industry as a whole, and the results are provided below.

To estimate the uncertainty associated with emissions of CF_4 and C_2F_6, the uncertainties associated with three variables were estimated for each smelter: (1) the quantity of aluminum produced, (2) the anode effect minutes per cell day (which may be reported directly or calculated as the product of anode effect frequency and anode effect duration), and (3) the smelter- or technology-specific slope coefficient. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emission estimate for each smelter or company and for the U.S. aluminum industry as a whole.

The results of this quantitative uncertainty analysis are summarized in Table 4-61. Aluminum production-related CO_2 emissions were estimated to be between 3.7 and 4.1 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 5 percent below to 5 percent above the emission estimate of 3.9 Tg CO_2 Eq. Also, production-related CF_4 emissions were estimated to be between 1.9 and 2.3 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 9 percent below to 9 percent above the emission estimate of 2.1 Tg CO_2 Eq. Finally, aluminum production-related C_2F_6 emissions were estimated to be between 0.3 and 0.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 17 percent below to 17 percent above the emission estimate of 0.4 Tg CO_2 Eq.

The 2006 emission estimate was developed using IPCC (2001) slope coefficients for 7 of the 8 operating smelters without site-specific PFC measurements. If these slope coefficients were revised to incorporate recent IPCC (2006)

Table 4-61: Tier 2 Quantitative Uncertainty Estimates for CO_2 and PFC Emissions from Aluminum Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Aluminum Production	CO_2	3.9	3.7	4.1	-5%	+5%
Aluminum Production	CF_4	2.1	1.9	2.3	-9%	+9%
Aluminum Production	C_2F_6	0.4	0.3	0.4	-17%	+17%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

slope data, overall PFC emission estimates for 2006 would probably be on the order of 10 percent lower than current estimates. Additionally, since these smelters are owned by one company, data have been reported on a company-wide basis as totals or weighted averages. Consequently, uncertainties in anode effect minutes per cell day, slope coefficients, and aluminum production have been applied to the company as a whole, and not on a smelter-specific basis. This probably overestimates the uncertainty associated with the cumulative emissions from these smelters, because errors that were in fact independent were treated as if they were correlated. It is therefore likely that uncertainties calculated above for the total U.S. 2006 emission estimates for CF_4 and C_2F_6 are also overestimated.

This Inventory may slightly underestimate greenhouse gas emissions from aluminum production and casting because it does not account for the possible use of SF_6 as a cover gas or a fluxing and degassing agent in experimental and specialized casting operations. The extent of such use in the United States is not known. Historically, SF_6 emissions from aluminum activities have been omitted from estimates of global SF_6 emissions, with the explanation that any emissions would be insignificant (Ko et al. 1993, Victor and MacDonald 1998). The concentration of SF_6 in the mixtures is small and a portion of the SF_6 is decomposed in the process (MacNeal et al. 1990, Gariepy and Dube 1992, Ko et al. 1993, Ten Eyck and Lukens 1996, Zurecki 1996).

Recalculations Discussion

The 2005 emission estimates were updated to reflect revised prebake smelter production data. This change has resulted in a less than one percent increase in PFC and CO_2 emissions for 2005.

4.16. Magnesium Production and Processing (IPCC Source Category 2C4)

The magnesium metal production and casting industry uses sulfur hexafluoride (SF_6) as a cover gas to prevent the rapid oxidation of molten magnesium in the presence of air. A dilute gaseous mixture of SF_6 with dry air and/or CO_2 is blown over molten magnesium metal to induce and stabilize the formation of a protective crust. A small portion of the SF_6 reacts with the magnesium to form a thin molecular film of mostly magnesium oxide and magnesium fluoride. The amount of SF_6 reacting in magnesium production and processing is assumed to be negligible and thus all SF_6 used is assumed to be emitted into the atmosphere. Sulfur hexafluoride has been used in this application around the world for the last twenty years.

The magnesium industry emitted 3.2 Tg CO_2 Eq. (0.1 Gg) of SF_6 in 2006, representing a decrease of approximately 3 percent from 2005 emissions (see Table 4-62). The recent closure of a production facility in Canada has resulted in

Table 4-62: SF_6 Emissions from Magnesium Production and Processing (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	5.4	0.2
1995	5.6	0.2
2000	3.0	0.1
2001	2.9	0.1
2002	2.9	0.1
2003	3.4	0.1
2004	3.2	0.1
2005	3.3	0.1
2006	3.2	0.1

supply pressures in North America for magnesium ingot that may encourage the expansion of primary magnesium production in the United States (USGS 2007a). The automotive industry is continuing to work towards converting components to magnesium for fuel efficiency gains. As a result of this shift, magnesium die casting processing is forecasted to grow by 3 percent for 2007 with another 4 percent gain in 2008 (NADCA 2007).

Methodology

Emission estimates for the magnesium industry incorporate information provided by industry participants in EPA's SF_6 Emission Reduction Partnership for the Magnesium Industry. The Partnership started in 1999 and, currently, participating companies represent 100 percent of U.S. primary and secondary production and 90 percent of the casting sector production (i.e., die, sand, permanent mold, wrought, and anode casting). Absolute emissions for 1999 through 2006 from primary production, secondary production (i.e., recycling), and die casting were generally reported by Partnership participants. When a Partner did not report emissions, they were estimated based on the metal processed and emission rate reported by that Partner in previous years. (The extrapolation was based on the trend shown by Partners reporting in the current and previous years.) Emissions for one Partner that is a secondary producer were estimated based on the average emission factor for other Partners that are secondary producers.

Emission factors for 2002 to 2006 for sand casting activities were also acquired through the Partnership. The 1999 through 2006 emissions from casting operations (other than die) were estimated by multiplying emission factors (kg SF_6 per metric ton of Mg produced or processed) by the amount of metal produced or consumed. The emission factors for casting activities are provided below in Table 4-63. The emission factors for primary production, secondary production and sand casting are withheld to protect company-specific production information. However, the emission factor for primary production has not risen above the average 1995 Partner value of 1.1 kg SF_6 per metric ton.

Die casting emissions for 1999 through 2006, which accounted for 25 to 52 percent of all SF_6 emissions from the U.S. magnesium industry during this period, were estimated based on information supplied by industry Partners. From 2000 to 2006, Partners accounted for all U.S. die casting that was tracked by USGS. In 1999, Partners did not account for all die casting tracked by USGS, and, therefore, it was necessary to estimate the emissions of die casters who were not Partners. Die casters who were not Partners were assumed to be similar to Partners who cast small parts. Due to process requirements, these casters consume larger quantities of SF_6 per metric ton of processed magnesium than casters that process large parts. Consequently, emissions estimates from this group of die casters were developed using an average emission factor of 5.2 kg SF_6 per metric ton of magnesium. The emission factors for the other industry sectors (i.e., permanent mold, wrought, and anode casting) were based on discussions with industry representatives.

Data used to develop SF_6 emission estimates were provided by the Magnesium Partnership participants and the USGS. U.S. magnesium metal production (primary and secondary) and consumption (casting) data from 1990 through 2006 were available from the USGS (USGS 2002, 2003, 2005, 2006, 2007b). Emission factors from 1990 through 1998 were based on a number of sources. Emission factors for primary production were available from U.S. primary producers for 1994 and 1995, and an emission factor for die casting of 4.1 kg per metric ton was available for the mid-1990s from an international survey (Gjestland & Magers 1996).

To estimate emissions for 1990 through 1998, industry emission factors were multiplied by the corresponding metal production and consumption (casting) statistics from USGS. The primary production emission factors were 1.2 kg per

Table 4-63: SF_6 Emission Factors (kg SF_6 per metric ton of Magnesium)

Year	Die Casting	Permanent Mold	Wrought	Anodes
1999	2.14[a]	2	1	1
2000	0.72	2	1	1
2001	0.72	2	1	1
2002	0.71	2	1	1
2003	0.81	2	1	1
2004	0.81	2	1	1
2005	0.76	2	1	1
2006	0.86	2	1	1

[a] Weighted average that includes an estimated emission factor of 5.2 kg SF_6 per metric ton of magnesium for die casters that do not participate in the Partnership.

metric ton for 1990 through 1993, and 1.1 kg per metric ton for 1994 through 1997. For die casting, an emission factor of 4.1 kg per metric ton was used for the period 1990 through 1996. For 1996 through 1998, the emission factors for primary production and die casting were assumed to decline linearly to the level estimated based on Partner reports in 1999. This assumption is consistent with the trend in SF_6 sales to the magnesium sector that is reported in the RAND survey of major SF_6 manufacturers, which shows a decline of 70 percent from 1996 to 1999 (RAND 2002). Sand casting emission factors for 2002 through 2006 were provided by the Magnesium Partnership participants and 1990 through 2001 emission factors for this process were assumed to have been the same as the 2002 emission factor. The emission factor for secondary production from 1990 through 1998 was assumed to be constant at the 1999 average partner value. The emission factors for the other processes (i.e., permanent mold, wrought, and anode casting), about which less is known, were assumed to remain constant at levels defined in Table 4-63.

Uncertainty

To estimate the uncertainty of the estimated 2006 SF_6 emissions from magnesium production and processing, EPA estimated the uncertainties associated with three variables (1) emissions reported by magnesium producers and processors that participate in the SF_6 Emission Reduction Partnership, (2) emissions estimated for magnesium producers and processors that participate in the Partnership but did not report this year, and (3) emissions estimated for magnesium producers and processors that do not participate in the Partnership.

Additional uncertainties exist in these estimates, such as the basic assumption that SF_6 neither reacts nor decomposes during use. The melt surface reactions and high temperatures associated with molten magnesium could potentially cause some gas degradation. Recent measurement studies have identified SF_6 cover gas degradation in die casting applications on the order of 20 percent (Bartos et al. 2007). As is the case for other sources of SF_6 emissions, total SF_6 consumption data for magnesium production and processing in the United States were not available. Sulfur hexafluoride may also be used as a cover gas for the casting of molten aluminum with high magnesium content; however, to what extent this technique is used in the United States is unknown.

The results of this Tier 2 quantitative uncertainty analysis are summarized in Table 4-64. SF_6 emissions associated with magnesium production and processing were estimated to be between 2.7 and 3.6 Tg CO_2 Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 14 percent below to 14 percent above the 2006 emissions estimate of 3.2 Tg CO_2 Eq.

Recalculations Discussion

Data from the USGS (USGS 2007b) slightly revised the amount of magnesium processed in 2005 for the wrought, sand and permanent mold casting sectors. In addition, wrought production numbers for 1990 and 1992 were revised to match historical USGS publications based on a data review. Revisions were also made to the approach for extrapolating and interpolating data for non-reporting Partners in order to improve accuracy. Emission estimates for secondary production activities by a non-reporting Partner were added for the years 2001 through 2006. The default historical emission factor for secondary production from 1990 to 1998 was also revised to be held constant at the 1999 Partner reported value. These changes resulted in an average annual increase in SF_6 emissions of 0.03 Tg CO_2 Eq. (approximately 0.5 percent) for 1990 to 1998 and 0.6 Tg CO_2 Eq. (approximately 22 percent) for 2001 to 2005 relative to the previous report.

Table 4-64: Tier 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Magnesium Production and Processing (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Magnesium Production	SF_6	3.2	2.7	3.6	-14%	+14%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

Planned Improvements

As more work assessing the degree of cover gas degradation and associated byproducts is undertaken and published, results could potentially be used to refine the emission estimates, which currently assume (per IPCC *Good Practice Guidance*, IPCC 2006) that all SF_6 utilized is emitted to the atmosphere. EPA-funded measurements of SF_6 in die casting applications have indicated that the latter assumption may be incorrect, with observed SF_6 degradation on the order of 20 percent (Bartos et al. 2007). Another issue that will be addressed in future Inventories is the likely adoption of alternate cover gases by U.S. magnesium producers and processors. These cover gases, which include AM-cover™ (containing HFC-134a) and Novec™ 612, have lower GWPs than SF_6, and tend to quickly decompose during their exposure to the molten metal. Magnesium producers and processors have already begun using these cover gases during this inventory year in a limited fashion; because the amounts are negligible these emissions are only being monitored and recorded at this time. Additionally, as more companies join the Partnership, in particular those from sectors not currently represented, such as permanent mold and anode casting, emission factors will be refined to incorporate these additional data.

4.17. Zinc Production (IPCC Source Category 2C5)

Zinc production in the United States consists of both primary and secondary processes. Primary production techniques used in the United States are the electro-thermic and electrolytic process while secondary techniques used in the United States include a range of metallurgical, hydrometallurgical, and pyrometallurgical processes. Worldwide primary zinc production also employs a pyrometallurgical process using the Imperial Smelting Furnace process; however, this process is not used in the United States (Sjardin 2003). Of the primary and secondary processes used in the United States, the electro-thermic process results in non-energy CO_2 emissions, as does the Waelz Kiln process—a technique used to produce secondary zinc from electric-arc furnace (EAF) dust (Viklund-White 2000).

During the electro-thermic zinc production process, roasted zinc concentrate and, when available, secondary zinc products enter a sinter feed where they are burned to remove impurities before entering an electric retort furnace. Metallurgical coke added to the electric retort furnace reduces the zinc oxides and produces vaporized zinc, which is then captured in a vacuum condenser. This reduction process produces non-energy CO_2 emissions (Sjardin 2003). The electrolytic zinc production process does not produce non-energy CO_2 emissions.

In the Waelz Kiln process, EAF dust, which is captured during the recycling of galvanized steel, enters a kiln along with a reducing agent—often metallurgical coke. When kiln temperatures reach approximately 1100–1200°C, zinc fumes are produced, which are combusted with air entering the kiln. This combustion forms zinc oxide, which is collected in a baghouse or electrostatic precipitator, and is then leached to remove chloride and fluoride. Through this process, approximately 0.33 ton of zinc is produced for every ton of EAF dust treated (Viklund-White 2000).

In 2006, U.S. primary and secondary zinc production totaled 510,000 metric tons (USGS 2008). The resulting emissions of CO_2 from zinc production in 2006 were estimated to be 0.5 Tg CO_2 Eq. (529 Gg) (see Table 4-65). All 2006 CO_2 emissions result from secondary zinc production.

After a gradual increase in total emissions from 1990 to 2000, largely due to an increase in secondary zinc production, emissions have decreased in recent years due to the closing of an electro-thermic-process zinc plant in Monaca, PA (USGS 2004). In 2006, emissions, which are nearly half those of 1990 (44 percent), increased by 14 percent over 2005 levels despite decreases in overall production due to an increase in production from emissive secondary zinc production processes.

Table 4-65: CO$_2$ Emissions from Zinc Production (Tg CO$_2$ Eq. and Gg)

Year	Tg CO$_2$ Eq.	Gg
1990	0.9	949
1995	1.0	1,013
2000	1.1	1,140
2001	1.0	986
2002	0.9	937
2003	0.5	507
2004	0.5	477
2005	0.5	465
2006	0.5	529

Methodology

Non-energy CO_2 emissions from zinc production result from those processes that use metallurgical coke or other C-based materials as reductants. Sjardin (2003) provides an emission factor of 0.43 metric tons CO_2/ton zinc produced for emissive zinc production processes; however, this emission factor is based on the Imperial Smelting Furnace production process. Because the Imperial Smelting Furnace production process is not used in the United States, emission factors specific to those emissive zinc production processes used in the United States, which consist of the electro-thermic and Waelz Kiln processes, were needed. Due to the limited amount of information available for these electro-thermic processes, only Waelz Kiln process-specific emission factors were developed. These emission factors were applied to both the Waelz Kiln process and the electro-thermic zinc production processes. A Waelz Kiln emission factor based on the amount of zinc produced was developed based on the amount of metallurgical coke consumed for non-energy purposes per ton of zinc produced, 1.19 metric tons coke/metric ton zinc produced (Viklund-White 2000), and the following equation:

$$EF_{\text{Waelz Kiln}} = \frac{1.19 \text{ metric tons coke}}{\text{metric tons zinc}} \times$$

$$\frac{0.84 \text{ metric tons C}}{\text{metric tons coke}} \times$$

$$\frac{3.67 \text{ metric tons CO}_2}{\text{metric tons C}} =$$

$$\frac{3.66 \text{ metric tons CO}_2}{\text{metric tons zinc}}$$

The USGS disaggregates total U.S. primary zinc production capacity into zinc produced using the electro-thermic process and zinc produced using the electrolytic process; however, the USGS does not report the amount of zinc produced using each process, only the total zinc production capacity of the zinc plants using each process. The total electro-thermic zinc production capacity is divided by total primary zinc production capacity to estimate the percent of primary zinc produced using the electro-thermic process. This percent is then multiplied by total primary zinc production to estimate the amount of zinc produced using the electro-thermic process, and the resulting value is multiplied by the Waelz Kiln process emission factor to obtain total CO_2 emissions for primary zinc production. According to the USGS, the only remaining plant producing primary zinc using the electro-thermic process closed in 2003 (USGS

2004). Therefore, CO_2 emissions for primary zinc production are reported only for years 1990 through 2002.

In the United States, secondary zinc is produced through either the electro-thermic or Waelz Kiln process. In 1997, the Horsehead Corporation plant, located in Monaca, PA, produced 47,174 metric tons of secondary zinc using the electro-thermic process (Queneau et al. 1998). This is the only plant in the United States that uses the electro-thermic process to produce secondary zinc, which, in 1997, accounted for 13 percent of total secondary zinc production. This percentage was applied to all years within the time series up until the Monaca plant's closure in 2003 (USGS 2004) to estimate the total amount of secondary zinc produced using the electro-thermic process. This value is then multiplied by the Waelz Kiln process emission factor to obtain total CO_2 emissions for secondary zinc produced using the electro-thermic process.

U.S. secondary zinc is also produced by processing recycled EAF dust in a Waelz Kiln furnace. Due to the complexities of recovering zinc from recycled EAF dust, an emission factor based on the amount of EAF dust consumed rather than the amount of secondary zinc produced is believed to represent actual CO_2 emissions from the process more accurately (Stuart 2005). An emission factor based on the amount of EAF dust consumed was developed based on the amount of metallurgical coke consumed per ton of EAF dust consumed, 0.4 metric tons coke/metric ton EAF dust consumed (Viklund-White 2000), and the following equation:

$$EF_{\text{EAF Dust}} = \frac{0.4 \text{ metric tons coke}}{\text{metric tons EAF dust}} \times$$

$$\frac{0.84 \text{ metric tons C}}{\text{metric tons coke}} \times$$

$$\frac{3.67 \text{ metric tons CO}_2}{\text{metric tons C}} =$$

$$\frac{1.23 \text{ metric tons CO}_2}{\text{metric tons EAF dust}}$$

The Horsehead Corporation plant, located in Palmerton, PA, is the only large plant in the United States that produces secondary zinc by recycling EAF dust (Stuart 2005). In 2003, this plant consumed 408,240 metric tons of EAF dust, producing 137,169 metric tons of secondary zinc (Recycling Today 2005). This zinc production accounted for 36 percent of total secondary zinc produced in 2003. This percentage was applied to the USGS data for total secondary zinc production for all years within the time series to estimate the total amount of secondary zinc produced by consuming

Table 4-66: Zinc Production (Metric Tons)

Year	Primary	Secondary
1990	262,704	341,400
1995	231,840	353,000
2000	227,800	440,000
2001	203,000	375,000
2002	181,800	366,000
2003	186,900	381,000
2004	188,200	358,000
2005	191,120	349,000
2006	113,000	397,000

recycled EAF dust in a Waelz Kiln furnace. This value is multiplied by the Waelz Kiln process emission factor for EAF dust to obtain total CO_2 emissions.

The 1990 through 2006 activity data for primary and secondary zinc production (see Table 4-66) were obtained through the USGS *Mineral Yearbook: Zinc* (USGS 1994 through 2008).

Uncertainty

The uncertainties contained in these estimates are two-fold, relating to activity data and emission factors used.

First, there are uncertainties associated with the percent of total zinc production, both primary and secondary, that is attributed to the electro-thermic and Waelz Kiln emissive zinc production processes. For primary zinc production, the amount of zinc produced annually using the electro-thermic process is estimated from the percent of primary-zinc production capacity that electro-thermic production capacity constitutes for each year of the time series. This assumes that each zinc plant is operating at the same percentage of total production capacity, which may not be the case and this calculation could either overestimate or underestimate the percentage of the total primary zinc production that is

produced using the electro-thermic process. The amount of secondary zinc produced using the electro-thermic process is estimated from the percent of total secondary zinc production that this process accounted for during a single year, 2003. The amount of secondary zinc produced using the Waelz Kiln process is estimated from the percent of total secondary zinc production this process accounted for during a single year, 1997. This calculation could either overestimate or underestimate the percentage of the total secondary zinc production that is produced using the electro-thermic or Waelz Kiln processes. Therefore, there is uncertainty associated with the fact that percents of total production data estimated from production capacity, rather than actual production data, are used for emission estimates.

Second, there are uncertainties associated with the emission factors used to estimate CO_2 emissions from the primary and secondary production processes. Because the only published emission factors are based on the Imperial Smelting Furnace, which is not used in the United States, country-specific emission factors were developed for the Waelz Kiln zinc production process. Data limitations prevented the development of emission factors for the electro-thermic process. Therefore, emission factors for the Waelz Kiln process were applied to both electro-thermic and Waelz Kiln production processes. Furthermore, the Waelz Kiln emission factors are based on materials balances for metallurgical coke and EAF dust consumed during zinc production provided by Viklund-White (2000). Therefore, the accuracy of these emission factors depend upon the accuracy of these materials balances.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-67. Zinc production CO_2 emissions were estimated to be between 0.4 and 0.7 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 21 percent below and 25 percent above the emission estimate of 0.5 Tg CO_2 Eq.

Table 4-67: Tier 2 Quantitative Uncertainty Estimates for CO_2 Emissions from Zinc Production (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Zinc Production	CO_2	0.5	0.4	0.7	-21%	+25%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

4.18. Lead Production (IPCC Source Category 2C5)

Lead production in the United States consists of both primary and secondary processes—both of which emit CO_2 (Sjardin 2003). Primary lead production, in the form of direct smelting, mostly occurs at plants located in Alaska and Missouri, though to a lesser extent in Idaho, Montana, and Washington. Secondary production largely involves the recycling of lead acid batteries at 18 separate smelters located in 11 states (USGS 2006). Secondary lead production has increased in the United States over the past decade while primary lead production has decreased. In 2006, secondary lead production accounted for approximately 88 percent of total lead production (Smith 2007, USGS 1995).

Primary production of lead through the direct smelting of lead concentrate produces CO_2 emissions as the lead concentrates are reduced in a furnace using metallurgical coke (Sjardin 2003). U.S. primary lead production increased by 7 percent from 2005 to 2006 and has decreased by 62 percent since 1990 (Smith 2007, USGS 1995).

Approximately 92 percent of U.S. secondary lead is produced by recycling lead acid batteries in either blast furnaces or reverberatory furnaces (USGS 2006). The remaining 8 percent of secondary lead is produced from lead scrap. Similar to primary lead production, CO_2 emissions result when a reducing agent, usually metallurgical coke, is added to the smelter to aid in the reduction process (Sjardin 2003). U.S. secondary lead production increased by half a percent from 2005 to 2006, and has increased by 25 percent since 1990.

At last reporting, the United States was the third largest mine producer of lead in the world, behind China and Australia, accounting for 13 percent of world production in 2005 (USGS 2006). In 2006, U.S. primary and secondary lead production totaled 1,313,000 metric tons (Smith 2007). The resulting emissions of CO_2 from 2006 production were estimated to be 0.3 Tg CO_2 Eq. (270 Gg) (see Table 4-68). The majority of 2006 lead production is from secondary processes, which account for 86 percent of total 2006 CO_2 emissions.

After a gradual increase in total emissions from 1990 to 2000, total emissions have decreased by five percent since 1990, largely due to a decrease in primary production (62 percent since 1990) and a transition within the United States

Table 4-68: CO_2 Emissions from Lead Production (Tg CO_2 Eq. and Gg)

Year	Tg CO_2 Eq.	Gg
1990	0.3	285
1995	0.3	298
2000	0.3	311
2001	0.3	291
2002	0.3	286
2003	0.3	289
2004	0.3	263
2005	0.3	266
2006	0.3	270

from primary lead production to secondary lead production, which is less emissive than primary production, although the sharp decrease leveled off in 2005 and even increased slightly in 2006 (USGS 2006, Smith 2007).

Methodology

Non-energy CO_2 emissions from lead production result from primary and secondary production processes that use metallurgical coke or other C-based materials as reductants. For primary lead production using direct smelting, Sjardin (2003) and the IPCC (2006) provide an emission factor of 0.25 metric tons CO_2/ton lead. For secondary lead production, Sjardin (2003) and IPCC (2006) provide an emission factor of 0.2 metric tons CO_2/ton lead produced. Both factors are multiplied by total U.S. primary and secondary lead production, respectively, to estimate CO_2 emissions.

The 1990 through 2006 activity data for primary and secondary lead production (see Table 4-69) were obtained

Table 4-69: Lead Production (Metric Tons)

Year	Primary	Secondary
1990	404,000	922,000
1995	374,000	1,020,000
2000	341,000	1,130,000
2001	290,000	1,090,000
2002	262,000	1,100,000
2003	245,000	1,140,000
2004	148,000	1,127,000
2005	143,000	1,154,000
2006	153,000	1,160,000

Table 4-70: Tier 2 Quantitative Uncertainty Estimates for CO$_2$ Emissions from Lead Production (Tg CO$_2$ Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO$_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO$_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Lead Production	CO$_2$	0.3	0.2	0.3	-16%	+16%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

through the USGS *Mineral Yearbook: Lead* (USGS 1994 through 2008).

Uncertainty

Uncertainty associated with lead production relates to the emission factors and activity data used. The direct smelting emission factor used in primary production is taken from Sjardin (2003) who averages the values provided by three other studies (Dutrizac et al. 2000, Morris et al. 1983, Ullman 1997). For secondary production, Sjardin (2003) reduces this factor by 50 percent and adds a CO$_2$ emission factor associated with battery treatment. The applicability of these emission factors to plants in the United States is uncertain. There is also a smaller level of uncertainty associated with the accuracy of primary and secondary production data provided by the USGS.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-70. Lead production CO$_2$ emissions were estimated to be between 0.2 and 0.3 Tg CO$_2$ Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 16 percent above the emission estimate of 0.3 Tg CO$_2$ Eq.

Recalculations Discussion

Estimates of CO$_2$ emissions from lead production were revised for the 2001, 2002, 2004, 2005, and 2006 to reflect updated secondary production activity (USGS 2008). This change resulted in a less than 2 percent decrease in emissions for 2001 and 2002, and a less than 2 percent increase in emissions for 2004 and 2005.

4.19. HCFC-22 Production (IPCC Source Category 2E1)

Trifluoromethane (HFC-23 or CHF$_3$) is generated as a byproduct during the production of chlorodifluoromethane (HCFC-22), which is primarily employed in refrigeration and air conditioning systems and as a chemical feedstock for manufacturing synthetic polymers. Between 1990 and 2000, U.S. production of HCFC-22 increased significantly as HCFC-22 replaced chlorofluorocarbons (CFCs) in many applications. Since 2000, U.S. production has fluctuated but has generally remained above 1990 levels. Because HCFC-22 depletes stratospheric ozone, its production for non-feedstock uses is scheduled to be phased out by 2020 under the U.S. Clean Air Act.[13] Feedstock production, however, is permitted to continue indefinitely.

HCFC-22 is produced by the reaction of chloroform (CHCl$_3$) and hydrogen fluoride (HF) in the presence of a catalyst, SbCl$_5$. The reaction of the catalyst and HF produces SbCl$_x$F$_y$, (where x + y = 5), which reacts with chlorinated hydrocarbons to replace chlorine atoms with fluorine. The HF and chloroform are introduced by submerged piping into a continuous-flow reactor that contains the catalyst in a hydrocarbon mixture of chloroform and partially fluorinated intermediates. The vapors leaving the reactor contain HCFC-21 (CHCl$_2$F), HCFC-22 (CHClF$_2$), HFC-23 (CHF$_3$), HCl, chloroform, and HF. The under-fluorinated intermediates (HCFC-21) and chloroform are then condensed and returned to the reactor, along with residual catalyst, to undergo further fluorination. The final vapors leaving the condenser are primarily HCFC-22, HFC-23, HCl and residual HF. The HCl is recovered as a useful byproduct, and the HF is removed. Once separated

---

[13] As construed, interpreted, and applied in the terms and conditions of the *Montreal Protocol on Substances that Deplete the Ozone Layer* [42 U.S.C. §7671m(b), CAA §614].

Table 4-71: HFC-23 Emissions from HCFC-22 Production (Tg CO$_2$ Eq. and Gg)

Year	Tg CO$_2$ Eq.	Gg
1990	36.4	3
1995	33.0	3
2000	28.6	2
2001	19.7	2
2002	21.1	2
2003	12.3	1
2004	17.2	1
2005	15.8	1
2006	13.8	1

Table 4-72: HCFC-22 Production (Gg)

Year	Gg
1990	139
1995	155
2000	186
2001	152
2002	149
2003	138
2004	155
2005	156
2006	154

from HCFC-22, the HFC-23 is generally vented to the atmosphere as an unwanted byproduct, but it is sometimes captured for use in a limited number of applications.

Emissions of HFC-23 in 2006 were estimated to be 13.8 Tg CO$_2$ Eq. (1.2 Gg) (Table 4-71). This quantity represents a 13 percent decline from 2005 emissions and a 62 percent decline from 1990 emissions. Both declines are primarily due to decreases in the HFC-23 emission rate. These decreases are primarily attributable to four factors: (a) five plants that did not capture and destroy the HFC-23 generated have ceased production of HCFC-22 since 1990, (b) one plant that captures and destroys the HFC-23 generated began to produce HCFC-22, (c) one plant implemented and documented a process change that reduced the amount of HFC-23 generated, and (d) the same plant began recovering HFC-23, primarily for destruction and secondarily for sale. Three HCFC-22 production plants operated in the United States in 2006, two of which used thermal oxidation to significantly lower their HFC-23 emissions.

Methodology

To estimate their emissions of HFC-23, five of the eight HCFC-22 plants that have operated in the United States since 1990 use (or, for those plants that have closed, used) methods comparable to the Tier 3 methods in the 2006 IPCC Guidelines. The other three plants, the last of which closed in 1993, used methods comparable to the Tier 1 method in the 2006 IPCC Guidelines. Emissions from these three plants have been recalculated using the recommended emission

factor for unoptimized plants operating before 1995 (0.04 kg HCFC-23/kg HCFC-22 produced).

The five plants that have operated since 1994 measure(d) concentrations of HFC-23 to estimate their emissions of HFC-23. Plants using thermal oxidation to abate their HFC-23 emissions monitor the performance of their oxidizers to verify that the HFC-23 is almost completely destroyed. Plants that release (or historically have released) some of their byproduct HFC-23 periodically measure HFC-23 concentrations in the output stream using gas chromatography. This information is combined with information on quantities of products (e.g., HCFC-22) to estimate HFC-23 emissions.

Production data and emission estimates were prepared in cooperation with the U.S. producers of HCFC-22 (ARAP 1997, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007; RTI 1997; RTI 2008). Annual estimates of U.S. HCFC-22 production are presented in Table 4-72.

Uncertainty

The uncertainty analysis presented in this section was based on a Monte Carlo simulation as described in the 2006 IPCC Guidelines for each plant for 2006. The Monte Carlo analysis used estimates of the uncertainties in the individual variables in each plant's estimating procedure. This analysis was based on the generation of 10,000 random samples of model inputs from the probability density functions for each input. A normal probability density function was assumed for all measurements and biases except the equipment leak estimates for one plant; a log-normal probability density function was used for this plant's equipment leak estimates.

Table 4-73: Quantitative Uncertainty Estimates for HFC-23 Emissions from HCFC-22 Production (Tg CO$_2$ Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO$_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO$_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
HCFC-22 Production	HFC-23	13.8	12.9	15.2	-7%	+10%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-73. HCFC-22 production HFC emissions were estimated to be between 12.9 and 15.2 Tg CO$_2$ Eq. at the 95 percent confidence level. This indicates a range of approximately 7 percent below and 10 percent above the emission estimate of 13.8 Tg CO$_2$ Eq.

Recalculations

EPA recently completed a comprehensive review of plant-level estimates of HFC-23 emissions and HCFC-22 production (RTI, 2008). This review resulted in generally small adjustments to estimates of HCFC-22 production and HFC-23 emissions. As noted above, the HFC-23 emissions for three plants that operated in the early 1990s were re-calculated to conform with the 2006 IPCC Guidelines using the Tier 1 emission factor of 0.04 kg HFC-23/kg HCFC-22. This revision increased the estimated U.S. emissions by 4 to 6 percent for 1990 to 1993. The largest adjustment was for the year 1995, for which the HFC-23 emissions estimate increased by 22 percent. This increase reflected a correction made by one plant to its emissions estimate. This calculation was documented in the plant's files and made the plant's 1995 emission rate more consistent with its emission rates for previous and following years. There were also minor revisions (ranging from -4 percent to +10 percent) to the emissions estimated for 2000, 2002, 2004 and 2005. These changes reflected revisions that plants made to their estimates after they were submitted to the Alliance for Responsible Atmospheric Policy, which aggregates the emissions of the plants and sends the total to EPA. Again, the revised estimates were documented in the plants' files.

4.20. Substitution of Ozone Depleting Substances (IPCC Source Category 2F)

Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) are used as alternatives to several classes of ozone depleting substances (ODSs) that are being phased out under the terms of the *Montreal Protocol* and the Clean Air Act Amendments of 1990.[14] Ozone depleting substances—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—are used in a variety of industrial applications including refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and aerosols. Although HFCs and PFCs are not harmful to the stratospheric ozone layer, they are potent greenhouse gases. Emission estimates for HFCs and PFCs used as substitutes for ODSs are provided in Table 4-74 and Table 4-75.

In 1990 and 1991, the only significant emissions of HFCs and PFCs as substitutes to ODSs were relatively small amounts of HFC-152a—used as an aerosol propellant and also a component of the refrigerant blend R-500 used in chillers—and HFC-134a in refrigeration end-uses. Beginning in 1992, HFC-134a was used in growing amounts as a refrigerant in motor vehicle air-conditioners and in refrigerant blends such as R-404A.[15] In 1993, the use of HFCs in foam production began, and in 1994 these compounds also found applications as solvents and sterilants. In 1995, ODS substitutes for halons entered widespread use in the United States as halon production was phased-out.

---

[14] [42 U.S.C § 7671, CAA § 601]

[15] R-404A contains HFC-125, HFC-143a, and HFC-134a.

Table 4-74: Emissions of HFCs and PFCs from ODS Substitutes (Tg CO$_2$ Eq.)

Gas	1990	1995	2000	2001	2002	2003	2004	2005	2006
HFC-23	+	+	+	+	+	+	+	+	+
HFC-32	+	+	+	0.1	0.1	0.2	0.3	0.4	0.6
HFC-125	+	0.8	5.2	6.0	6.8	7.8	9.0	10.3	12.3
HFC-134a	+	25.4	57.2	62.0	66.3	70.0	73.8	76.3	76.6
HFC-143a	+	0.5	4.1	5.4	6.8	8.3	10.1	12.2	14.4
HFC-236fa	+	0.2	0.5	0.6	0.6	0.7	0.7	0.8	0.8
CF$_4$	+	+	+	+	+	+	+	+	+
Others*	0.3	1.6	4.0	3.9	4.3	4.9	5.2	5.4	5.7
Total	**0.3**	**28.5**	**71.2**	**78.0**	**85.0**	**92.0**	**99.1**	**105.4**	**110.4**

+ Does not exceed 0.05 Tg CO$_2$ Eq.
* Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-4310mee, C$_4$F$_{10}$, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications. For estimating purposes, the GWP value used for PFC/PFPEs was based upon C$_6$F$_{14}$.
Note: Totals may not sum due to independent rounding.

Table 4-75: Emissions of HFCs and PFCs from ODS Substitutes (Mg)

Gas	1990	1995	2000	2001	2002	2003	2004	2005	2006
HFC-23	+	+	1	1	1	1	1	1	1
HFC-32	+	+	44	92	166	268	400	562	913
HFC-125	+	291	1,873	2,150	2,442	2,798	3,220	3,675	4,395
HFC-134a	+	19,536	44,001	47,712	51,016	53,843	56,787	58,700	58,923
HFC-143a	+	132	1,089	1,415	1,781	2,194	2,654	3,200	3,782
HFC-236fa	+	36	85	94	103	111	118	125	131
CF$_4$	+	+	1	1	1	2	2	2	2
Others*	M	M	M	M	M	M	M	M	M

M (Mixture of Gases)
+ Does not exceed 0.5 Mg
* Others include HFC-152a, HFC-227ea, HFC-245fa, HFC-4310mee, C$_4$F$_{10}$, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications.

The use and subsequent emissions of HFCs and PFCs as ODS substitutes has been increasing from small amounts in 1990 to 110.4 Tg CO$_2$ Eq. in 2006. This increase was in large part the result of efforts to phase out CFCs and other ODSs in the United States. In the short term, this trend is expected to continue, and will likely accelerate over the next decade as HCFCs, which are interim substitutes in many applications, are themselves phased-out under the provisions of the Copenhagen Amendments to the *Montreal Protocol*. Improvements in the technologies associated with the use of these gases and the introduction of alternative gases and technologies, however, may help to offset this anticipated increase in emissions.

Table 4-76 presents HFCs and PFCs emissions by end-use sector for 1990 through 2006. The end-use sectors that contributed the most toward emissions of HFCs and PFCs

Table 4-76: Emissions of HFCs and PFCs from ODS Substitutes (Tg CO$_2$ Eq.) by Sector

Gas	1990	1995	2000	2001	2002	2003	2004	2005	2006
Refrigeration/Air Conditioning	+	19.3	58.6	65.3	71.6	77.7	84.4	90.1	94.6
Aerosols	+	8.1	10.1	10.3	10.6	10.8	11.1	11.3	11.6
Foams	+	+	+	+	1.0	1.8	2.0	2.2	2.4
Solvents	+	0.9	2.1	1.8	1.6	1.3	1.3	1.3	1.3
Fire Protection	+	+	+	+	+	+	+	0.5	0.6
Total	**+**	**28.5**	**71.2**	**78.0**	**85.0**	**92.0**	**99.1**	**105.4**	**110.4**

as ODS substitutes in 2006 include refrigeration and air-conditioning (94.6 Tg CO_2 Eq., or approximately 86 percent), aerosols (11.6 Tg CO_2 Eq., or approximately 10 percent), and foams (2.4 Tg CO_2 Eq., or approximately 2 percent). Within the refrigeration and air-conditioning end-use sector, motor vehicle air-conditioning was the highest emitting end-use (55.8 Tg CO_2 Eq.), followed by retail food and refrigerated transport. Each of the end-use sectors is described in more detail below.

Refrigeration/Air Conditioning

The refrigeration and air-conditioning sector includes a wide variety of equipment types that have historically used CFCs or HCFCs. End uses within this sector include motor vehicle air-conditioning, retail food refrigeration, refrigerated transport (e.g., ship holds, truck trailers, railway freight cars), household refrigeration, residential and small commercial air-conditioning/heat pumps, chillers (large comfort cooling), cold storage facilities, and industrial process refrigeration (e.g., systems used in food processing, chemical, petrochemical, pharmaceutical, oil and gas, and metallurgical industries). As the ODS phaseout is taking effect, most equipment is being or will eventually be retrofitted or replaced to use HFC-based substitutes. Common HFCs in use today in refrigeration/air-conditioning equipment are HFC-134a, R-410A, R-404A, and R-507A. These HFCs are emitted to the atmosphere during equipment manufacture and operation (as a result of component failure, leaks, and purges), as well as at servicing and disposal events.

Aerosols

Aerosol propellants are used in metered dose inhalers (MDIs) and a variety of personal care products and technical/specialty products (e.g., duster sprays and safety horns). Many pharmaceutical companies that produce MDIs—a type of inhaled therapy used to treat asthma and chronic obstructive pulmonary disease—have committed to replace the use of CFCs with HFC-propellant alternatives. The earliest ozone-friendly MDIs were produced with HFC-134a, but eventually, the industry expects to use HFC-227ea as well. Conversely, since the use of CFC propellants was banned in 1978, most consumer aerosol products have not transitioned to HFCs, but to "not-in-kind" technologies, such as solid roll-on deodorants and finger-pump sprays. The transition away from ODS in specialty aerosol products has also led to the introduction of non-fluorocarbon alternatives (e.g., hydrocarbon propellants) in certain applications, in addition to HFC-134a or HFC-152a. These propellants are released into the atmosphere as the aerosol products are used.

Foams

CFCs and HCFCs have traditionally been used as foam blowing agents to produce polyurethane (PU), polystyrene, polyolefin, and phenolic foams, which are used in a wide variety of products and applications. Since the Montreal Protocol, flexible PU foams as well as other types of foam, such as polystyrene sheet, polyolefin, and phenolic foam, have transitioned almost completely away from fluorocompounds, into alternatives such as CO_2, methylene chloride, and hydrocarbons. The majority of rigid PU foams have transitioned to HFCs—primarily HFC-134a and HFC-245fa. Today, these HFCs are used to produce polyurethane appliance foam, PU commercial refrigeration, PU spray, and PU panel foams—used in refrigerators, vending machines, roofing, wall insulation, garage doors, and cold storage applications. In addition, HFC-152a is used to produce polystyrene sheet/board foam, which is used in food packaging and building insulation. Emissions of blowing agents occur when the foam is manufactured as well as during the foam lifetime and at foam disposal, depending on the particular foam type.

Solvents

CFCs, methyl chloroform (1,1,1-trichloroethane or TCA), and to a lesser extent carbon tetrachloride (CCl_4) were historically used as solvents in a wide range of cleaning applications, including precision, electronics, and metal cleaning. Since their phaseout, metal cleaning end-use applications have primarily transitioned to non-fluorocarbon solvents and not-in-kind processes. The precision and electronics cleaning end-uses have transitioned in part to high-GWP gases, due to their high reliability, excellent compatibility, good stability, low toxicity, and selective solvency. These applications rely on HFC-4310mee, HFC-365mfc, HFC-245fa, and to a lesser extent, PFCs. Electronics cleaning involves removing flux residue that remains after

a soldering operation for printed circuit boards and other contamination-sensitive electronics applications. Precision cleaning may apply to either electronic components or to metal surfaces, and is characterized byproducts, such as disk drives, gyroscopes, and optical components, that require a high level of cleanliness and generally have complex shapes, small clearances, and other cleaning challenges. The use of solvents yields fugitive emissions of these HFCs and PFCs.

Fire Protection

Fire protection applications include portable fire extinguishers ("streaming" applications) that originally used halon 1211, and total flooding applications that originally used halon 1301, as well as some halon 2402. Since the production and sale of halons were banned in the United States in 1994, the halon replacement agent of choice in the streaming sector has been dry chemical, although HFC-236ea is also used to a limited extent. In the total flooding sector, HFC-227ea has emerged as the primary replacement for halon 1301 in applications that require clean agents. Other HFCs, such as HFC-23, HFC-236fa, and HFC-125, are used in smaller amounts. The majority of HFC-227ea in total flooding systems is used to protect essential electronics, as well as in civil aviation, military mobile weapons systems, oil/gas/other process industries, and merchant shipping. As fire protection equipment is tested or deployed, emissions of these HFCs are released.

Methodology

A detailed Vintaging Model of ODS-containing equipment and products was used to estimate the actual—versus potential—emissions of various ODS substitutes, including HFCs and PFCs. The name of the model refers to the fact that the model tracks the use and emissions of various compounds for the annual "vintages" of new equipment that enter service in each end-use. This Vintaging Model predicts ODS and ODS substitute use in the United States based on modeled estimates of the quantity of equipment or products sold each year containing these chemicals and the amount of the chemical required to manufacture and/or maintain equipment and products over time. Emissions for each end-use were estimated by applying annual leak rates and release profiles, which account for the lag in emissions

from equipment as they leak over time. By aggregating the data for more than 50 different end-uses, the model produces estimates of annual use and emissions of each compound. Further information on the Vintaging Model is contained in Annex 3.8.

Uncertainty

Given that emissions of ODS substitutes occur from thousands of different kinds of equipment and from millions of point and mobile sources throughout the United States, emission estimates must be made using analytical tools such as the Vintaging Model or the methods outlined in IPCC (2006). Though the model is more comprehensive than the IPCC default methodology, significant uncertainties still exist with regard to the levels of equipment sales, equipment characteristics, and end-use emissions profiles that were used to estimate annual emissions for the various compounds.

The Vintaging Model estimates emissions from over 50 end-uses. The uncertainty analysis, however, quantifies the level of uncertainty associated with the aggregate emissions resulting from the top 16 end-uses, comprising over 95 percent of the total emissions, and 5 other end-uses. In an effort to improve the uncertainty analysis, additional end-uses are added annually, with the intention that over time uncertainty for all emissions from the Vintaging Model will be fully characterized. This year, one new end-use was included in the uncertainty estimate—fire extinguishing streaming agents. Any end-uses included in previous years' uncertainty analysis were included in the current uncertainty analysis, whether or not those end-uses were included in the top 95 percent of emissions from ODS Substitutes.

In order to calculate uncertainty, functional forms were developed to simplify some of the complex "vintaging" aspects of some end-use sectors, especially with respect to refrigeration and air-conditioning, and to a lesser degree, fire extinguishing. These sectors calculate emissions based on the entire lifetime of equipment, not just equipment put into commission in the current year, thereby necessitating simplifying equations. The functional forms used variables that included growth rates, emission factors, transition from ODSs, change in charge size as a result of the transition, disposal quantities, disposal emission rates, and either stock for the current year or original ODS consumption. Uncertainty

Table 4-77: Tier 2 Quantitative Uncertainty Estimates for HFC and PFC Emissions from ODS Substitutes (Tg CO$_2$ Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO$_2$ Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO$_2$ Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Substitution of Ozone Depleting Substances	HFCs and PFCs	110.4	110.1	129.6	-0.3%	+17%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

was estimated around each variable within the functional forms based on expert judgment, and a Monte Carlo analysis was performed. The most significant sources of uncertainty for this source category include the emission factors for mobile air-conditioning and retail food refrigeration, as well as the stock (MT) of retail food refrigerant.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-77. Substitution of ozone depleting substances HFC and PFC emissions were estimated to be between 110.1 and 129.6 Tg CO$_2$ Eq. at the 95 percent confidence level (or in 19 out of 20 Monte Carlo Stochastic Simulations). This indicates a range of approximately 0.3 percent below to 17 percent above the emission estimate of 110.4 Tg CO$_2$ Eq.

Recalculations Discussion

An extensive review of the chemical substitution trends, market sizes, growth rates, and charge sizes, together with input from industry representatives, resulted in updated assumptions for the Vintaging Model. These changes resulted in an average annual net decrease of 8.5 Tg CO$_2$ Eq. (14 percent) in HFC and PFC emissions from the substitution of ozone depleting substances for the period 1990 through 2005. The refrigeration and air conditioning sector was the source of the greatest change, with an average annual net decrease of 10.2 Tg CO$_2$ Eq. (15 percent) in emissions. This decrease can be attributed to changes in the assumptions regarding the quantity of emissions at end of life (disposal) across the entire sector, based on revised assumptions considering input from industry representatives, as well significant modification to assumptions for chiller end uses, based on industry input.

4.21. Semiconductor Manufacture (IPCC Source Category 2F6)

The semiconductor industry uses multiple long-lived fluorinated gases in plasma etching and plasma enhanced chemical vapor deposition (PECVD) processes to produce semiconductor products. The gases most commonly employed are trifluoromethane (HFC-23 or CHF$_3$), perfluoromethane (CF$_4$), perfluoroethane (C$_2$F$_6$), nitrogen trifluoride (NF$_3$), and sulfur hexafluoride (SF$_6$), although other compounds such as perfluoropropane (C$_3$F$_8$) and perfluorocyclobutane (c-C$_4$F$_8$) are also used. The exact combination of compounds is specific to the process employed.

A single 300 mm silicon wafer that yields between 400 to 500 semiconductor products (devices or chips) may require as many as 100 distinct fluorinated-gas-using process steps, principally to deposit and pattern dielectric films. Plasma etching (or patterning) of dielectric films, such as silicon dioxide and silicon nitride, is performed to provide pathways for conducting material to connect individual circuit components in each device. The patterning process uses plasma-generated fluorine atoms, which chemically react with exposed dielectric film, to selectively remove the desired portions of the film. The material removed as well as undissociated fluorinated gases flow into waste streams and, unless emission abatement systems are employed, into the atmosphere. PECVD chambers, used for depositing dielectric films, are cleaned periodically using fluorinated and other gases. During the cleaning cycle the gas is converted to fluorine atoms in plasma, which etches away residual material from chamber walls, electrodes, and chamber hardware. Undissociated fluorinated gases and other products pass

Table 4-78: PFC, HFC, and SF$_6$ Emissions from Semiconductor Manufacture (Tg CO$_2$ Eq.)

Gas	1990	1995	2000	2001	2002	2003	2004	2005	2006
CF$_4$	0.7	1.3	1.8	1.3	1.1	1.0	1.1	1.1	1.2
C$_2$F$_6$	1.5	2.5	3.0	2.1	2.2	2.1	2.1	2.0	2.2
C$_3$F$_8$	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0
C$_4$F$_8$	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
HFC-23	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.3
SF$_6$	0.5	0.9	1.1	0.7	0.7	0.8	0.8	1.0	1.0
NF$_3$*	0.0	0.0	0.1	0.1	0.3	0.2	0.2	0.2	0.3
Total	**2.9**	**5.0**	**6.3**	**4.5**	**4.3**	**4.3**	**4.3**	**4.4**	**4.8**

Note: Totals may not sum due to independent rounding.
* NF$_3$ emissions are presented for informational purposes, using a GWP of 8,000, and are not included in totals.

Table 4-79: PFC, HFC, and SF$_6$ Emissions from Semiconductor Manufacture (Mg)

Gas	1990	1995	2000	2001	2002	2003	2004	2005	2006
CF$_4$	115	193	281	202	174	161	172	169	183
C$_2$F$_6$	160	272	322	230	241	227	225	217	242
C$_3$F$_8$	0	0	18	14	10	14	6	5	5
C$_4$F$_8$	0	0	0	0	6	9	9	13	13
HFC-23	15	25	23	15	15	16	17	18	22
SF$_6$	22	38	45	31	28	35	35	41	40
NF$_3$	3	6	11	12	32	30	30	26	40

from the chamber to waste streams and, unless abatement systems are employed, into the atmosphere. In addition to emissions of unreacted gases, some fluorinated compounds can also be transformed in the plasma processes into different fluorinated compounds which are then exhausted, unless abated, into the atmosphere. For example, when C$_2$F$_6$ is used in cleaning or etching, CF$_4$ is generated and emitted as a process byproduct. Besides dielectric film etching and PECVD chamber cleaning, much smaller quantities of fluorinated gases are used to etch polysilicon films and refractory metal films like tungsten.

For 2006, total weighted emissions of all fluorinated greenhouse gases by the U.S. semiconductor industry were estimated to be 4.8 Tg CO$_2$ Eq. Combined emissions of all fluorinated greenhouse gases are presented in Table 4-78 and Table 4-79 for years 1990, 1995 and the period 2000 to 2006. The rapid growth of this industry and the increasing complexity (growing number of layers) of semiconductor products led to an increase in emissions of 149 percent between 1990 and 1999, when emissions peaked at 7.2 Tg CO$_2$ eq. The emissions growth rate began to slow after 1998, and emissions declined by 34 percent between 1999 and 2006. Together, industrial growth and use of abatement technologies resulted in a net increase in emissions of 64 percent between 1990 and 2006.

Methodology

Emissions are based on Partner reported emissions data received through the EPA's PFC Reduction/Climate Partnership and the EPA's PFC Emissions Vintage Model (PEVM), a model which estimates industry emissions in the absence of emission control strategies (Burton and Beizaie 2001).[16] The availability and applicability of Partner data differs across the 1990 through 2006 time series. Consequently, emissions from semiconductor manufacturing were estimated using three distinct methods, one each for the periods 1990 through 1994, 1995 through 1999, and 2000 and beyond.

---

[16] A Partner refers to a participant of the U.S. EPA PFC Reduction/Climate Partnership for the Semiconductor Industry. Through a Memorandum of Understanding (MoU) with the EPA, Partners voluntarily report their PFC emissions to the EPA by way of a third party.

1990 through 1994

For 1990 through 1994, Partnership data was unavailable and emissions were modeled using the PEVM (Burton and Beizaie 2001).[17] 1990 to 1994 emissions are assumed to be primarily uncontrolled, since reduction strategies such as chemical substitution and abatement were not widespread during this period.

PEVM is based on the assumption that PFC emissions from semiconductor manufacturing vary with (1) the number of layers on different kinds of semiconductor devices (including both silicon wafer and metal interconnect layers), and (2) silicon consumption (i.e., the area of semiconductors produced) for each kind of device. The product of these two quantities, Total Manufactured Layer Area (TMLA), constitutes the activity data for semiconductor manufacturing. PEVM also incorporates an emission factor that expresses emissions per unit of layer area. Emissions are estimated by multiplying TMLA by this emission factor.

PEVM incorporates information on the two attributes of semiconductor devices that affect the number of layers: (1) linewidth technology (the smallest feature size),[18] and (2) product type (discrete, memory or logic).[19] For each linewidth technology, a weighted average number of layers is estimated using VLSI product-specific worldwide silicon demand data in conjunction with complexity factors (i.e., the number of layers per IC) specific to product type (Burton and Beizaie 2001, ITRS 2007). PEVM derives historical consumption of silicon (i.e., square inches) by linewidth

technology from published data on annual wafer starts and average wafer size (VLSI Research, 2007).

The emission factor in PEVM is the average of the four historical emission factors derived by dividing the total annual emissions reported by the Partners for each year between 1996 and 1999 by the total TMLA estimated for the Partners in each of those years. Since Partners are not believed to have applied significant emission reduction measures before 2000, the resulting average emission factor does not reflect such measures.

1995 through 1999

For 1995 through 1999, total U.S. emissions were extrapolated from the total annual emissions reported by the Partners (1995 through 1999). Partner-reported emissions are considered more accurate than PEVM estimated emissions, and are used to generate total U.S. emissions when applicable. The emissions reported by the Partners were divided by the ratio of the total layer-weighted capacity of the plants operated by the Partners and the total layer-weighted capacity of all of the semiconductor plants in the United States; this ratio represents the share of layer-weighted capacity attributable to the Partnership. The layer-weighted capacity of a plant (or group of plants) consists of the silicon capacity of that plant multiplied by the estimated number of layers used to fabricate products at that plant. This method assumes that Partners and non-Partners have similar capacity utilizations and per-layer emission factors. Plant capacity, linewidth technology, and products manufactured information is contained in the World Fab Watch (WFW) database, which is updated quarterly (see for example, Semiconductor Equipment and Materials Industry 2007).

2000 through 2006

The U.S. estimate for the years 2000 through 2006—the period during which Partners began the consequential application of PFC-reduction measures—was estimated using a combination of Partner reported emissions and PEVM modeled emissions. The emissions reported by Partners for each year were accepted as the quantity emitted from the share of the industry represented by those Partners. Remaining emissions (those from non-Partners), however, were estimated using PEVM and the method described above. This is because non-Partners are assumed not to have implemented any PFC-reduction measures, and PEVM

---

[17] Various versions of the PEVM exist, to reflect changing industrial practices. From 1990 to 1994 emissions estimates are from PEVM v1.0, completed in September 1998. The emission factor used to estimate 1990 to 1994 emissions is an average of the 1995 and 1996 emission factors, which were derived from Partner reported data for those years.

[18] By decreasing features of IC components, more components can be manufactured per device, which increases its functionality. However, as those individual components shrink it requires more layers to interconnect them to achieve the functionality. For example, a microprocessor manufactured with the smallest feature sizes (65 nm) might contain as many as 1 billion transistors and require as many as 11 layers of component interconnects to achieve functionality while a device manufactured with 130 nm feature size might contain a few hundred million transistors and require 8 layers of component interconnects (ITRS, 2007).

[19] Memory devices manufactured with the same feature sizes as microprocessors (a logic device) require approximately one-half the number of interconnect layers, whereas discrete devices require only a silicon base layer and no interconnect layers (ITRS, 2007). Since discrete devices did not start using PFCs appreciably until 2004, they are only accounted for in the PEVM emissions estimates from 2004 onwards.

models emissions without such measures. The portion of the U.S. total attributed to non-Partners is obtained by multiplying PEVM's total world emissions figure by the non-Partner share of total layer-weighted silicon capacity for each year (as described above).[20] Annual updates to PEVM reflect published figures for actual silicon consumption from VLSI Research, Inc., revisions and additions to the world population of semiconductor manufacturing plants, and changes in IC fabrication practices within the semiconductor industry (see Semiconductor Equipment and Materials Industry 2007).[21, 22, 23]

Gas-Specific Emissions

Two different approaches were also used to estimate the distribution of emissions of specific PFCs. Before 1999, when there was no consequential adoption of PFC-reducing measures, a fixed distribution was assumed to apply to the entire U.S. industry. This distribution was based upon the average PFC purchases by semiconductor manufacturers during this period and the application of IPCC default emission factors for each gas (Burton and Beizaie 2001). For the 2000 through 2006 period, the 1990 through 1999 distribution was assumed to apply to the non-Partners. Partners, however, began to report gas-specific emissions during this period. Thus, gas specific emissions for 2000 through 2006 were estimated by adding the emissions reported by the Partners to those estimated for the non-Partners.[24]

Data Sources

Partners estimate their emissions using a range of methods. For 2006, we assume that most Partners used a method as least as accurate as the IPCC's Tier 2c Methodology, recommended in the IPCC (2000), since that has been their approach for the past several years. Although some of the default emission factors have been updated in the IPCC (2006) guidelines, as of the 2006 reporting year Partners continue to use the IPCC (2000) default emission factors.[25] The Partners with relatively high emissions use leading-edge manufacturing technology, the newest process equipment. When purchased, this equipment is supplied with PFC emission factors, measured using industry standard guidelines (International Sematech, 2006). The larger emitting Partners likely use these process-specific emission factors instead of the less accurate default emission factors provided in IPCC guidelines; however, the documentation regarding Partner emissions is incomplete (Burton and Kshetry, 2007).

Data used to develop emission estimates were prepared in cooperation with the Partnership. Estimates of operating plant capacities and characteristics for Partners and non-Partners were derived from the Semiconductor Equipment and Materials Industry (SEMI) *World Fab Watch* (formerly *International Fabs on Disk*) database (1996 through 2007). Estimates of silicon consumed by linewidth from 1990 through 2006 were derived from information from VLSI Research

---

[20] Generally 5 percent or less of the fields needed to estimate TMLA shares are missing values in the World Fab Watch databases. In the 2007 World Fab Watch database, used to generate the 2006 non-Partner TMLA capacity share, these missing values were replaced with the corresponding mean TMLA across fabs manufacturing similar classes of products. However, the impact of replacing missing values on the non-Partner TMLA capacity share was inconsequential.

[21] Special attention was given to the manufacturing capacity of plants that use wafers with 300 mm diameters because the actual capacity of these plants is ramped up to design capacity, typically over a 2–3 year period. To prevent overstating estimates of partner-capacity shares from plants using 300 mm wafers, *design* capacities contained in WFW were replaced with estimates of *actual installed* capacities for 2004 published by Citigroup Smith Barney (2005). Without this correction, the partner share of capacity would be overstated, by approximately 5 percentage points. For perspective, approximately 95 percent of all new capacity additions in 2004 used 300 mm wafers and by year-end those plants, on average, could operate at approximately 70 percent of the design capacity. For 2005, actual installed capacities was estimated using an entry in the World Fab Watch database (April 2006 Edition) called "wafers/month, 8-inch equivalent," which denoted the actual installed capacity instead of the fully-ramped capacity. For 2006, actual installed capacities of new fabs were estimated using an average monthly ramp rate of 1100 wafer starts per month (wspm) derived from various sources such as semiconductor fabtech, industry analysts, and articles in the trade press. The monthly ramp rate was applied from the first-quarter of silicon volume (FQSV), to determine the average design capacity over the 2006 period.

[22] In 2006, the industry trend in co-owernship of manufacturing facilities continued. Several manufacturers, who are Partners, now operate fabs with other manufacturers, who in some cases are also Partners and in other cases not Partners. Special attention was given to this occurrence when estimating the Partner and non-Partner shares of U.S. layer-weighted manufacturing capacity.

[23] Two versions of PEVM are used to model non-Partner emissions during this period. For the years 2000 to 2003 PEVM v3.2.0506.0507 was used to estimate non-Partner emissions. During this time discrete devices did not use PFCs during manufacturing and, therefore, only memory and logic devices were modeled in the PEVM v3.2.0506.0507. From 2004 onwards discrete device fabrication started to use PFCs, hence PEVM v4.0.0701.0701, the first version of PEVM to account for PFC emissions from discrete devices, was used to estimate non-Partner emissions for this time period.

---

[24] In recent years, the Partnership started reporting gas-specific emissions using GWP values from the Third Assessment Report (TAR), while in previous years the values were taken from the Second Assessment Report (SAR). The emissions reported here are restated using GWPs from the SAR.

[25] Currently, the majority of Partners use the IPCC (2000) Tier 2c guidelines, which most closely resemble the IPCC (2006) Tier 2a guidelines.

(2007), and the number of layers per linewidth was obtained from International Technology Roadmap for Semiconductors: 2006 Update (Burton and Beizaie 2001, ITRS 2007).

Uncertainty

A quantitative uncertainty analysis[26] of this source category was performed using the IPCC-recommended Tier 2 uncertainty estimation methodology, the Monte Carlo Stochastic Simulation technique. The equation used to estimate uncertainty is:

U.S. emissions = ∑Partnership gas-specific submittals + (non-Partner share of world TMLA) × (PEVM emission factor × world TMLA)

The Monte Carlo analysis results presented below relied on estimates of uncertainty attributed to the four quantities on the right side of the equation. Estimates of uncertainty for the four quantities were in turn developed using the estimated uncertainties associated with the individual inputs to each quantity, error propagation analysis, Monte Carlo simulation and expert judgment. The relative uncertainty associated with the world TMLA estimate in 2006 is approximately ±10 percent, based on the uncertainty estimate obtained from discussions with VLSI, Inc. For the share of world layer-weighted silicon capacity accounted for by non-Partners, a relative uncertainty of ±8 percent was estimated based on a separate Monte Carlo simulation to account for the random occurrence of missing data in the *World Fab Watch* database. For the aggregate PFC emissions data supplied to the partnership, a relative uncertainty of ±50 percent was estimated

for each gas-specific PFC emissions value reported by an individual Partner, and error propagation techniques were used to estimate uncertainty for total Partnership gas-specific submittals.[27] A relative error of approximately 11 percent was estimated for the PEVM emission factor, based on the standard deviation of the 1996 to 1999 emission factors.[28]

Consideration was also given to the nature and magnitude of the potential bias that World activity data (i.e., world TMLA) might have in its estimates of the number of layers associated with devices manufactured at each technology node. The result of a brief analysis indicated that U.S. TMLA overstates the average number of layers across all product categories and all manufacturing technologies for 2004 by 0.12 layers or 2.9 percent. The same upward bias is assumed for world TMLA, and is represented in the uncertainty analysis by deducting the absolute bias value from the world activity estimate when it is incorporated into the Monte Carlo analysis.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-80. The emissions estimate for total U.S. PFC emissions from semiconductor manufacturing were estimated to be between 4.8 and 5.5 Tg CO_2 Eq. at a 95 percent confidence level. This range represents 10 percent below to 8 percent above the 2006 emission estimate of 5.1 Tg CO_2 Eq. This range and the associated percentages apply to the estimate of total emissions rather than those of individual gases. Uncertainties associated with individual gases will be somewhat higher than the aggregate, but were not explicitly modeled.

Table 4-80: Tier 2 Quantitative Uncertainty Estimates for HFC, PFC, and SF_6 Emissions from Semiconductor Manufacture (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate[a] (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[b]			
			(Tg CO_2 Eq.)		(%)	
			Lower Bound[c]	Upper Bound[c]	Lower Bound	Upper Bound
Semiconductor Manufacture	HFC, PFC, and SF_6	5.1	4.8	5.5	-10%	+8%

[a] Because the uncertainty analysis covered all emissions (including NF_3), the emission estimate presented here does not match that shown in Table 4-78.
[b] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.
[c] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.

[27] Error propagation resulted in Partnership gas-specific uncertainties ranging from 17 to 33 percent.

[26] All uncertainties listed in this section are 95 percent confidence intervals.

[28] The average of 1996 to 1999 emission factor is used to derive the PEVM emission factor.

Planned Improvements

The method to estimate non-Partner related emissions (i.e., PEVM) is not expected to change (with the exception of possible future updates to emission factors and added technology nodes). Future improvements to the national emission estimates will primarily be associated with determining the portion of national emissions to attribute to Partner report totals (about 80 percent in recent years) and improvements in Partner emission reporting (e.g., adoption of the IPCC (2006) guidelines). As the nature of the Partner reports change through time and industry-wide reduction efforts increase, consideration will be given to what emission reduction efforts—if any—are likely to be occurring at non-Partner facilities. (Currently none are assumed to occur.)

4.22. Electrical Transmission and Distribution (IPCC Source Category 2F7)

The largest use of SF$_6$, both in the United States and internationally, is as an electrical insulator and interrupter in equipment that transmits and distributes electricity (RAND 2004). The gas has been employed by the electric power industry in the United States since the 1950s because of its dielectric strength and arc-quenching characteristics. It is used in gas-insulated substations, circuit breakers, and other switchgear. Sulfur hexafluoride has replaced flammable insulating oils in many applications and allows for more compact substations in dense urban areas.

Fugitive emissions of SF$_6$ can escape from gas-insulated substations and switch gear through seals, especially from older equipment. The gas can also be released during equipment manufacturing, installation, servicing, and disposal. Emissions of SF$_6$ from equipment manufacturing and from electrical transmission and distribution systems were estimated to be 13.2 Tg CO$_2$ Eq. (0.6 Gg) in 2006. This quantity represents a 51 percent decrease from the estimate for 1990 (see Table 4-81 and Table 4-82). This decrease is believed to be a response to increases in the price of SF$_6$ during the 1990s and to a growing awareness of the environmental impact of SF$_6$ emissions, through programs such as the EPA's SF$_6$ Emission Reduction Partnership for Electric Power Systems.

Table 4-81: SF$_6$ Emissions from Electric Power Systems and Electrical Equipment Manufacturers (Tg CO$_2$ Eq.)

Year	Electric Power Systems	Electrical Equipment Manufacturers	Total
1990	26.4	0.3	26.7
1995	20.9	0.5	21.5
2000	14.4	0.7	15.1
2001	14.5	0.6	15.0
2002	13.6	0.8	14.4
2003	13.2	0.7	13.8
2004	13.3	0.7	13.9
2005	13.2	0.8	14.0
2006	12.4	0.8	13.2

Table 4-82: SF$_6$ Emissions from Electric Power Systems and Electrical Equipment Manufacturers (Gg)

Year	Emissions
1990	1.1
1995	0.9
2000	0.6
2001	0.6
2002	0.6
2003	0.6
2004	0.6
2005	0.6
2006	0.6

Methodology

The estimates of emissions from electric transmission and distribution are comprised of emissions from electric power systems and emissions from the manufacture of electrical equipment. The methodologies for estimating both sets of emissions are described below.

1999 through 2006 Emissions from Electric Power Systems

Emissions from electric power systems from 1999 to 2006 were estimated based on: (1) reporting from utilities participating in EPA's SF$_6$ Emission Reduction Partnership for Electric Power Systems (Partners), which began in 1999; and, (2) the relationship between emissions and utilities' transmission miles as reported in the 2001, 2004 and 2007 Utility Data Institute (UDI) Directories of Electric

Power Producers and Distributors (UDI 2001, 2004, 2007). (Transmission miles are defined as the miles of lines carrying voltages above 34.5 kV.) Over the period from 1999 to 2006, Partner utilities, which for inventory purposes are defined as utilities that either currently are or previously have been part of the Partnership, represented between 42 percent and 46 percent of total U.S. transmission miles. For each year, the emissions reported by Partner utilities were added to the emissions estimated for utilities that have never participated in the Partnership (i.e., non-Partners).

Emissions from Partner utilities were estimated using a combination of reported data and, where reported data were unavailable, interpolated or extrapolated data. If a Partner utility did not provide data for a historical year, emissions were interpolated between years for which data were available or extrapolated based on Partner-specific transmission mile growth rates. In 2006, non-reporting Partners account for approximately 6 percent of the total emissions attributable to Partner utilities.

Emissions from non-Partners in every year since 1999 were estimated using the results of a regression analysis that showed that the emissions from reporting utilities were most strongly correlated with their transmission miles. The results of this analysis are not surprising given that, in the United States, SF_6 is contained primarily in transmission equipment rated at or above 34.5 kV. The equations were developed based on the 1999 SF_6 emissions reported by 43 Partner utilities (representing approximately 24 percent of U.S. transmission miles), and 2000 transmission mileage data obtained from the 2001 UDI Directory of Electric Power Producers and Distributors (UDI 2001). Two equations were developed, one for small and one for large utilities (i.e., with less or more than 10,000 transmission miles, respectively). The distinction between utility sizes was made because the regression analysis showed that the relationship between emissions and transmission miles differed for small and large transmission networks. The same equations were used to estimate non-Partner emissions in 1999 and every year thereafter because non-Partners were assumed not to have implemented any changes that would have resulted in reduced emissions since 1999.

The regression equations are:

Non-Partner small utilities (less than 10,000 transmission miles, in kilograms):

Emissions (kg) = 0.88 × Transmission Miles

Non-Partner large utilities (more than 10,000 transmission miles, in kilograms):

Emissions (kg) = 0.58 × Transmission Miles

Data on transmission miles for each non-Partner utility for the years 2000, 2003 and 2006 were obtained from the 2001, 2004 and 2007 UDI Directories of Electric Power Producers and Distributors, respectively (UDI 2001, 2004, 2007). The U.S. transmission system grew by over 22,000 miles between 2000 and 2003 and by over 55,000 miles between 2003 and 2006. These periodic increases are assumed to have occurred gradually, therefore transmission mileage were assumed to increase at an annual rate of 1.2 percent between 2000 and 2003 and 2.8 percent between 2003 and 2006.

As a final step, total emissions were determined for each year by summing the Partner reported and estimated emissions (reported data was available through the EPA's SF_6 Emission Reduction Partnership for Electric Power Systems), and the non-Partner emissions (determined using the 1999 regression equations).

1990 through 1998 Emissions from Electric Power Systems

Because most participating utilities reported emissions only for 1999 through 2006, modeling was used to estimate SF_6 emissions from electric power systems for the years 1990 through 1998. To perform this modeling, U.S. emissions were assumed to follow the same trajectory as global emissions from this source during the 1990 to 1998 period. To estimate global emissions, the RAND survey of global SF_6 sales were used, together with the following equation for estimating emissions, which is derived from the mass-balance equation for chemical emissions (Volume 3, Equation 7.3) in the IPCC *Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). (Although equation 7.3 of the IPCC Guidelines appears in the discussion of substitutes for ozone depleting substances, it is applicable to emissions from any long-

lived pressurized equipment that is periodically serviced during its lifetime.)

$$\text{Emissions (kilograms SF}_6) = \text{SF}_6 \text{ purchased to refill existing equipment (kilograms)} + \text{nameplate capacity}^{29} \text{ of retiring equipment (kilograms)}$$

Note that the above equation holds whether the gas from retiring equipment is released or recaptured; if the gas is recaptured, it is used to refill existing equipment, thereby lowering the amount of SF_6 purchased by utilities for this purpose.

Sulfur hexafluoride purchased to refill existing equipment in a given year was assumed to be approximately equal to the SF_6 purchased by utilities in that year. Gas purchases by utilities and equipment manufacturers from 1961 through 2003 are available from the RAND (2004) survey. To estimate the quantity of SF_6 released or recovered from retiring equipment, the nameplate capacity of retiring equipment in a given year was assumed to equal 81.2 percent of the amount of gas purchased by electrical equipment manufacturers 40 years previous (e.g., in 2000, the nameplate capacity of retiring equipment was assumed to equal 81.2 percent of the gas purchased in 1960). The remaining 18.8 percent was assumed to have been emitted at the time of manufacture. The 18.8 percent emission factor is an average of IPCC default SF_6 emission rates for Europe and Japan for 1995 (IPCC 2006). The 40-year lifetime for electrical equipment is also based on IPCC (2006). The results of the two components of the above equation were then summed to yield estimates of global SF_6 emissions from 1990 through 1998.

U.S. emissions between 1990 and 1998 are assumed to follow the same trajectory as global emissions during this period. To estimate U.S. emissions, global emissions for each year from 1990 through 1998 were divided by the estimated global emissions from 1999. The result was a time series of factors that express each year's global emissions as a multiple of 1999 global emissions. Historical U.S. emissions were estimated by multiplying the factor for each respective year by the estimated U.S. emissions of SF_6 from electric power systems in 1999 (estimated to be 15.0 Tg CO_2 Eq.).

Two factors may affect the relationship between the RAND sales trends and actual global emission trends. One is utilities' inventories of SF_6 in storage containers. When SF_6 prices rise, utilities are likely to deplete internal inventories before purchasing new SF_6 at the higher price, in which case SF_6 sales will fall more quickly than emissions. On the other hand, when SF_6 prices fall, utilities are likely to purchase more SF_6 to rebuild inventories, in which case sales will rise more quickly than emissions. This effect was accounted for by applying 3-year smoothing to utility SF_6 sales data. The other factor that may affect the relationship between the RAND sales trends and actual global emissions is the level of imports from and exports to Russia and China. SF_6 production in these countries is not included in the RAND survey, but may have been significant during the 1990 through 1999 period. This factor was not accounted for; however, atmospheric studies confirmed that the downward trend in the estimated global emissions between 1995 and 1998 was real (see the Uncertainty discussion below).

1990 through 2006 Emissions from Manufacture of Electrical Equipment

The 1990 to 2006 emissions estimates for original equipment manufacturers (OEMs) were derived by assuming that manufacturing emissions equal 10 percent of the quantity of SF_6 charged into new equipment. The quantity of SF_6 charged into new equipment was estimated based on statistics compiled by the National Electrical Manufacturers Association (NEMA). These statistics were provided for 1990 to 2000; the quantities of SF_6 charged into new equipment for 2001 to 2006 were estimated using partner reported data and the total industry SF_6 nameplate capacity estimate (128.4 Tg CO_2 Eq. in 2006). Specifically, the ratio of new nameplate capacity to total nameplate capacity of a subset of Partners for which new nameplate capacity data was available from 1999 to 2006 was calculated. This ratio was then multiplied by the total industry nameplate capacity estimate to derive the amount of SF_6 charged into new equipment for the entire industry. The 10 percent emission rate is the average of the "ideal" and "realistic" manufacturing emission rates (4 percent and 17 percent, respectively) identified in a paper prepared under the auspices of the International Council on Large Electric Systems (CIGRE) in February 2002 (O'Connell et al. 2002).

---

[29] Nameplate capacity is defined as the amount of SF_6 within fully charged electrical equipment.

Uncertainty

To estimate the uncertainty associated with emissions of SF_6 from electric transmission and distribution, uncertainties associated with three quantities were estimated: (1) emissions from Partners, (2) emissions from non-Partners, and (3) emissions from manufacturers of electrical equipment. A Monte Carlo analysis was then applied to estimate the overall uncertainty of the emissions estimate.

Total emissions from the SF_6 Emission Reduction Partnership include emissions from both reporting and non-reporting Partners. For reporting partners, individual partner-reported SF_6 data was assumed to have an uncertainty of 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of all partner reported data was estimated to be 4.1 percent. The uncertainty associated with extrapolated or interpolated emissions from non-reporting Partners was assumed to be 20 percent.

There are two sources of uncertainty associated with the regression equations used to estimate emissions in 2006 from non-partners: (1) uncertainty in the coefficients (as defined by the regression standard error estimate), and (2) the uncertainty in total transmission miles for non-Partners. In addition, there is uncertainty associated with the assumption that the emission factor used for non-Partner utilities (which accounted for approximately 58 percent of U.S. transmission miles in 2006) will remain at levels defined by Partners who reported in 1999. However, the last source of uncertainty was not modeled.

Uncertainties were also estimated regarding the quantity of SF_6 charged into equipment by equipment manufacturers, which is projected from Partner provided nameplate capacity data and industry SF_6 nameplate capacity estimates, and the manufacturers' SF_6 emissions rate.

The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 4-83. Electrical Transmission and Distribution SF_6 emissions were estimated to be between 11.1 and 15.4 Tg CO_2 Eq. at the 95 percent confidence level. This indicates a range of approximately 16 percent below and 17 percent above the emission estimate of 13.2 Tg CO_2 Eq.

In addition to the uncertainty quantified above, there is uncertainty associated with using global SF_6 sales data to estimate U.S. emission trends from 1990 through 1999. However, the trend in global emissions implied by sales of SF_6 appears to reflect the trend in global emissions implied by changing SF_6 concentrations in the atmosphere. That is, emissions based on global sales declined by 29 percent between 1995 and 1998, and emissions based on atmospheric measurements declined by 27 percent over the same period. However, U.S. emission patterns may differ from global emission patterns.

Recalculations Discussion

Relative to the previous Inventory report, SF_6 emission estimates for the period 1990 through 2006 were updated based on (1) new data from EPA's SF_6 Emission Reduction Partnership, (2) revisions to the assumptions used in interpolating and extrapolating non-reported Partner data, (3) new information on transmission mile growth available in the UDI 2007 database, (4) removal of double counting between parent companies and their subsidiaries in UDI databases, and (5) revision in the methodology for estimating 2001 to 2006 OEM emissions. For the period 1999 through 2006, estimates have been revised to incorporate additional data from new Partners. Additionally, Partner estimates are now based on Partner-specific transmission mile growth rates, obtained via the UDI 2001, 2004, and 2007 databases. Partner data and the industry SF_6 nameplate capacity estimates are now used to estimate OEM emissions from 2001 onwards, since NEMA data for these years does not exist. Based on the revisions listed above, SF_6 emissions from electric transmission and distribution decreased from 1990 to 2000 and in 2003 and

Table 4-83: Tier 2 Quantitative Uncertainty Estimates for SF_6 Emissions from Electrical Transmission and Distribution (Tg CO_2 Eq. and Percent)

Source	Gas	2006 Emission Estimate (Tg CO_2 Eq.)	Uncertainty Range Relative to Emission Estimate[a] (Tg CO_2 Eq.)		(%)	
			Lower Bound	Upper Bound	Lower Bound	Upper Bound
Electrical Transmission and Distribution	SF_6	13.2	11.1	15.4	-16%	+17%

[a] Range of emission estimates predicted by Monte Carlo Stochastic Simulation for a 95 percent confidence interval.

increased in 2002, 2004 and 2005, compared to the 1990 to 2005 Inventory. The magnitude of the differences between the 1990 to 2005 inventory estimates and this year's estimates varied by year and ranged from 0 to 6 percent.

Box 4-1: Potential Emission Estimates of HFCs, PFCs, and SF_6

Emissions of HFCs, PFCs and SF_6 from industrial processes can be estimated in two ways, either as potential emissions or as actual emissions. Emission estimates in this chapter are "actual emissions," which are defined by the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) as estimates that take into account the time lag between consumption and emissions. In contrast, "potential emissions" are defined to be equal to the amount of a chemical consumed in a country, minus the amount of a chemical recovered for destruction or export in the year of consideration. Potential emissions will generally be greater for a given year than actual emissions, since some amount of chemical consumed will be stored in products or equipment and will not be emitted to the atmosphere until a later date, if ever. Although actual emissions are considered to be the more accurate estimation approach for a single year, estimates of potential emissions are provided for informational purposes.

Separate estimates of potential emissions were not made for industrial processes that fall into the following categories:

- **Byproduct emissions.** Some emissions do not result from the consumption or use of a chemical, but are the unintended byproducts of another process. For such emissions, which include emissions of CF_4 and C_2F_6 from aluminum production and of HFC-23 from HCFC-22 production, the distinction between potential and actual emissions is not relevant.

- **Potential emissions that equal actual emissions.** For some sources, such as magnesium production and processing, no delay between consumption and emission is assumed and, consequently, no destruction of the chemical takes place. In this case, actual emissions equal potential emissions.

Table 4-84 presents potential emission estimates for HFCs and PFCs from the substitution of ozone depleting substances, HFCs, PFCs, and SF_6 from semiconductor manufacture, and SF_6 from magnesium production and processing and electrical transmission and distribution.[30] Potential emissions associated with the substitution for ozone depleting substances were calculated using the EPA's Vintaging Model. Estimates of HFCs, PFCs, and SF_6 consumed by semiconductor manufacture were developed by dividing chemical-by-chemical emissions by the appropriate chemical-specific emission factors from the IPCC *Good Practice Guidance* (Tier 2c). Estimates of CF_4 consumption were adjusted to account for the conversion of other chemicals into CF_4 during the semiconductor manufacturing process, again using the default factors from the IPCC *Good Practice Guidance*. Potential SF_6 emission estimates for electrical transmission and distribution were developed using U.S. utility purchases of SF_6 for electrical equipment. From 1999 through 2006, estimates were obtained from reports submitted by participants in EPA's SF_6 Emission Reduction Program for Electric Power Systems. U.S. utility purchases of SF_6 for electrical equipment from 1990 through 1998 were backcasted based on world sales of SF_6 to utilities. Purchases of SF_6 by utilities were added to SF_6 purchases by electrical equipment manufacturers to obtain total SF_6 purchases by the electrical equipment sector.

Table 4-84: 2006 Potential and Actual Emissions of HFCs, PFCs, and SF_6 from Selected Sources (Tg CO_2 Eq.)

Source	Potential	Actual
Substitution of Ozone Depleting Substances	182.1	110.4
Aluminum Production	-	2.5
HCFC-22 Production	-	13.8
Semiconductor Manufacture	7.6	4.8
Magnesium Production and Processing	3.2	3.2
Electrical Transmission and Distribution	22.6	13.2

- Not applicable.

---

[30] See Annex 5 for a discussion of sources of SF_6 emissions excluded from the actual emissions estimates in this report.

4.23. Industrial Sources of Indirect Greenhouse Gases

In addition to the main greenhouse gases addressed above, many industrial processes generate emissions of indirect greenhouse gases. Total emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and non-CH_4 volatile organic compounds (NMVOCs) from non-energy industrial processes from 1990 to 2006 are reported in Table 4-85.

Methodology

These emission estimates were obtained from preliminary data (EPA 2008), and disaggregated based on EPA (2003), which, in its final iteration, will be published on the National Emission Inventory (NEI) Air Pollutant Emission Trends web site. Emissions were calculated either for individual categories or for many categories combined, using basic activity data (e.g., the amount of raw material processed) as an indicator of emissions. National activity data were collected for individual categories from various agencies. Depending on the category, these basic activity data may include data on production, fuel deliveries, raw material processed, etc.

Activity data were used in conjunction with emission factors, which together relate the quantity of emissions to the activity. Emission factors are generally available from the EPA's *Compilation of Air Pollutant Emission Factors, AP-42* (EPA 1997). The EPA currently derives the overall emission control efficiency of a source category from a variety of information sources, including published reports, the 1985 National Acid Precipitation and Assessment Program emissions inventory, and other EPA databases.

Uncertainty

Uncertainties in these estimates are partly due to the accuracy of the emission factors used and accurate estimates of activity data. A quantitative uncertainty analysis was not performed.

Table 4-85: NO_x, CO, and NMVOC Emissions from Industrial Processes (Gg)

Gas/Source	1990	1995	2000	2001	2002	2003	2004	2005	2006
NO_x	**591**	**607**	**626**	**656**	**534**	**528**	**524**	**519**	**515**
Other Industrial Processes	343	362	434	457	390	385	381	377	373
Chemical & Allied Product Manufacturing	152	143	95	97	63	61	61	61	61
Metals Processing	88	89	81	86	63	63	63	63	62
Storage and Transport	3	5	14	15	17	17	17	17	17
Miscellaneous*	5	8	2	1	2	1	1	1	1
CO	**4,125**	**3,959**	**2,217**	**2,339**	**1,744**	**1,724**	**1,724**	**1,724**	**1,724**
Metals Processing	2,395	2,159	1,175	1,252	895	895	895	895	895
Other Industrial Processes	487	566	538	558	444	444	444	443	443
Chemical & Allied Product Manufacturing	1,073	1,110	327	338	258	257	257	257	257
Storage and Transport	69	23	154	162	107	107	107	107	107
Miscellaneous*	101	102	23	30	39	22	22	22	22
NMVOCs	**2,422**	**2,642**	**1,773**	**1,769**	**2,036**	**1,972**	**1,931**	**1,890**	**1,849**
Storage and Transport	1,352	1,499	1,067	1,082	1,346	1,304	1,274	1,245	1,215
Other Industrial Processes	364	408	412	381	401	394	386	379	372
Chemical & Allied Product Manufacturing	575	599	230	238	226	223	220	217	214
Metals Processing	111	113	61	65	42	42	42	42	41
Miscellaneous*	20	23	3	4	20	10	9	8	7

* Miscellaneous includes the following categories: catastrophic/accidental release, other combustion, health services, cooling towers, and fugitive dust. It does not include agricultural fires or slash/prescribed burning, which are accounted for under the Field Burning of Agricultural Residues source.
Note: Totals may not sum due to independent rounding.