# Annexes

The following seven annexes provide additional information related to the material presented in the main body of this report as directed in the *UNFCCC Guidelines on Reporting and Review* (GE.03-60887). Annex 1 contains an analysis of the key categories of emissions discussed in this report and a review of the methodology used to identify those key categories. Annex 2 describes the methodologies used to estimate $CO_2$ emissions from fossil fuel combustion, the carbon content of fossil fuels, and the amount of carbon stored in products from non-energy uses of fossil fuels. Annex 3 discusses the methodologies used for a number of individual source categories in greater detail than was presented in the main body of the report and includes explicit activity data and emission factor tables. Annex 4 presents the IPCC reference approach for estimating $CO_2$ emissions from fossil fuel combustion. Annex 5 addresses the criteria for the inclusion of an emission source category and discusses some of the sources that are excluded from U.S. estimates. Annex 6 provides a range of additional information that is relevant to the contents of this report. Finally, Annex 7 provides data on the uncertainty of the emission estimates included in this report.


ANNEX 1 Key Category Analysis ..... 2
ANNEX 2 Methodology and Data for Estimating $CO_2$ Emissions from Fossil Fuel Combustion ..... 29
2.1. Methodology for Estimating Emissions of $CO_2$ from Fossil Fuel Combustion ..... 29
2.2. Methodology for Estimating the Carbon Content of Fossil Fuels ..... 58
2.3. Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels ..... 96
ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories ..... 123
3.1. Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Indirect Greenhouse Gases from Stationary Combustion ..... 123
3.2. Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related GHG Emissions ..... 131
3.3. Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption – TO BE UPDATED ..... 162
3.4. Methodology for Estimating $CH_4$ Emissions from Coal Mining ..... 165
3.5. Methodology for Estimating $CH_4$ and $CO_2$ Emissions from Natural Gas Systems ..... 172
3.6. Methodology for Estimating $CH_4$ and $CO_2$ Emissions from Petroleum Systems ..... 200
3.7. Methodology for Estimating $CO_2$, $N_2O$ and $CH_4$ Emissions from the Incineration of Waste ..... 206
3.8. Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military ..... 212
3.9. Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances ..... 217
3.10. Methodology for Estimating $CH_4$ Emissions from Enteric Fermentation ..... 238
3.11. Methodology for Estimating $CH_4$ and $N_2O$ Emissions from Manure Management ..... 253
3.12. Methodology for Estimating $N_2O$ Emissions and Soil Organic C Stock Changes from Agricultural Soil Management (Cropland and Grassland) ..... 278
3.13. Methodology for Estimating Net Carbon Stock Changes in Forest Lands Remaining Forest Lands ..... 327
3.14. Methodology for Estimating $CH_4$ Emissions from Landfills ..... 358
ANNEX 4 IPCC Reference Approach for Estimating $CO_2$ Emissions from Fossil Fuel Combustion ..... 368
ANNEX 5 Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included ..... 378
ANNEX 6 Additional Information ..... 380
6.1. Global Warming Potential Values ..... 380
6.2. Ozone Depleting Substance Emissions ..... 388
6.3. Sulfur Dioxide Emissions – TO BE UPDATED ..... 390
6.4. Complete List of Source Categories ..... 392
6.5. Constants, Units, and Conversions ..... 393
6.6. Abbreviations ..... 396
6.7. Chemical Formulas ..... 401
ANNEX 7 Uncertainty – TO BE UDPATED ..... 404
7.1. Overview ..... 404
7.2. Methodology and Results ..... 404
7.3. Planned Improvements ..... 410
7.4. Additional Information on Uncertainty Analyses by Source ..... 411

# ANNEX 1 Key Category Analysis

The United States has identified national key categories based on the estimates presented in this report. The IPCC's *Good Practice Guidance* (IPCC 2000) describes a key category as a "[category] that is prioritized within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both."[1] By definition, key categories are sources or sinks that have the greatest contribution to the absolute overall level of national emissions in any of the years covered by the time series. In addition, when an entire time series of emission estimates is prepared, a determination of key categories must also account for the influence of the trends of individual categories. Therefore, a trend assessment is conducted to identify source and sink categories for which significant uncertainty in the estimate would have considerable effects on overall emission trends. Finally, a qualitative evaluation of key categories should be performed, in order to capture any key categories that were not identified in either of the quantitative analyses, but can be considered key because of the unique country-specific estimation methods.

The methodology for conducting a key category analysis, as defined by IPCC's *Good Practice Guidance* (IPCC 2000), IPCC's *Good Practice Guidance for Land Use, Land-Use Change, and Forestry (IPCC 2003)*, and IPCC's *2006 Guidelines for National Greenhouse Gas Inventories* IPCC (2006); includes:

- Tier 1 approach (including both level and trend assessments);
- Tier 2 approach (including both level and trend assessments, and incorporating uncertainty analysis); and
- Qualitative approach.

This Annex presents an analysis of key categories, both for sources only and also for sources and sinks (i.e., including LULUCF); discusses Tier 1, Tier 2, and qualitative approaches to identifying key categories; provides level and trend assessment equations; and provides a brief statistical evaluation of IPCC's quantitative methodologies for defining key categories. Table A- 1 presents the key categories for the United States (including and excluding LULUCF categories) using emissions and uncertainty data in this report, and ranked according to their sector and global warming potential-weighted emissions in 2011. The table also indicates the criteria used in identifying these categories (i.e., level, trend, Tier 1, Tier 2, and/or qualitative assessments).

Table A-1: Key Source Categories for the United States (1990-2011)

| IPCC Source Categories | Gas | Tier 1 | | | | Tier 2 | | | | Qual | 2011 Emissions (Tg $CO_2$ Eq.) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Level Without LULUCF | Trend Without LULUCF | Level With LULUCF | Trend With LULUCF | Level Without LULUCF | Trend Without LULUCF | Level With LULUCF | Trend With LULUCF | | |
| **Energy** | | | | | | | | | | | |
| $CO_2$ Emissions from Stationary Combustion - Coal - Electricity Generation | $CO_2$ | • | • | • | • | • | • | • | | | 1,718.0 |
| $CO_2$ Emissions from Mobile Combustion: Road | $CO_2$ | • | • | • | • | • | • | • | • | | 1,473.2 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Electricity Generation | $CO_2$ | • | • | • | • | • | • | • | • | | 410.2 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Industrial | $CO_2$ | • | • | • | • | • | • | • | • | | 409.7 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Industrial | $CO_2$ | • | • | • | • | • | • | • | • | | 279.9 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Residential | $CO_2$ | • | | • | | • | | • | | | 255.7 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Commercial | $CO_2$ | • | • | • | • | • | | • | | | 171.1 |
| $CO_2$ Emissions from Mobile Combustion: Aviation | $CO_2$ | • | • | • | • | • | • | • | • | | 142.8 |
| $CO_2$ Emissions from Non-Energy Use of Fuels | $CO_2$ | • | | • | • | • | | • | | | 130.5 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Industrial | $CO_2$ | • | • | • | • | • | • | • | • | | 90.0 |
| $CO_2$ Emissions from Mobile Combustion: Other | $CO_2$ | • | | • | • | | | | | | 79.2 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Residential | $CO_2$ | • | • | • | • | | • | | | | 78.2 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Commercial | $CO_2$ | • | • | • | • | | | | | | 49.8 |
| $CO_2$ Emissions from Stationary Combustion - Oil - U.S. Territories | $CO_2$ | • | • | • | • | | • | | | | 44.7 |
| $CO_2$ Emissions from Mobile Combustion: Marine | $CO_2$ | • | • | • | • | | | | | | 36.5 |
| $CO_2$ Emissions from Natural Gas Systems | $CO_2$ | • | • | • | • | • | • | • | • | | 32.3 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Electricity Generation | $CO_2$ | • | • | • | • | | • | | • | | 25.1 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Commercial | $CO_2$ | | • | | • | | | | | | 4.9 |
| Fugitive Emissions from Natural Gas Systems | $CH_4$ | • | • | • | | • | • | • | | | 215.4 |
| Fugitive Emissions from Coal Mining | $CH_4$ | • | • | • | • | • | • | • | • | | 72.6 |
| Fugitive Emissions from Petroleum Systems | $CH_4$ | • | • | • | • | • | • | • | • | | 31.5 |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $CH_4$ | | | | | | • | | • | | 3.6 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $N_2O$ | | • | | • | • | • | • | • | | 17.9 |
| $N_2O$ Emissions from Mobile Combustion: Road | $N_2O$ | • | • | • | • | | • | | • | | 16.7 |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $N_2O$ | | | | | | • | | | | 2.7 |
| International Bunker Fuels[b] | Several | | | | | | | | | • | 1.9 |
| **Industrial Processes** | | | | | | | | | | | |
| $CO_2$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CO_2$ | • | • | • | • | • | • | • | • | | 64.3 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $CO_2$ Emissions from Cement Production | $CO_2$ | • | | • | • | | | | | | 31.6 |
| $CO_2$ Emissions from Ammonia Production | $CO_2$ | | • | | • | | | | | | 8.8 |
| $CO_2$ Emissions from Aluminum Production | $CO_2$ | | | | | | • | | • | | 3.3 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | | | | | • | | | | | 16.7 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | | • | | • | | | | | | 10.6 |
| Emissions from Substitutes for Ozone Depleting Substances | HiGWP | • | • | • | • | | • | • | • | | 121.7 |
| $SF_6$ Emissions from Electrical Transmission and Distribution | HiGWP | | • | | • | | • | | • | | 11.7 |
| HFC-23 Emissions from HCFC-22 Production | HiGWP | • | • | • | • | | • | | • | | 6.9 |
| PFC Emissions from Aluminum Production | HiGWP | | • | | • | • | • | • | • | | 2.9 |
| $SF_6$ Emissions from Magnesium Production and Processing | HiGWP | | • | | • | | | | | | 1.3 |
| **Agriculture** | | | | | | | | | | | |
| $CH_4$ Emissions from Enteric Fermentation | $CH_4$ | • | • | • | • | • | | • | | | 139.3 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | • | • | • | • | • | • | • | • | | 52.3 |
| $CH_4$ Emissions from Rice Cultivation | $CH_4$ | | | | | • | • | • | • | | 6.6 |
| Direct $N_2O$ Emissions from Agricultural Soil Management | $N_2O$ | • | • | • | • | • | • | • | • | | 285.6 |
| Indirect $N_2O$ Emissions from Applied Nitrogen | $N_2O$ | • | | • | • | • | • | • | • | | 57.6 |
| **Waste** | | | | | | | | | | | |
| $CH_4$ Emissions from Landfills | $CH_4$ | • | • | • | • | • | • | • | • | | 103.0 |
| **Land Use, Land Use Change, and Forestry** | | | | | | | | | | | |
| $CO_2$ Emissions from Changes in Forest Carbon Stocks | $CO_2$ | | | • | • | | | • | • | | (921.8) |
| $CO_2$ Emissions from Urban Trees | $CO_2$ | | | • | • | | | • | • | | (98.0) |
| $CO_2$ Emissions from Landfilled Yard Trimmings and Food Scraps | $CO_2$ | | | | • | | | • | • | | (13.0) |
| $CO_2$ Emissions from Grassland Remaining Grassland | $CO_2$ | | | • | • | | | • | • | | (9.0) |
| $CO_2$ Emissions from Land Converted to Cropland | $CO_2$ | | | | • | | | • | • | | 12.5 |
| $CH_4$ Emissions from Forest Fires | $CH_4$ | | | | | | | | • | | 4.8 |
| $N_2O$ Emissions from Forest Fires | $N_2O$ | | | | | | | | • | | 4.0 |
| $CO_2$ Emissions from Cropland Remaining Cropland | $CO_2$ | | | | • | | | • | • | | 2.4 |
| **Subtotal Without LULUCF** | | | | | | | | | | | **6,716.5** |
| **Total Emissions Without LULUCF** | | | | | | | | | | | **6,851.2** |
| **Percent of Total Without LULUCF** | | | | | | | | | | | **98.0%** |
| **Subtotal With LULUCF** | | | | | | | | | | | **5,698.4** |
| **Total Emissions With LULUCF** | | | | | | | | | | | **5,829.4** |
| **Percent of Total With LULUCF** | | | | | | | | | | | **97.8%** |

[a]Qualitative criteria.

[b]Emissions from this source not included in totals.

Note: Parentheses indicate negative values (or sequestration).Table A-2 provides a complete listing of source categories by IPCC sector, along with notations on the criteria used in identifying key categories, without LULUCF sources and sinks. Similarly, Table A-3 provides a complete listing of source and sink categories by IPCC sector, along with notations on the criteria used in identifying key categories, including LULUCF sources and sinks. The notations refer specifically to the year(s) in the inventory time series (i.e., 1990 to 2009) in which each source category reached the threshold for being a key category based on either a Tier 1 or Tier 2 level assessment.

In addition to conducting Tier 1 and 2 level and trend assessments, a qualitative assessment of the source categories, as described in the IPCC's *Good Practice Guidance* (IPCC 2000), was conducted to capture any key categories that were not identified by any quantitative method. One additional key category, international bunker fuels, was identified using this qualitative assessment. International bunker fuels are fuels consumed for aviation or marine international transport activities, and emissions from these fuels are reported separately from totals in accordance with IPCC guidelines. If these emissions were included in the totals, bunker fuels would qualify as a key category according to the Tier 1 approach. The amount of uncertainty associated with estimation of emissions from international bunker fuels also supports the qualification of this source category as key, which would qualify it as a key category according to the Tier 2 approach.

Table A-2: U.S Greenhouse Gas Inventory Source Categories without LULUCF

| IPCC Source Categories | Direct GHG | 2011 Emissions (Tg $CO_2$ Eq.) | Key Category? | ID Criteria[a] | Level in which year(s)?[b] |
|---|---|---|---|---|---|
| **Energy** | | | | | |
| $CO_2$ Emissions from Stationary Combustion - Coal - Electricity Generation | $CO_2$ | 1,718.0 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Mobile Combustion: Road | $CO_2$ | 1,473.2 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Electricity Generation | $CO_2$ | 410.2 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Industrial | $CO_2$ | 409.7 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Industrial | $CO_2$ | 279.9 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Residential | $CO_2$ | 255.7 | • | $L_1$ $L_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Commercial | $CO_2$ | 171.1 | • | $L_1$ $T_1$ $L_2$ | 1990, 2011 |
| $CO_2$ Emissions from Mobile Combustion: Aviation | $CO_2$ | 142.8 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Non-Energy Use of Fuels | $CO_2$ | 130.5 | • | $L_1$ $L_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Industrial | $CO_2$ | 90.0 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Mobile Combustion: Other | $CO_2$ | 79.2 | • | $L_1$ | $1990_1$, $2011_1$ |
| $CO_2$ Emissions from Stationary Combustion - Oil - Residential | $CO_2$ | 78.2 | • | $L_1$ $T_1$ $T_2$ | 1990, $2011_1$ |
| $CO_2$ Emissions from Stationary Combustion - Oil - Commercial | $CO_2$ | 49.8 | • | $L_1$ $T_1$ | $1990_1$, $2011_1$ |
| $CO_2$ Emissions from Stationary Combustion - Oil - U.S. Territories | $CO_2$ | 44.7 | • | $L_1$ $T_1$ $T_2$ | 1990, $2011_1$ |
| $CO_2$ Emissions from Mobile Combustion: Marine | $CO_2$ | 36.5 | • | $L_1$ $T_1$ | $1990_1$, $2011_1$ |
| $CO_2$ Emissions from Natural Gas Systems | $CO_2$ | 32.3 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, $2011_1$ |
| $CO_2$ Emissions from Stationary Combustion - Oil - Electricity Generation | $CO_2$ | 25.1 | • | $L_1$ $T_1$ $T_2$ | $1990_1$ |
| $CO_2$ Emissions from Incineration of Waste | $CO_2$ | 12.0 | | | |
| $CO_2$ Emissions from Stationary Combustion - Coal - Commercial | $CO_2$ | 4.9 | • | $T_1$ | |
| $CO_2$ Emissions from Stationary Combustion - Coal - U.S. Territories | $CO_2$ | 3.5 | | | |
| $CO_2$ Emissions from Stationary Combustion - Gas - U.S. Territories | $CO_2$ | 1.5 | | | |
| $CO_2$ Emissions from Stationary Combustion - Coal - Residential | $CO_2$ | 0.6 | | | |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.4 | | | |
| $CO_2$ Emissions from Petroleum Systems | $CO_2$ | 0.3 | | | |
| Fugitive Emissions from Natural Gas Systems | $CH_4$ | 215.4 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |

| | | | | | |
|---|---|---|---|---|---|
| Fugitive Emissions from Coal Mining | $CH_4$ | 72.6 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| Fugitive Emissions from Petroleum Systems | $CH_4$ | 31.5 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011[2] |
| Fugitive Emissions from Abandoned Underground Coal Mines | $CH_4$ | 5.0 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $CH_4$ | 3.6 | • | $T_2$ | |
| $CH_4$ Emissions from Mobile Combustion: Road | $CH_4$ | 1.4 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $CH_4$ | 1.3 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $CH_4$ | 0.9 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $CH_4$ | 0.4 | | | |
| $CH_4$ Emissions from Mobile Combustion: Other | $CH_4$ | 0.4 | | | |
| $CH_4$ Emissions from Mobile Combustion: Aviation | $CH_4$ | 0.1 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $CH_4$ | 0.1 | | | |
| $CH_4$ Emissions from Mobile Combustion: Marine | $CH_4$ | + | | | |
| $CH_4$ Emissions from Incineration of Waste | $CH_4$ | + | | | |
| $N_2O$ Emissions from Mobile Combustion: Road | $N_2O$ | 16.7 | • | $L_1$ $T_1$ $T_2$ | 1990 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $N_2O$ | 17.9 | • | $T_1$ $L_2$ $T_2$ | 1990[2], 2011[2] |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $N_2O$ | 2.7 | • | $T_2$ | |
| $N_2O$ Emissions from Mobile Combustion: Other | $N_2O$ | 1.9 | | | |
| $N_2O$ Emissions from Mobile Combustion: Aviation | $N_2O$ | 1.4 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $N_2O$ | 0.9 | | | |
| $N_2O$ Emissions from Mobile Combustion: Marine | $N_2O$ | 0.5 | | | |
| $N_2O$ Emissions from Incineration of Waste | $N_2O$ | 0.4 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $N_2O$ | 0.3 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $N_2O$ | 0.1 | | | |
| International Bunker Fuels[c] | Several | 1.9 | | | |
| **Industrial Processes** | | | | | |
| $CO_2$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CO_2$ | 64.3 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 31.6 | • | $L_1$ | 1990[1] |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 13.8 | | | |
| $CO_2$ Emissions from Limestone and Dolomite Use | $CO_2$ | 9.5 | | | |
| $CO_2$ Emissions from Ammonia Production | $CO_2$ | 8.8 | • | $T_1$ | |
| $CO_2$ Emissions from Urea Consumption for Non-Ag Purposes | $CO_2$ | 4.3 | | | |
| $CO_2$ Emissions from Petrochemical Production | $CO_2$ | 3.5 | | | |
| $CO_2$ Emissions from Aluminum Production | $CO_2$ | 3.3 | • | $T_2$ | |
| $CO_2$ Emissions from Soda Ash Production and Consumption | $CO_2$ | 2.7 | | | |
| $CO_2$ Emissions from Carbon Dioxide Consumption | $CO_2$ | 2.2 | | | |
| $CO_2$ Emissions from Titanium Dioxide Production | $CO_2$ | 1.9 | | | |
| $CO_2$ Emissions from Ferroalloy Production | $CO_2$ | 1.7 | | | |

| | | | | | |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Glass Production | $CO_2$ | 1.5 | | | |
| $CO_2$ Emissions from Zinc Production | $CO_2$ | 1.3 | | | |
| $CO_2$ Emissions from Phosphoric Acid Production | $CO_2$ | 1.1 | | | |
| $CO_2$ Emissions from Lead Production | $CO_2$ | 0.5 | | | |
| $CO_2$ Emissions from Silicon Carbide Production and Consumption | $CO_2$ | 0.2 | | | |
| $CH_4$ Emissions from Petrochemical Production | $CH_4$ | 3.1 | | | |
| $CH_4$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CH_4$ | 0.6 | | | |
| $CH_4$ Emissions from Ferroalloy Production | $CH_4$ | + | | | |
| $CH_4$ Emissions from Silicon Carbide Production and Consumption | $CH_4$ | + | | | |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 16.7 | • | $L_2$ | $1990_2$ |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 10.6 | • | $T_1$ | |
| $N_2O$ Emissions from Product Uses | $N_2O$ | 4.4 | | | |
| Emissions from Substitutes for Ozone Depleting Substances | HiGWP | 121.7 | • | $L_1$ $T_1$ $T_2$ | $2011_1$ |
| $SF_6$ Emissions from Electrical Transmission and Distribution | HiGWP | 11.7 | • | $T_1$ $T_2$ | |
| HFC-23 Emissions from HCFC-22 Production | HiGWP | 6.9 | • | $L_1$ $T_1$ $T_2$ | $1990_1$ |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacture | HiGWP | 5.4 | | | |
| PFC Emissions from Aluminum Production | HiGWP | 2.9 | • | $T_1$ $L_2$ $T_2$ | $1990_2$ |
| $SF_6$ Emissions from Magnesium Production and Processing | HiGWP | 1.3 | • | $T_1$ | |
| **Agriculture** | | | | | |
| $CH_4$ Emissions from Enteric Fermentation | $CH_4$ | 139.3 | • | $L_1$ $T_1$ $L_2$ | 1990, 2011 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 52.3 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 2011 |
| $CH_4$ Emissions from Rice Cultivation | $CH_4$ | 6.6 | • | $L_2$ $T_2$ | $1990_2$, $2011_2$ |
| $CH_4$ Emissions from Field Burning of Agricultural Residues | $CH_4$ | 0.2 | | | |
| Direct $N_2O$ Emissions from Agricultural Soil Management | $N_2O$ | 285.6 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| Indirect $N_2O$ Emissions from Applied Nitrogen | $N_2O$ | 57.6 | • | $L_1$ $L_2$ $T_2$ | 1990, 2011 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 18.5 | | | |
| $N_2O$ Emissions from Field Burning of Agricultural Residues | $N_2O$ | 0.1 | | | |
| **Waste** | | | | | |
| $CH_4$ Emissions from Landfills | $CH_4$ | 103.0 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CH_4$ Emissions from Wastewater Treatment | $CH_4$ | 16.2 | | | |
| $CH_4$ Emissions from Composting | $CH_4$ | 1.5 | | | |
| $N_2O$ Emissions from Wastewater Treatment | $N_2O$ | 5.2 | | | |
| $N_2O$ Emissions from Composting | $N_2O$ | 1.7 | | | |

[a] For the ID criteria, L refers to a key category identified through a level assessment; T refers to a key category identified through a trend assessment and the subscripted number refers to either a Tier 1 or Tier 2 assessment (e.g., $L_2$ designates a source is a key category for a Tier 2 level assessment).
[b] If the source is a key category for both $L_1$ and $L_2$ (as designated in the ID criteria column), it is a key category for both assessments in the years provided unless noted by a subscript, in which case it is a key category for that assessment in that year only (.e.g., $1990_2$ designates a source is a key category for the Tier 2 assessment only in 1990).
[c] Emissions from these sources not included in totals.
+ Does not exceed 0.05 Tg $CO_2$ Eq.

Note: LULUCF sources and sinks are not included in this analysis.

Table A-3: U.S Greenhouse Gas Inventory Source Categories with LULUCF

| IPCC Source Categories | Gas | 2011 Emissions (Tg $CO_2$ Eq.) | Key Category? | ID Criteria[a] | Level in which year(s)?[b] |
|---|---|---|---|---|---|
| **Energy** | | | | | |
| $CO_2$ Emissions from Stationary Combustion - Coal - Electricity Generation | $CO_2$ | 1,718.0 | • | $L_1$ $T_1$ $L_2$ | 1990, 2011 |
| $CO_2$ Emissions from Mobile Combustion: Road | $CO_2$ | 1,473.2 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Electricity Generation | $CO_2$ | 410.2 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Industrial | $CO_2$ | 409.7 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Industrial | $CO_2$ | 279.9 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Residential | $CO_2$ | 255.7 | • | $L_1$ $L_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Commercial | $CO_2$ | 171.1 | • | $L_1$ $T_1$ $L_2$ | 1990, 2011 |
| $CO_2$ Emissions from Mobile Combustion: Aviation | $CO_2$ | 142.8 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Non-Energy Use of Fuels | $CO_2$ | 130.5 | • | $L_1$ $T_1$ $L_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Industrial | $CO_2$ | 90.0 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Mobile Combustion: Other | $CO_2$ | 79.2 | • | $L_1$ $T_1$ | $1990_1$, $2011_1$ |
| $CO_2$ Emissions from Stationary Combustion - Oil - Residential | $CO_2$ | 78.2 | • | $L_1$ $T_1$ | $1990_1$, $2011_1$ |
| $CO_2$ Emissions from Stationary Combustion - Oil - Commercial | $CO_2$ | 49.8 | • | $L_1$ $T_1$ | $1990_1$, $2011_1$ |
| $CO_2$ Emissions from Stationary Combustion - Oil - U.S. Territories | $CO_2$ | 44.7 | • | $L_1$ $T_1$ | $1990_1$, $2011_1$ |
| $CO_2$ Emissions from Mobile Combustion: Marine | $CO_2$ | 36.5 | • | $L_1$ $T_1$ | $1990_1$, $2011_1$ |
| $CO_2$ Emissions from Natural Gas Systems | $CO_2$ | 32.3 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Electricity Generation | $CO_2$ | 25.1 | • | $L_1$ $T_1$ $T_2$ | $1990_1$ |
| $CO_2$ Emissions from Incineration of Waste | $CO_2$ | 12.0 | | | |
| $CO_2$ Emissions from Stationary Combustion - Coal - Commercial | $CO_2$ | 4.9 | • | $T_1$ | |
| $CO_2$ Emissions from Stationary Combustion - Coal - U.S. Territories | $CO_2$ | 3.5 | | | |
| $CO_2$ Emissions from Stationary Combustion - Gas - U.S. Territories | $CO_2$ | 1.5 | | | |
| $CO_2$ Emissions from Stationary Combustion - Coal - Residential | $CO_2$ | 0.6 | | | |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.4 | | | |
| $CO_2$ Emissions from Petroleum Systems | $CO_2$ | 0.3 | | | |
| Fugitive Emissions from Natural Gas Systems | $CH_4$ | 215.4 | • | $L_1$ $L_2$ | 1990, 2011 |
| Fugitive Emissions from Coal Mining | $CH_4$ | 72.6 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| Fugitive Emissions from Petroleum Systems | $CH_4$ | 31.5 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, $2011_2$ |
| Fugitive Emissions from Abandoned Underground Coal Mines | $CH_4$ | 5.0 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $CH_4$ | 3.6 | • | $T_2$ | |
| $CH_4$ Emissions from Mobile Combustion: Road | $CH_4$ | 1.4 | | | |

| | | | | | |
|---|---|---|---|---|---|
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $CH_4$ | 1.3 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $CH_4$ | 0.9 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $CH_4$ | 0.4 | | | |
| $CH_4$ Emissions from Mobile Combustion: Other | $CH_4$ | 0.4 | | | |
| $CH_4$ Emissions from Mobile Combustion: Aviation | $CH_4$ | 0.1 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $CH_4$ | 0.1 | | | |
| $CH_4$ Emissions from Mobile Combustion: Marine | $CH_4$ | + | | | |
| $CH_4$ Emissions from Incineration of Waste | $CH_4$ | + | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $N_2O$ | 17.9 | • | $T_1$ $L_2$ $T_2$ | $1990_2$, $2011_2$ |
| $N_2O$ Emissions from Mobile Combustion: Road | $N_2O$ | 16.7 | • | $L_1$ $T_1$ $T_2$ | $1990_1$ |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $N_2O$ | 2.7 | | | |
| $N_2O$ Emissions from Mobile Combustion: Other | $N_2O$ | 1.9 | | | |
| $N_2O$ Emissions from Mobile Combustion: Aviation | $N_2O$ | 1.4 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $N_2O$ | 0.9 | | | |
| $N_2O$ Emissions from Mobile Combustion: Marine | $N_2O$ | 0.5 | | | |
| $N_2O$ Emissions from Incineration of Waste | $N_2O$ | 0.4 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $N_2O$ | 0.3 | | | |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $N_2O$ | 0.1 | | | |
| International Bunker Fuels[c] | Several | 1.9 | • | | |
| **Industrial Processes** | | | | | |
| $CO_2$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CO_2$ | 64.3 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 31.6 | • | $L_1$ $T_1$ | $1990_1$, $2011_1$ |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 13.8 | | | |
| $CO_2$ Emissions from Limestone and Dolomite Use | $CO_2$ | 9.5 | | | |
| $CO_2$ Emissions from Ammonia Production | $CO_2$ | 8.8 | • | $T_1$ | |
| $CO_2$ Emissions from Urea Consumption for Non-Ag Purposes | $CO_2$ | 4.3 | | | |
| $CO_2$ Emissions from Petrochemical Production | $CO_2$ | 3.5 | | | |
| $CO_2$ Emissions from Aluminum Production | $CO_2$ | 3.3 | • | $T_2$ | |
| $CO_2$ Emissions from Soda Ash Production and Consumption | $CO_2$ | 2.7 | | | |
| $CO_2$ Emissions from Carbon Dioxide Consumption | $CO_2$ | 2.2 | | | |
| $CO_2$ Emissions from Titanium Dioxide Production | $CO_2$ | 1.9 | | | |
| $CO_2$ Emissions from Ferroalloy Production | $CO_2$ | 1.7 | | | |
| $CO_2$ Emissions from Glass Production | $CO_2$ | 1.5 | | | |
| $CO_2$ Emissions from Zinc Production | $CO_2$ | 1.3 | | | |
| $CO_2$ Emissions from Phosphoric Acid Production | $CO_2$ | 1.1 | | | |
| $CO_2$ Emissions from Lead Production | $CO_2$ | 0.5 | | | |

| | | | | | |
|---|---|---|---|---|---|
| $CO_2$ Emissions from Silicon Carbide Production and Consumption | $CO_2$ | 0.2 | | | |
| $CH_4$ Emissions from Petrochemical Production | $CH_4$ | 3.1 | | | |
| $CH_4$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CH_4$ | 0.6 | | | |
| $CH_4$ Emissions from Ferroalloy Production | $CH_4$ | + | | | |
| $CH_4$ Emissions from Silicon Carbide Production and Consumption | $CH_4$ | + | | | |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 16.7 | | | |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 10.6 | • | $T_1$ | |
| $N_2O$ Emissions from Product Uses | $N_2O$ | 4.4 | | | |
| Emissions from Substitutes for Ozone Depleting Substances | HiGWP | 121.7 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 2011 |
| $SF_6$ Emissions from Electrical Transmission and Distribution | HiGWP | 11.7 | • | $T_1$ $T_2$ | |
| HFC-23 Emissions from HCFC-22 Production | HiGWP | 6.9 | • | $L_1$ $T_1$ $T_2$ | $1990_1$ |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacture | HiGWP | 5.4 | | | |
| PFC Emissions from Aluminum Production | HiGWP | 2.9 | • | $T_1$ $L_2$ $T_2$ | $1990_2$ |
| $SF_6$ Emissions from Magnesium Production and Processing | HiGWP | 1.3 | • | $T_1$ | |
| **Agriculture** | | | | | |
| $CH_4$ Emissions from Enteric Fermentation | $CH_4$ | 139.3 | • | $L_1$ $T_1$ $L_2$ | 1990, 2011 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 52.3 | • | $L_1$ $T_1$ $L_2$ $T_2$ | $1990_1$, 2011 |
| $CH_4$ Emissions from Rice Cultivation | $CH_4$ | 6.6 | • | $L_2$ $T_2$ | $1990_2$, $2011_2$ |
| $CH_4$ Emissions from Field Burning of Agricultural Residues | $CH_4$ | 0.2 | | | |
| Direct $N_2O$ Emissions from Agricultural Soil Management | $N_2O$ | 285.6 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| Indirect $N_2O$ Emissions from Applied Nitrogen | $N_2O$ | 57.6 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 18.5 | | | |
| $N_2O$ Emissions from Field Burning of Agricultural Residues | $N_2O$ | 0.1 | | | |
| **Waste** | | | | | |
| $CH_4$ Emissions from Landfills | $CH_4$ | 103.0 | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CH_4$ Emissions from Wastewater Treatment | $CH_4$ | 16.2 | | | |
| $CH_4$ Emissions from Composting | $CH_4$ | 1.5 | | | |
| $N_2O$ Emissions from Wastewater Treatment | $N_2O$ | 5.2 | | | |
| $N_2O$ Emissions from Composting | $N_2O$ | 1.7 | | | |
| **Land Use, Land Use Change, and Forestry** | | | | | |
| $CO_2$ Emissions from Changes in Forest Carbon Stocks | $CO_2$ | (921.8) | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Urban Trees | $CO_2$ | (98.0) | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990, 2011 |
| $CO_2$ Emissions from Land Converted to Grassland | $CO_2$ | (14.6) | | | |
| $CO_2$ Emissions from Cropland Remaining Cropland | $CO_2$ | 2.4 | • | $T_1$ $L_2$ $T_2$ | $1990_2$ |
| $CO_2$ Emissions from Landfilled Yard Trimmings and Food Scraps | $CO_2$ | (13.0) | • | $T_1$ $L_2$ $T_2$ | $1990_2$, $2011_2$ |
| $CO_2$ Emissions from Grassland Remaining Grassland | $CO_2$ | (9.0) | • | $L_1$ $T_1$ $L_2$ $T_2$ | 1990 |
| $CO_2$ Emissions from Land Converted to Cropland | $CO_2$ | 12.5 | • | $T_1$ $L_2$ $T_2$ | $1990_2$ |

| | | | | |
|---|---|---|---|---|
| $CO_2$ Emissions from Liming of Agricultural Soils | $CO_2$ | 4.5 | | |
| $CO_2$ Emissions from Urea Fertilization | $CO_2$ | 3.7 | | |
| $CO_2$ Emissions from Wetlands Remaining Wetlands | $CO_2$ | 1.0 | | |
| $CH_4$ Emissions from Forest Fires | $CH_4$ | 4.8 | • | $T_2$ |
| $N_2O$ Emissions from Forest Fires | $N_2O$ | 4.0 | • | $T_2$ |
| $N_2O$ Emissions from Settlement Soils | $N_2O$ | 1.5 | | |
| $N_2O$ Emissions from Forest Soils | $N_2O$ | 0.4 | | |
| $N_2O$ Emissions from Wetlands Remaining Wetlands | $N_2O$ | + | | |

[a] For the ID criteria, L refers to a key category identified through a level assessment; T refers to a key category identified through a trend assessment and the subscripted number refers to either a Tier 1 or Tier 2 assessment (e.g., $L_2$ designates a source is a key category for a Tier 2 level assessment).
[b] If the source is a key category for both $L_1$ and $L_2$ (as designated in the ID criteria column), it is a key category for both assessments in the years provided unless noted by a subscript, in which case it is a key category only for that assessment in only that year (.e.g., $1990_2$ designates a source is a key category for the Tier 2 assessment only in 1990).
[c] Emissions from these sources not included in totals.
+ Does not exceed 0.05 Tg $CO_2$ Eq.
Note: Parentheses indicate negative values (or sequestration).

## Evaluation of Key Categories

### Level Assessment

When using a Tier 1 approach for the level assessment, a predetermined cumulative emissions threshold is used to identify key categories. When source and sink categories are sorted in order of decreasing absolute emissions, those that fall at the top of the list and cumulatively account for 95 percent of emissions are considered key categories. The 95 percent threshold in the IPCC *Good Practice Guidance* (IPCC 2000) was designed to establish a general level where the key category analysis covers approximately 75 to 92 percent of inventory uncertainty.

Including the Tier 2 approach provides additional insight into why certain source categories are considered key, and how to prioritize inventory improvements. In the Tier 2 approach, the level assessment for each category from the Tier 1 approach is multiplied by its percent relative uncertainty. If the uncertainty reported is asymmetrical, the absolute value of the larger uncertainty is used. Uncertainty is not estimated for the following sources: $CO_2$ emissions from stationary combustion – geothermal energy; $CO_2$ emissions from mobile combustion by mode of transportation; $CH_4$ and $N_2O$ emissions from mobile combustion by mode of off-road transportation; and $CH_4$ from the incineration of waste. While $CO_2$ emissions from geothermal energy are included in the overall emissions estimate, they are not an official IPCC source category. As a result, there are no guidelines to associate uncertainty with the emissions estimate; therefore, an uncertainty analysis was not conducted. The uncertainty associated with $CO_2$ from mobile combustion is applied to each mode's emissions estimate, and the uncertainty associated with off-road vehicle $CH_4$ and $N_2O$ emissions are applied to both $CH_4$ and $N_2O$ emissions from aviation, marine, and other sources. No uncertainty was associated with $CH_4$ emissions from waste incineration because emissions are less than 0.05 Gg $CH_4$ and an uncertainty analysis was not conducted. When source and sink categories are sorted in decreasing order of this calculation, those that fall at the top of the list and cumulatively account for 90 percent of emissions are considered key categories. The key categories identified by the Tier 2 level assessment may differ from those identified by the Tier 1 assessment. The final set of key categories includes all source and sink categories identified as key by either the Tier 1 or the Tier 2 assessment, keeping in mind that the two assessments are not mutually exclusive.

It is important to note that a key category analysis can be sensitive to the definitions of the source and sink categories. If a large source category is split into many subcategories, then the subcategories may have contributions to the total inventory that are too small for those source categories to be considered key. Similarly, a collection of small, non-key source categories adding up to less than 5 percent of total emissions could become key source categories if those source categories were aggregated into a single source category. The United States has attempted to define source and sink categories by the conventions which would allow comparison with other international key categories, while still maintaining the category definitions that constitute how the emissions estimates were calculated for this report. As such, some of the category names used in the key category analysis may differ from the names used in the main body of the report. Additionally, the United States accounts for some source categories, including fossil fuel feedstocks, international bunkers, and emissions from U.S. territories, that are derived from unique data sources using country-specific methodologies.

Table A- 4 through Table A- 7 contain the 1990 and 2011 level assessments for both with and without LULUCF sources and sinks, and contain further detail on where each source falls within the analysis. Tier 1 key categories are shaded dark gray. Additional key categories identified by the Tier 2 assessment are shaded light gray.

### Trend Assessment

The Tier 1 approach for trend assessment is defined as the product of the source or sink category level assessment and the absolute difference between the source or sink category trend and the total trend. In turn, the source or sink category trend is defined as the change in emissions from the base year to the current year, as a percentage of current year emissions from that source or sink category. The total trend is the percentage change in total inventory emissions from the base year to the current year.

Thus, the source or sink category trend assessment will be large if the source or sink category represents a large percentage of emissions and/or has a trend that is quite different from the overall inventory trend. To determine key categories, the trend assessments are sorted in decreasing order, so that the source or sink categories with the highest trend assessments appear first. The trend assessments are summed until the threshold of 95 percent is reached; all categories that fall within that cumulative 95 percent are considered key categories.

For the Tier 2 approach, the trend assessment for each category from the Tier 1 approach is multiplied by its percent relative uncertainty. If the uncertainty reported is asymmetrical, the larger uncertainty is used. When source and sink categories are sorted in decreasing order of this calculation, those that fall at the top of the list and cumulatively account for 90 percent of emissions are considered key categories. The key categories identified by the Tier 2 trend assessment may differ from those identified by the Tier 1 assessment. The final set of key categories includes all source and sink categories identified as key by either the Tier 1 or the Tier 2 assessment, keeping in mind that the two assessments are not mutually exclusive.

Table A- 8 and Table A- 9 contain the 1990 through 2011 trend assessment for both with and without LULUCF sources and sinks, and contain further detail on where each source falls within the analysis. Tier 1 key categories are shaded dark gray. Additional key categories identified by the Tier 2 assessment are shaded light gray.

Table A- 4: 1990 Key Source Category Tier 1 and Tier 2 Analysis—Level Assessment, without LULUCF

| IPCC Source Categories | Direct GHG | 1990 Estimate (Tg $CO_2$ Eq.) | Tier 1 Level Assessment | Cumulative Total | Uncertainty | Tier 2 Level Assessment |
|---|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal - Electricity Generation | $CO_2$ | 1,547.6 | 0.25 | 0.25 | 10% | 0.024 |
| $CO_2$ Emissions from Mobile Combustion: Road | $CO_2$ | 1,188.9 | 0.19 | 0.44 | 8% | 0.016 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Industrial | $CO_2$ | 408.9 | 0.07 | 0.50 | 13% | 0.008 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Industrial | $CO_2$ | 284.4 | 0.05 | 0.55 | 18% | 0.008 |
| Direct $N_2O$ Emissions from Agricultural Soil Management | $N_2O$ | 272.1 | 0.04 | 0.59 | 58% | 0.025 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Residential | $CO_2$ | 238.0 | 0.04 | 0.63 | 7% | 0.003 |
| Fugitive Emissions from Natural Gas Systems | $CH_4$ | 189.6 | 0.03 | 0.66 | 30% | 0.009 |
| $CO_2$ Emissions from Mobile Combustion: Aviation | $CO_2$ | 179.3 | 0.03 | 0.68 | 8% | 0.002 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Electricity Generation | $CO_2$ | 175.3 | 0.03 | 0.71 | 5% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Industrial | $CO_2$ | 155.3 | 0.02 | 0.74 | 17% | 0.004 |
| $CH_4$ Emissions from Landfills | $CH_4$ | 147.8 | 0.02 | 0.76 | 52% | 0.012 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Commercial | $CO_2$ | 142.1 | 0.02 | 0.78 | 7% | 0.002 |
| $CH_4$ Emissions from Enteric Fermentation | $CH_4$ | 133.8 | 0.02 | 0.80 | 18% | 0.004 |
| $CO_2$ Emissions from Non-Energy Use of Fuels | $CO_2$ | 117.4 | 0.02 | 0.82 | 21% | 0.004 |
| $CO_2$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CO_2$ | 99.8 | 0.02 | 0.84 | 17% | 0.003 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Electricity Generation | $CO_2$ | 97.5 | 0.02 | 0.85 | 7% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Residential | $CO_2$ | 97.4 | 0.02 | 0.87 | 6% | 0.001 |
| Fugitive Emissions from Coal Mining | $CH_4$ | 84.1 | 0.01 | 0.88 | 16% | 0.002 |
| $CO_2$ Emissions from Mobile Combustion: Other | $CO_2$ | 73.3 | 0.01 | 0.90 | 8% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Commercial | $CO_2$ | 64.9 | 0.01 | 0.91 | 5% | <0.001 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Indirect $N_2O$ Emissions from Applied Nitrogen | $N_2O$ | 54.8 | 0.01 | 0.91 | 153% | 0.013 |
| $CO_2$ Emissions from Mobile Combustion: Marine | $CO_2$ | 44.5 | 0.01 | 0.92 | 8% | 0.001 |
| $N_2O$ Emissions from Mobile Combustion: Road | $N_2O$ | 40.3 | 0.01 | 0.93 | 17% | 0.001 |
| $CO_2$ Emissions from Natural Gas Systems | $CO_2$ | 37.6 | 0.01 | 0.93 | 30% | 0.002 |
| HFC-23 Emissions from HCFC-22 Production | HFCs | 36.4 | 0.01 | 0.94 | 10% | 0.001 |
| Fugitive Emissions from Petroleum Systems | $CH_4$ | 35.2 | 0.01 | 0.95 | 149% | 0.008 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.3 | 0.01 | 0.95 | 14% | 0.001 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 31.7 | 0.01 | 0.96 | 20% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Oil - U.S. Territories | $CO_2$ | 27.2 | <0.01 | 0.96 | 11% | <0.001 |
| $SF_6$ Emissions from Electrical Transmission and Distribution | $SF_6$ | 26.7 | <0.01 | 0.96 | 25% | 0.001 |
| PFC Emissions from Aluminum Production | PFCs | 18.4 | <0.01 | 0.97 | 51% | 0.002 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.6 | <0.01 | 0.97 | 43% | 0.001 |
| $CH_4$ Emissions from Wastewater Treatment | $CH_4$ | 15.9 | <0.01 | 0.97 | 31% | 0.001 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 15.8 | <0.01 | 0.97 | 9% | <0.001 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 14.8 | <0.01 | 0.98 | 24% | 0.001 |
| $CO_2$ Emissions from Ammonia Production | $CO_2$ | 13.0 | <0.01 | 0.98 | 25% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Commercial | $CO_2$ | 12.0 | <0.01 | 0.98 | 15% | <0.001 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.5 | <0.01 | 0.98 | 9% | <0.001 |
| $CO_2$ Emissions from Incineration of Waste | $CO_2$ | 8.0 | <0.01 | 0.98 | 24% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $N_2O$ | 7.4 | <0.01 | 0.99 | 187% | 0.002 |
| $CH_4$ Emissions from Rice Cultivation | $CH_4$ | 7.1 | <0.01 | 0.99 | 153% | 0.002 |
| $CO_2$ Emissions from Aluminum Production | $CO_2$ | 6.8 | <0.01 | 0.99 | 49% | 0.001 |
| Fugitive Emissions from Abandoned Underground Coal Mines | $CH_4$ | 6.0 | <0.01 | 0.99 | 22% | <0.001 |
| $SF_6$ Emissions from Magnesium Production and Processing | $SF_6$ | 5.4 | <0.01 | 0.99 | 4% | <0.001 |
| $CO_2$ Emissions from Limestone and Dolomite Use | $CO_2$ | 4.9 | <0.01 | 0.99 | 18% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $CH_4$ | 4.6 | <0.01 | 0.99 | 127% | 0.001 |
| $N_2O$ Emissions from Product Uses | $N_2O$ | 4.4 | <0.01 | 0.99 | 8% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Road | $CH_4$ | 4.2 | <0.01 | 0.99 | 15% | <0.001 |
| $CO_2$ Emissions from Urea Consumption for Non-Ag Purposes | $CO_2$ | 3.8 | <0.01 | 0.99 | 48% | <0.001 |
| $N_2O$ Emissions from Wastewater Treatment | $N_2O$ | 3.5 | <0.01 | 0.99 | 99% | 0.001 |
| $CO_2$ Emissions from Petrochemical Production | $CO_2$ | 3.4 | <0.01 | 0.99 | 31% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $N_2O$ | 3.3 | <0.01 | 0.99 | 187% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Residential | $CO_2$ | 3.0 | <0.01 | 0.99 | 15% | <0.001 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacture | Several | 2.9 | <0.01 | 0.99 | 11% | <0.001 |
| $CO_2$ Emissions from Soda Ash Production and Consumption | $CO_2$ | 2.8 | <0.01 | 1.00 | 7% | <0.001 |
| $CH_4$ Emissions from Petrochemical Production | $CH_4$ | 2.3 | <0.01 | 1.00 | 30% | <0.001 |
| $CO_2$ Emissions from Ferroalloy Production | $CO_2$ | 2.2 | <0.01 | 1.00 | 12% | <0.001 |
| $N_2O$ Emissions from Mobile Combustion: Aviation | $N_2O$ | 1.7 | <0.01 | 1.00 | 68% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $CH_4$ | 1.6 | <0.01 | 1.00 | 127% | <0.001 |
| $CO_2$ Emissions from Glass Production | $CO_2$ | 1.5 | <0.01 | 1.00 | 10% | <0.001 |
| $CO_2$ Emissions from Phosphoric Acid Production | $CO_2$ | 1.5 | <0.01 | 1.00 | 18% | <0.001 |
| $CO_2$ Emissions from Carbon Dioxide Consumption | $CO_2$ | 1.4 | <0.01 | 1.00 | 30% | <0.001 |
| $N_2O$ Emissions from Mobile Combustion: Other | $N_2O$ | 1.3 | <0.01 | 1.00 | 47% | <0.001 |
| $CO_2$ Emissions from Titanium Dioxide Production | $CO_2$ | 1.2 | <0.01 | 1.00 | 13% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $N_2O$ | 1.1 | <0.01 | 1.00 | 187% | <0.001 |
| $CH_4$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CH_4$ | 1.0 | <0.01 | 1.00 | 22% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $CH_4$ | 0.9 | <0.01 | 1.00 | 127% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - U.S. Territories | $CO_2$ | 0.6 | <0.01 | 1.00 | 19% | <0.001 |

| | | | | | | |
|---|---|---|---|---|---|---|
| $CO_2$ Emissions from Zinc Production | $CO_2$ | 0.6 | <0.01 | 1.00 | 19% | <0.001 |
| $N_2O$ Emissions from Mobile Combustion: Marine | $N_2O$ | 0.6 | <0.01 | 1.00 | 57% | <0.001 |
| $CO_2$ Emissions from Lead Production | $CO_2$ | 0.5 | <0.01 | 1.00 | 15% | <0.001 |
| $N_2O$ Emissions from Incineration of Waste | $N_2O$ | 0.5 | <0.01 | 1.00 | 320% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.4 | <0.01 | 1.00 | NA | <0.001 |
| $CO_2$ Emissions from Petroleum Systems | $CO_2$ | 0.4 | <0.01 | 1.00 | 149% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $N_2O$ | 0.4 | <0.01 | 1.00 | 187% | <0.001 |
| $CO_2$ Emissions from Silicon Carbide Production and Consumption | $CO_2$ | 0.4 | <0.01 | 1.00 | 10% | <0.001 |
| $N_2O$ Emissions from Composting | $N_2O$ | 0.4 | <0.01 | 1.00 | 50% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $CH_4$ | 0.3 | <0.01 | 1.00 | 127% | <0.001 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.3 | <0.01 | 1.00 | 8% | <0.001 |
| $CH_4$ Emissions from Composting | $CH_4$ | 0.3 | <0.01 | 1.00 | 50% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Other | $CH_4$ | 0.3 | <0.01 | 1.00 | 47% | <0.001 |
| $CH_4$ Emissions from Field Burning of Agricultural Residues | $CH_4$ | 0.2 | <0.01 | 1.00 | 42% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Aviation | $CH_4$ | 0.2 | <0.01 | 1.00 | 61% | <0.001 |
| $N_2O$ Emissions from Field Burning of Agricultural Residues | $N_2O$ | 0.1 | <0.01 | 1.00 | 31% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $N_2O$ | 0.1 | <0.01 | 1.00 | 187% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $CH_4$ | + | <0.01 | 1.00 | 127% | <0.001 |
| $CH_4$ Emissions from Silicon Carbide Production and Consumption | $CH_4$ | + | <0.01 | 1.00 | 9% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Marine | $CH_4$ | + | <0.01 | 1.00 | 73% | <0.001 |
| $CH_4$ Emissions from Ferroalloy Production | $CH_4$ | + | <0.01 | 1.00 | 12% | <0.001 |
| $CH_4$ Emissions from Incineration of Waste | $CH_4$ | + | <0.01 | 1.00 | 24% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Gas - U.S. Territories | $CO_2$ | + | <0.01 | 1.00 | 17% | <0.001 |

Note: LULUCF sources and sinks are not included in this analysis.
[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.
NE Uncertainty not estimated.
+ Does not exceed 0.05 Tg $CO_2$ Eq.

Table A- 5: 1990 Key Source Category Tier 1 and Tier 2 Analysis—Level Assessment, with LULUCF

| IPCC Source Categories | Direct GHG | 1990 Estimate (Tg $CO_2$ Eq.) | Tier 1 Level Assessment | Cumulative Total | Uncertainty | Tier 2 Level Assessment |
|---|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal - Electricity Generation | $CO_2$ | 1,547.6 | 0.22 | 0.22 | 10% | 0.021 |
| $CO_2$ Emissions from Mobile Combustion: Road | $CO_2$ | 1,188.9 | 0.17 | 0.38 | 8% | 0.014 |
| $CO_2$ Emissions from Changes in Forest Carbon Stocks | $CO_2$ | 701.4 | 0.10 | 0.48 | 12% | 0.012 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Industrial | $CO_2$ | 408.9 | 0.06 | 0.53 | 13% | 0.007 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Industrial | $CO_2$ | 284.4 | 0.04 | 0.57 | 18% | 0.007 |
| Direct $N_2O$ Emissions from Agricultural Soil Management | $N_2O$ | 272.1 | 0.04 | 0.61 | 58% | 0.022 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Residential | $CO_2$ | 238.0 | 0.03 | 0.65 | 7% | 0.002 |
| Fugitive Emissions from Natural Gas Systems | $CH_4$ | 189.6 | 0.03 | 0.67 | 30% | 0.008 |
| $CO_2$ Emissions from Mobile Combustion: Aviation | $CO_2$ | 179.3 | 0.02 | 0.70 | 8% | 0.002 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Electricity Generation | $CO_2$ | 175.3 | 0.02 | 0.72 | 5% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - | $CO_2$ | 155.3 | 0.02 | 0.74 | 17% | 0.004 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Industrial | | | | | | |
| $CH_4$ Emissions from Landfills | $CH_4$ | 147.8 | 0.02 | 0.76 | 52% | 0.011 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Commercial | $CO_2$ | 142.1 | 0.02 | 0.78 | 7% | 0.001 |
| $CH_4$ Emissions from Enteric Fermentation | $CH_4$ | 133.8 | 0.02 | 0.80 | 18% | 0.003 |
| $CO_2$ Emissions from Non-Energy Use of Fuels | $CO_2$ | 117.4 | 0.02 | 0.82 | 21% | 0.003 |
| $CO_2$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CO_2$ | 99.8 | 0.01 | 0.83 | 17% | 0.002 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Electricity Generation | $CO_2$ | 97.5 | 0.01 | 0.85 | 7% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Residential | $CO_2$ | 97.4 | 0.01 | 0.86 | 6% | 0.001 |
| Fugitive Emissions from Coal Mining | $CH_4$ | 84.1 | 0.01 | 0.87 | 16% | 0.002 |
| $CO_2$ Emissions from Mobile Combustion: Other | $CO_2$ | 73.3 | 0.01 | 0.88 | 8% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Commercial | $CO_2$ | 64.9 | 0.01 | 0.89 | 5% | <0.001 |
| $CO_2$ Emissions from Urban Trees | $CO_2$ | 57.1 | 0.01 | 0.90 | 23% | 0.002 |
| Indirect $N_2O$ Emissions from Applied Nitrogen | $N_2O$ | 54.8 | 0.01 | 0.91 | 153% | 0.012 |
| $CO_2$ Emissions from Grassland Remaining Grassland | $CO_2$ | 52.5 | 0.01 | 0.91 | 32% | 0.002 |
| $CO_2$ Emissions from Mobile Combustion: Marine | $CO_2$ | 44.5 | 0.01 | 0.92 | 8% | 0.001 |
| $N_2O$ Emissions from Mobile Combustion: Road | $N_2O$ | 40.3 | 0.01 | 0.92 | 17% | 0.001 |
| $CO_2$ Emissions from Natural Gas Systems | $CO_2$ | 37.6 | 0.01 | 0.93 | 30% | 0.002 |
| HFC-23 Emissions from HCFC-22 Production | HFCs | 36.4 | 0.01 | 0.93 | 10% | 0.001 |
| Fugitive Emissions from Petroleum Systems | $CH_4$ | 35.2 | <0.01 | 0.94 | 149% | 0.007 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.3 | <0.01 | 0.94 | 14% | 0.001 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 31.7 | <0.01 | 0.95 | 20% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Oil - U.S. Territories | $CO_2$ | 27.2 | <0.01 | 0.95 | 11% | <0.001 |
| $SF_6$ Emissions from Electrical Transmission and Distribution | $SF_6$ | 26.7 | <0.01 | 0.96 | 25% | 0.001 |
| $CO_2$ Emissions from Land Converted to Cropland | $CO_2$ | 25.1 | <0.01 | 0.96 | 40% | 0.001 |
| $CO_2$ Emissions from Landfilled Yard Trimmings and Food Scraps | $CO_2$ | 24.2 | <0.01 | 0.96 | 57% | 0.002 |
| PFC Emissions from Aluminum Production | PFCs | 18.4 | <0.01 | 0.97 | 51% | 0.001 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.6 | <0.01 | 0.97 | 43% | 0.001 |
| $CO_2$ Emissions from Cropland Remaining Cropland | $CO_2$ | 17.0 | <0.01 | 0.97 | 194% | 0.005 |
| $CH_4$ Emissions from Wastewater Treatment | $CH_4$ | 15.9 | <0.01 | 0.97 | 31% | 0.001 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 15.8 | <0.01 | 0.97 | 9% | <0.001 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 14.8 | <0.01 | 0.98 | 24% | <0.001 |
| $CO_2$ Emissions from Ammonia Production | $CO_2$ | 13.0 | <0.01 | 0.98 | 25% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Commercial | $CO_2$ | 12.0 | <0.01 | 0.98 | 15% | <0.001 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.5 | <0.01 | 0.98 | 9% | <0.001 |
| $CO_2$ Emissions from Land Converted to Grassland | $CO_2$ | 11.4 | <0.01 | 0.98 | 15% | <0.001 |
| $CO_2$ Emissions from Incineration of Waste | $CO_2$ | 8.0 | <0.01 | 0.98 | 24% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $N_2O$ | 7.4 | <0.01 | 0.99 | 187% | 0.002 |
| $CH_4$ Emissions from Rice Cultivation | $CH_4$ | 7.1 | <0.01 | 0.99 | 153% | 0.002 |
| $CO_2$ Emissions from Aluminum Production | $CO_2$ | 6.8 | <0.01 | 0.99 | 49% | <0.001 |
| Fugitive Emissions from Abandoned Underground Coal Mines | $CH_4$ | 6.0 | <0.01 | 0.99 | 22% | <0.001 |
| $SF_6$ Emissions from Magnesium Production and Processing | $SF_6$ | 5.4 | <0.01 | 0.99 | 4% | <0.001 |
| $CO_2$ Emissions from Limestone and Dolomite Use | $CO_2$ | 4.9 | <0.01 | 0.99 | 18% | <0.001 |
| $CO_2$ Emissions from Liming of Agricultural Soils | $CO_2$ | 4.7 | <0.01 | 0.99 | 112% | 0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $CH_4$ | 4.6 | <0.01 | 0.99 | 127% | 0.001 |

| | | | | | | |
|---|---|---|---|---|---|---|
| $N_2O$ Emissions from Product Uses | $N_2O$ | 4.4 | <0.01 | 0.99 | 8% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Road | $CH_4$ | 4.2 | <0.01 | 0.99 | 15% | <0.001 |
| $CO_2$ Emissions from Urea Consumption for Non-Ag Purposes | $CO_2$ | 3.8 | <0.01 | 0.99 | 48% | <0.001 |
| $N_2O$ Emissions from Wastewater Treatment | $N_2O$ | 3.5 | <0.01 | 0.99 | 99% | <0.001 |
| $CO_2$ Emissions from Petrochemical Production | $CO_2$ | 3.4 | <0.01 | 0.99 | 31% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $N_2O$ | 3.3 | <0.01 | 0.99 | 187% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Residential | $CO_2$ | 3.0 | <0.01 | 0.99 | 15% | <0.001 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacture | Several | 2.9 | <0.01 | 0.99 | 11% | <0.001 |
| $CO_2$ Emissions from Soda Ash Production and Consumption | $CO_2$ | 2.8 | <0.01 | 1.00 | 7% | <0.001 |
| $CH_4$ Emissions from Forest Fires | $CH_4$ | 2.5 | <0.01 | 1.00 | 148% | 0.001 |
| $CO_2$ Emissions from Urea Fertilization | $CO_2$ | 2.4 | <0.01 | 1.00 | 43% | <0.001 |
| $CH_4$ Emissions from Petrochemical Production | $CH_4$ | 2.3 | <0.01 | 1.00 | 30% | <0.001 |
| $CO_2$ Emissions from Ferroalloy Production | $CO_2$ | 2.2 | <0.01 | 1.00 | 12% | <0.001 |
| $N_2O$ Emissions from Forest Fires | $N_2O$ | 2.1 | <0.01 | 1.00 | 147% | <0.001 |
| $N_2O$ Emissions from Mobile Combustion: Aviation | $N_2O$ | 1.7 | <0.01 | 1.00 | 68% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $CH_4$ | 1.6 | <0.01 | 1.00 | 127% | <0.001 |
| $CO_2$ Emissions from Glass Production | $CO_2$ | 1.5 | <0.01 | 1.00 | 10% | <0.001 |
| $CO_2$ Emissions from Phosphoric Acid Production | $CO_2$ | 1.5 | <0.01 | 1.00 | 18% | <0.001 |
| $CO_2$ Emissions from Carbon Dioxide Consumption | $CO_2$ | 1.4 | <0.01 | 1.00 | 30% | <0.001 |
| $N_2O$ Emissions from Mobile Combustion: Other | $N_2O$ | 1.3 | <0.01 | 1.00 | 47% | <0.001 |
| $CO_2$ Emissions from Titanium Dioxide Production | $CO_2$ | 1.2 | <0.01 | 1.00 | 13% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $N_2O$ | 1.1 | <0.01 | 1.00 | 187% | <0.001 |
| $CO_2$ Emissions from Wetlands Remaining Wetlands | $CO_2$ | 1.0 | <0.01 | 1.00 | 38% | <0.001 |
| $N_2O$ Emissions from Settlement Soils | $N_2O$ | 1.0 | <0.01 | 1.00 | 163% | <0.001 |
| $CH_4$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CH_4$ | 1.0 | <0.01 | 1.00 | 22% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $CH_4$ | 0.9 | <0.01 | 1.00 | 127% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - U.S. Territories | $CO_2$ | 0.6 | <0.01 | 1.00 | 19% | <0.001 |
| $CO_2$ Emissions from Zinc Production | $CO_2$ | 0.6 | <0.01 | 1.00 | 19% | <0.001 |
| $N_2O$ Emissions from Mobile Combustion: Marine | $N_2O$ | 0.6 | <0.01 | 1.00 | 57% | <0.001 |
| $CO_2$ Emissions from Lead Production | $CO_2$ | 0.5 | <0.01 | 1.00 | 15% | <0.001 |
| $N_2O$ Emissions from Incineration of Waste | $N_2O$ | 0.5 | <0.01 | 1.00 | 320% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.4 | <0.01 | 1.00 | NA | <0.001 |
| $CO_2$ Emissions from Petroleum Systems | $CO_2$ | 0.4 | <0.01 | 1.00 | 149% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $N_2O$ | 0.4 | <0.01 | 1.00 | 187% | <0.001 |
| $CO_2$ Emissions from Silicon Carbide Production and Consumption | $CO_2$ | 0.4 | <0.01 | 1.00 | 10% | <0.001 |
| $N_2O$ Emissions from Composting | $N_2O$ | 0.4 | <0.01 | 1.00 | 50% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $CH_4$ | 0.3 | <0.01 | 1.00 | 127% | <0.001 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.3 | <0.01 | 1.00 | 8% | <0.001 |
| $CH_4$ Emissions from Composting | $CH_4$ | 0.3 | <0.01 | 1.00 | 50% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Other | $CH_4$ | 0.3 | <0.01 | 1.00 | 47% | <0.001 |
| $CH_4$ Emissions from Field Burning of Agricultural Residues | $CH_4$ | 0.2 | <0.01 | 1.00 | 42% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Aviation | $CH_4$ | 0.2 | <0.01 | 1.00 | 61% | <0.001 |

| | | | | | | |
|---|---|---|---|---|---|---|
| $N_2O$ Emissions from Field Burning of Agricultural Residues | $N_2O$ | 0.1 | <0.01 | 1.00 | 31% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $N_2O$ | 0.1 | <0.01 | 1.00 | 187% | <0.001 |
| $N_2O$ Emissions from Forest Soils | $N_2O$ | 0.1 | <0.01 | 1.00 | 211% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $CH_4$ | + | <0.01 | 1.00 | 127% | <0.001 |
| $CH_4$ Emissions from Silicon Carbide Production and Consumption | $CH_4$ | + | <0.01 | 1.00 | 9% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Marine | $CH_4$ | + | <0.01 | 1.00 | 73% | <0.001 |
| $CH_4$ Emissions from Ferroalloy Production | $CH_4$ | + | <0.01 | 1.00 | 12% | <0.001 |
| $N_2O$ Emissions from Wetlands Remaining Wetlands | $N_2O$ | + | <0.01 | 1.00 | 74% | <0.001 |
| $CH_4$ Emissions from Incineration of Waste | $CH_4$ | + | <0.01 | 1.00 | 24% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Gas - U.S. Territories | $CO_2$ | + | <0.01 | 1.00 | 17% | <0.001 |

[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.
NE Uncertainty not estimated.
+ Does not exceed 0.05 Tg $CO_2$ Eq.

Table A- 6: 2011 Key Source Category Tier 1 and Tier 2 Analysis—Level Assessment, without LULUCF

| IPCC Source Categories | Direct GHG | Current Year Estimate (Tg $CO_2$ Eq.) | Tier 1 Level Assessment | Cumulative Total | Uncertainty | Tier 2 Level Assessment |
|---|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal - Electricity Generation | $CO_2$ | 1,718.0 | 0.25 | 0.25 | 10% | 0.024 |
| $CO_2$ Emissions from Mobile Combustion: Road | $CO_2$ | 1,473.2 | 0.22 | 0.47 | 8% | 0.018 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Electricity Generation | $CO_2$ | 410.2 | 0.06 | 0.53 | 5% | 0.003 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Industrial | $CO_2$ | 409.7 | 0.06 | 0.59 | 13% | 0.008 |
| Direct $N_2O$ Emissions from Agricultural Soil Management | $N_2O$ | 285.6 | 0.04 | 0.63 | 58% | 0.024 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Industrial | $CO_2$ | 279.9 | 0.04 | 0.67 | 18% | 0.007 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Residential | $CO_2$ | 255.7 | 0.04 | 0.71 | 7% | 0.003 |
| Fugitive Emissions from Natural Gas Systems | $CH_4$ | 215.4 | 0.03 | 0.74 | 30% | 0.009 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Commercial | $CO_2$ | 171.1 | 0.02 | 0.76 | 7% | 0.002 |
| $CO_2$ Emissions from Mobile Combustion: Aviation | $CO_2$ | 142.8 | 0.02 | 0.78 | 8% | 0.002 |
| $CH_4$ Emissions from Enteric Fermentation | $CH_4$ | 139.3 | 0.02 | 0.80 | 18% | 0.004 |
| $CO_2$ Emissions from Non-Energy Use of Fuels | $CO_2$ | 130.5 | 0.02 | 0.82 | 21% | 0.004 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 121.7 | 0.02 | 0.84 | 8% | 0.001 |
| $CH_4$ Emissions from Landfills | $CH_4$ | 103.0 | 0.02 | 0.85 | 52% | 0.008 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Industrial | $CO_2$ | 90.0 | 0.01 | 0.87 | 17% | 0.002 |
| $CO_2$ Emissions from Mobile Combustion: Other | $CO_2$ | 79.2 | 0.01 | 0.88 | 8% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Residential | $CO_2$ | 78.2 | 0.01 | 0.89 | 6% | 0.001 |
| Fugitive Emissions from Coal Mining | $CH_4$ | 72.6 | 0.01 | 0.90 | 16% | 0.002 |
| $CO_2$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CO_2$ | 64.3 | 0.01 | 0.91 | 17% | 0.002 |
| Indirect $N_2O$ Emissions from Applied Nitrogen | $N_2O$ | 57.6 | 0.01 | 0.92 | 153% | 0.013 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 52.3 | 0.01 | 0.93 | 20% | 0.002 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Commercial | $CO_2$ | 49.8 | 0.01 | 0.93 | 5% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Oil - U.S. | $CO_2$ | 44.7 | 0.01 | 0.94 | 11% | 0.001 |

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|---|---|---|---|---|---|---|
| Territories | | | | | | |
| $CO_2$ Emissions from Mobile Combustion: Marine | $CO_2$ | 36.5 | 0.01 | 0.95 | 8% | <0.001 |
| $CO_2$ Emissions from Natural Gas Systems | $CO_2$ | 32.3 | <0.01 | 0.95 | 30% | 0.001 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 31.6 | <0.01 | 0.96 | 14% | 0.001 |
| Fugitive Emissions from Petroleum Systems | $CH_4$ | 31.5 | <0.01 | 0.96 | 149% | 0.007 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Electricity Generation | $CO_2$ | 25.1 | <0.01 | 0.96 | 7% | <0.001 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 18.5 | <0.01 | 0.97 | 24% | 0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $N_2O$ | 17.9 | <0.01 | 0.97 | 187% | 0.005 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 16.7 | <0.01 | 0.97 | 43% | 0.001 |
| $N_2O$ Emissions from Mobile Combustion: Road | $N_2O$ | 16.7 | <0.01 | 0.97 | 17% | <0.001 |
| $CH_4$ Emissions from Wastewater Treatment | $CH_4$ | 16.2 | <0.01 | 0.98 | 31% | 0.001 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 13.8 | <0.01 | 0.98 | 9% | <0.001 |
| $CO_2$ Emissions from Incineration of Waste | $CO_2$ | 12.0 | <0.01 | 0.98 | 24% | <0.001 |
| $SF_6$ Emissions from Electrical Transmission and Distribution | $SF_6$ | 11.7 | <0.01 | 0.98 | 25% | <0.001 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 10.6 | <0.01 | 0.98 | 9% | <0.001 |
| $CO_2$ Emissions from Limestone and Dolomite Use | $CO_2$ | 9.5 | <0.01 | 0.98 | 18% | <0.001 |
| $CO_2$ Emissions from Ammonia Production | $CO_2$ | 8.8 | <0.01 | 0.99 | 25% | <0.001 |
| HFC-23 Emissions from HCFC-22 Production | HFCs | 6.9 | <0.01 | 0.99 | 10% | <0.001 |
| $CH_4$ Emissions from Rice Cultivation | $CH_4$ | 6.6 | <0.01 | 0.99 | 153% | 0.001 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacture | Several | 5.4 | <0.01 | 0.99 | 11% | <0.001 |
| $N_2O$ Emissions from Wastewater Treatment | $N_2O$ | 5.2 | <0.01 | 0.99 | 99% | 0.001 |
| Fugitive Emissions from Abandoned Underground Coal Mines | $CH_4$ | 5.0 | <0.01 | 0.99 | 22% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Commercial | $CO_2$ | 4.9 | <0.01 | 0.99 | 15% | <0.001 |
| $N_2O$ Emissions from Product Uses | $N_2O$ | 4.4 | <0.01 | 0.99 | 8% | <0.001 |
| $CO_2$ Emissions from Urea Consumption for Non-Ag Purposes | $CO_2$ | 4.3 | <0.01 | 0.99 | 48% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $CH_4$ | 3.6 | <0.01 | 0.99 | 127% | 0.001 |
| $CO_2$ Emissions from Petrochemical Production | $CO_2$ | 3.5 | <0.01 | 0.99 | 31% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - U.S. Territories | $CO_2$ | 3.5 | <0.01 | 0.99 | 19% | <0.001 |
| $CO_2$ Emissions from Aluminum Production | $CO_2$ | 3.3 | <0.01 | 0.99 | 49% | <0.001 |
| $CH_4$ Emissions from Petrochemical Production | $CH_4$ | 3.1 | <0.01 | 0.99 | 30% | <0.001 |
| PFC Emissions from Aluminum Production | PFCs | 2.9 | <0.01 | 0.99 | 51% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $N_2O$ | 2.7 | <0.01 | 1.00 | 187% | 0.001 |
| $CO_2$ Emissions from Soda Ash Production and Consumption | $CO_2$ | 2.7 | <0.01 | 1.00 | 7% | <0.001 |
| $CO_2$ Emissions from Carbon Dioxide Consumption | $CO_2$ | 2.2 | <0.01 | 1.00 | 30% | <0.001 |
| $N_2O$ Emissions from Mobile Combustion: Other | $N_2O$ | 1.9 | <0.01 | 1.00 | 47% | <0.001 |
| $CO_2$ Emissions from Titanium Dioxide Production | $CO_2$ | 1.9 | <0.01 | 1.00 | 13% | <0.001 |
| $N_2O$ Emissions from Composting | $N_2O$ | 1.7 | <0.01 | 1.00 | 50% | <0.001 |
| $CO_2$ Emissions from Ferroalloy Production | $CO_2$ | 1.7 | <0.01 | 1.00 | 12% | <0.001 |
| $CH_4$ Emissions from Composting | $CH_4$ | 1.5 | <0.01 | 1.00 | 50% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Gas - U.S. Territories | $CO_2$ | 1.5 | <0.01 | 1.00 | 17% | <0.001 |
| $CO_2$ Emissions from Glass Production | $CO_2$ | 1.5 | <0.01 | 1.00 | 10% | <0.001 |
| $N_2O$ Emissions from Mobile Combustion: Aviation | $N_2O$ | 1.4 | <0.01 | 1.00 | 68% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Road | $CH_4$ | 1.4 | <0.01 | 1.00 | 15% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $CH_4$ | 1.3 | <0.01 | 1.00 | 127% | <0.001 |
| $CO_2$ Emissions from Zinc Production | $CO_2$ | 1.3 | <0.01 | 1.00 | 19% | <0.001 |

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|---|---|---|---|---|---|---|
| $SF_6$ Emissions from Magnesium Production and Processing | $SF_6$ | 1.3 | <0.01 | 1.00 | 4% | <0.001 |
| $CO_2$ Emissions from Phosphoric Acid Production | $CO_2$ | 1.1 | <0.01 | 1.00 | 18% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $CH_4$ | 0.9 | <0.01 | 1.00 | 127% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $N_2O$ | 0.9 | <0.01 | 1.00 | 187% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Residential | $CO_2$ | 0.6 | <0.01 | 1.00 | 15% | <0.001 |
| $CH_4$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CH_4$ | 0.6 | <0.01 | 1.00 | 22% | <0.001 |
| $CO_2$ Emissions from Lead Production | $CO_2$ | 0.5 | <0.01 | 1.00 | 15% | <0.001 |
| $N_2O$ Emissions from Mobile Combustion: Marine | $N_2O$ | 0.5 | <0.01 | 1.00 | 57% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $CH_4$ | 0.4 | <0.01 | 1.00 | 127% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.4 | <0.01 | 1.00 | NA | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Other | $CH_4$ | 0.4 | <0.01 | 1.00 | 47% | <0.001 |
| $N_2O$ Emissions from Incineration of Waste | $N_2O$ | 0.4 | <0.01 | 1.00 | 320% | <0.001 |
| $CO_2$ Emissions from Petroleum Systems | $CO_2$ | 0.3 | <0.01 | 1.00 | 149% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $N_2O$ | 0.3 | <0.01 | 1.00 | 187% | <0.001 |
| $CH_4$ Emissions from Field Burning of Agricultural Residues | $CH_4$ | 0.2 | <0.01 | 1.00 | 42% | <0.001 |
| $CO_2$ Emissions from Silicon Carbide Production and Consumption | $CO_2$ | 0.2 | <0.01 | 1.00 | 10% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $N_2O$ | 0.1 | <0.01 | 1.00 | 187% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Aviation | $CH_4$ | 0.1 | <0.01 | 1.00 | 61% | <0.001 |
| $N_2O$ Emissions from Field Burning of Agricultural Residues | $N_2O$ | 0.1 | <0.01 | 1.00 | 31% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $CH_4$ | 0.1 | <0.01 | 1.00 | 127% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Marine | $CH_4$ | + | <0.01 | 1.00 | 73% | <0.001 |
| $CH_4$ Emissions from Ferroalloy Production | $CH_4$ | + | <0.01 | 1.00 | 12% | <0.001 |
| $CH_4$ Emissions from Silicon Carbide Production and Consumption | $CH_4$ | + | <0.01 | 1.00 | 9% | <0.001 |
| $CH_4$ Emissions from Incineration of Waste | $CH_4$ | + | <0.01 | 1.00 | 24% | <0.001 |

Note: LULUCF sources and sinks are not included in this analysis.
[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.
NE Uncertainty not estimated.
+ Does not exceed 0.05 Tg $CO_2$ Eq.

Table A- 7: 2011 Key Source Category Tier 1 and Tier 2 Analysis—Level Assessment with LULUCF

| IPCC Source Categories | Direct GHG | 2011 Estimate (Tg $CO_2$ Eq.) | Tier 1 Level Assessment | Cumulative Total | Uncertainty | Tier 2 Level Assessment |
|---|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Coal - Electricity Generation | $CO_2$ | 1,718.0 | 0.22 | 0.22 | 10% | 0.021 |
| $CO_2$ Emissions from Mobile Combustion: Road | $CO_2$ | 1,473.2 | 0.19 | 0.40 | 8% | 0.016 |
| $CO_2$ Emissions from Changes in Forest Carbon Stocks | $CO_2$ | 921.8 | 0.12 | 0.52 | 12% | 0.014 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Electricity Generation | $CO_2$ | 410.2 | 0.05 | 0.57 | 5% | 0.003 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Industrial | $CO_2$ | 409.7 | 0.05 | 0.62 | 13% | 0.007 |
| Direct $N_2O$ Emissions from Agricultural Soil Management | $N_2O$ | 285.6 | 0.04 | 0.66 | 58% | 0.021 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Industrial | $CO_2$ | 279.9 | 0.04 | 0.69 | 18% | 0.006 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Residential | $CO_2$ | 255.7 | 0.03 | 0.72 | 7% | 0.002 |
| Fugitive Emissions from Natural Gas Systems | $CH_4$ | 215.4 | 0.03 | 0.75 | 30% | 0.008 |

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|---|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Gas - Commercial | $CO_2$ | 171.1 | 0.02 | 0.77 | 7% | 0.002 |
| $CO_2$ Emissions from Mobile Combustion: Aviation | $CO_2$ | 142.8 | 0.02 | 0.79 | 8% | 0.002 |
| $CH_4$ Emissions from Enteric Fermentation | $CH_4$ | 139.3 | 0.02 | 0.81 | 18% | 0.003 |
| $CO_2$ Emissions from Non-Energy Use of Fuels | $CO_2$ | 130.5 | 0.02 | 0.83 | 21% | 0.003 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 121.7 | 0.02 | 0.84 | 8% | 0.001 |
| $CH_4$ Emissions from Landfills | $CH_4$ | 103.0 | 0.01 | 0.85 | 52% | 0.007 |
| $CO_2$ Emissions from Urban Trees | $CO_2$ | 98.0 | 0.01 | 0.87 | 23% | 0.003 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Industrial | $CO_2$ | 90.0 | 0.01 | 0.88 | 17% | 0.002 |
| $CO_2$ Emissions from Mobile Combustion: Other | $CO_2$ | 79.2 | 0.01 | 0.89 | 8% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Residential | $CO_2$ | 78.2 | 0.01 | 0.90 | 6% | 0.001 |
| Fugitive Emissions from Coal Mining | $CH_4$ | 72.6 | 0.01 | 0.91 | 16% | 0.001 |
| $CO_2$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CO_2$ | 64.3 | 0.01 | 0.91 | 17% | 0.001 |
| Indirect $N_2O$ Emissions from Applied Nitrogen | $N_2O$ | 57.6 | 0.01 | 0.92 | 153% | 0.011 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 52.3 | 0.01 | 0.93 | 20% | 0.001 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Commercial | $CO_2$ | 49.8 | 0.01 | 0.93 | 5% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Oil - U.S. Territories | $CO_2$ | 44.7 | 0.01 | 0.94 | 11% | 0.001 |
| $CO_2$ Emissions from Mobile Combustion: Marine | $CO_2$ | 36.5 | <0.01 | 0.94 | 8% | <0.001 |
| $CO_2$ Emissions from Natural Gas Systems | $CO_2$ | 32.3 | <0.01 | 0.95 | 30% | 0.001 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 31.6 | <0.01 | 0.95 | 14% | 0.001 |
| Fugitive Emissions from Petroleum Systems | $CH_4$ | 31.5 | <0.01 | 0.96 | 149% | 0.006 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Electricity Generation | $CO_2$ | 25.1 | <0.01 | 0.96 | 7% | <0.001 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 18.5 | <0.01 | 0.96 | 24% | 0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $N_2O$ | 17.9 | <0.01 | 0.96 | 187% | 0.004 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 16.7 | <0.01 | 0.97 | 43% | 0.001 |
| $N_2O$ Emissions from Mobile Combustion: Road | $N_2O$ | 16.7 | <0.01 | 0.97 | 17% | <0.001 |
| $CH_4$ Emissions from Wastewater Treatment | $CH_4$ | 16.2 | <0.01 | 0.97 | 31% | 0.001 |
| $CO_2$ Emissions from Land Converted to Grassland | $CO_2$ | 14.6 | <0.01 | 0.97 | 15% | <0.001 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 13.8 | <0.01 | 0.97 | 9% | <0.001 |
| $CO_2$ Emissions from Landfilled Yard Trimmings and Food Scraps | $CO_2$ | 13.0 | <0.01 | 0.98 | 57% | 0.001 |
| $CO_2$ Emissions from Land Converted to Cropland | $CO_2$ | 12.5 | <0.01 | 0.98 | 40% | 0.001 |
| $CO_2$ Emissions from Incineration of Waste | $CO_2$ | 12.0 | <0.01 | 0.98 | 24% | <0.001 |
| $SF_6$ Emissions from Electrical Transmission and Distribution | $SF_6$ | 11.7 | <0.01 | 0.98 | 25% | <0.001 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 10.6 | <0.01 | 0.98 | 9% | <0.001 |
| $CO_2$ Emissions from Limestone and Dolomite Use | $CO_2$ | 9.5 | <0.01 | 0.98 | 18% | <0.001 |
| $CO_2$ Emissions from Grassland Remaining Grassland | $CO_2$ | 9.0 | <0.01 | 0.98 | 32% | <0.001 |
| $CO_2$ Emissions from Ammonia Production | $CO_2$ | 8.8 | <0.01 | 0.99 | 25% | <0.001 |
| HFC-23 Emissions from HCFC-22 Production | HFCs | 6.9 | <0.01 | 0.99 | 10% | <0.001 |
| $CH_4$ Emissions from Rice Cultivation | $CH_4$ | 6.6 | <0.01 | 0.99 | 153% | 0.001 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacture | Several | 5.4 | <0.01 | 0.99 | 11% | <0.001 |
| $N_2O$ Emissions from Wastewater Treatment | $N_2O$ | 5.2 | <0.01 | 0.99 | 99% | 0.001 |
| Fugitive Emissions from Abandoned Underground Coal Mines | $CH_4$ | 5.0 | <0.01 | 0.99 | 22% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Commercial | $CO_2$ | 4.9 | <0.01 | 0.99 | 15% | <0.001 |

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|---|---|---|---|---|---|---|
| $CH_4$ Emissions from Forest Fires | $CH_4$ | 4.8 | <0.01 | 0.99 | 148% | 0.001 |
| $CO_2$ Emissions from Liming of Agricultural Soils | $CO_2$ | 4.5 | <0.01 | 0.99 | 112% | 0.001 |
| $N_2O$ Emissions from Product Uses | $N_2O$ | 4.4 | <0.01 | 0.99 | 8% | <0.001 |
| $CO_2$ Emissions from Urea Consumption for Non-Ag Purposes | $CO_2$ | 4.3 | <0.01 | 0.99 | 48% | <0.001 |
| $N_2O$ Emissions from Forest Fires | $N_2O$ | 4.0 | <0.01 | 0.99 | 147% | 0.001 |
| $CO_2$ Emissions from Urea Fertilization | $CO_2$ | 3.7 | <0.01 | 0.99 | 43% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $CH_4$ | 3.6 | <0.01 | 0.99 | 127% | 0.001 |
| $CO_2$ Emissions from Petrochemical Production | $CO_2$ | 3.5 | <0.01 | 0.99 | 31% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - U.S. Territories | $CO_2$ | 3.5 | <0.01 | 0.99 | 19% | <0.001 |
| $CO_2$ Emissions from Aluminum Production | $CO_2$ | 3.3 | <0.01 | 0.99 | 49% | <0.001 |
| $CH_4$ Emissions from Petrochemical Production | $CH_4$ | 3.1 | <0.01 | 0.99 | 30% | <0.001 |
| PFC Emissions from Aluminum Production | PFCs | 2.9 | <0.01 | 1.00 | 51% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $N_2O$ | 2.7 | <0.01 | 1.00 | 187% | 0.001 |
| $CO_2$ Emissions from Soda Ash Production and Consumption | $CO_2$ | 2.7 | <0.01 | 1.00 | 7% | <0.001 |
| $CO_2$ Emissions from Cropland Remaining Cropland | $CO_2$ | 2.4 | <0.01 | 1.00 | 194% | 0.001 |
| $CO_2$ Emissions from Carbon Dioxide Consumption | $CO_2$ | 2.2 | <0.01 | 1.00 | 30% | <0.001 |
| $N_2O$ Emissions from Mobile Combustion: Other | $N_2O$ | 1.9 | <0.01 | 1.00 | 47% | <0.001 |
| $CO_2$ Emissions from Titanium Dioxide Production | $CO_2$ | 1.9 | <0.01 | 1.00 | 13% | <0.001 |
| $N_2O$ Emissions from Composting | $N_2O$ | 1.7 | <0.01 | 1.00 | 50% | <0.001 |
| $CO_2$ Emissions from Ferroalloy Production | $CO_2$ | 1.7 | <0.01 | 1.00 | 12% | <0.001 |
| $CH_4$ Emissions from Composting | $CH_4$ | 1.5 | <0.01 | 1.00 | 50% | <0.001 |
| $N_2O$ Emissions from Settlement Soils | $N_2O$ | 1.5 | <0.01 | 1.00 | 163% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Gas - U.S. Territories | $CO_2$ | 1.5 | <0.01 | 1.00 | 17% | <0.001 |
| $CO_2$ Emissions from Glass Production | $CO_2$ | 1.5 | <0.01 | 1.00 | 10% | <0.001 |
| $N_2O$ Emissions from Mobile Combustion: Aviation | $N_2O$ | 1.4 | <0.01 | 1.00 | 68% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Road | $CH_4$ | 1.4 | <0.01 | 1.00 | 15% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $CH_4$ | 1.3 | <0.01 | 1.00 | 127% | <0.001 |
| $CO_2$ Emissions from Zinc Production | $CO_2$ | 1.3 | <0.01 | 1.00 | 19% | <0.001 |
| $SF_6$ Emissions from Magnesium Production and Processing | $SF_6$ | 1.3 | <0.01 | 1.00 | 4% | <0.001 |
| $CO_2$ Emissions from Phosphoric Acid Production | $CO_2$ | 1.1 | <0.01 | 1.00 | 18% | <0.001 |
| $CO_2$ Emissions from Wetlands Remaining Wetlands | $CO_2$ | 1.0 | <0.01 | 1.00 | 38% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $CH_4$ | 0.9 | <0.01 | 1.00 | 127% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $N_2O$ | 0.9 | <0.01 | 1.00 | 187% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Residential | $CO_2$ | 0.6 | <0.01 | 1.00 | 15% | <0.001 |
| $CH_4$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CH_4$ | 0.6 | <0.01 | 1.00 | 22% | <0.001 |
| $CO_2$ Emissions from Lead Production | $CO_2$ | 0.5 | <0.01 | 1.00 | 15% | <0.001 |
| $N_2O$ Emissions from Mobile Combustion: Marine | $N_2O$ | 0.5 | <0.01 | 1.00 | 57% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $CH_4$ | 0.4 | <0.01 | 1.00 | 127% | <0.001 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.4 | <0.01 | 1.00 | NA | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Other | $CH_4$ | 0.4 | <0.01 | 1.00 | 47% | <0.001 |
| $N_2O$ Emissions from Incineration of Waste | $N_2O$ | 0.4 | <0.01 | 1.00 | 320% | <0.001 |
| $N_2O$ Emissions from Forest Soils | $N_2O$ | 0.4 | <0.01 | 1.00 | 211% | <0.001 |

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|---|---|---|---|---|---|---|
| $CO_2$ Emissions from Petroleum Systems | $CO_2$ | 0.3 | <0.01 | 1.00 | 149% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $N_2O$ | 0.3 | <0.01 | 1.00 | 187% | <0.001 |
| $CH_4$ Emissions from Field Burning of Agricultural Residues | $CH_4$ | 0.2 | <0.01 | 1.00 | 42% | <0.001 |
| $CO_2$ Emissions from Silicon Carbide Production and Consumption | $CO_2$ | 0.2 | <0.01 | 1.00 | 10% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $N_2O$ | 0.1 | <0.01 | 1.00 | 187% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Aviation | $CH_4$ | 0.1 | <0.01 | 1.00 | 61% | <0.001 |
| $N_2O$ Emissions from Field Burning of Agricultural Residues | $N_2O$ | 0.1 | <0.01 | 1.00 | 31% | <0.001 |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $CH_4$ | 0.1 | <0.01 | 1.00 | 127% | <0.001 |
| $CH_4$ Emissions from Mobile Combustion: Marine | $CH_4$ | + | <0.01 | 1.00 | 73% | <0.001 |
| $CH_4$ Emissions from Ferroalloy Production | $CH_4$ | + | <0.01 | 1.00 | 12% | <0.001 |
| $CH_4$ Emissions from Silicon Carbide Production and Consumption | $CH_4$ | + | <0.01 | 1.00 | 9% | <0.001 |
| $N_2O$ Emissions from Wetlands Remaining Wetlands | $N_2O$ | + | <0.01 | 1.00 | 74% | <0.001 |
| $CH_4$ Emissions from Incineration of Waste | $CH_4$ | + | <0.01 | 1.00 | 24% | <0.001 |

[a] Percent relative uncertainty. If the corresponding uncertainty is asymmetrical, the uncertainty given here is the larger and always positive.
NE Uncertainty not estimated.
+ Does not exceed 0.05 Tg $CO_2$ Eq.

Table A- 8: 1990-2011 Key Source Category Tier 1 and 2 Analysis—Trend Assessment, without LULUCF

| IPCC Source Categories | Direct GHG | 1990 Estimate (Tg $CO_2$ Eq.) | 2011 Estimate (Tg $CO_2$ Eq.) | Tier 1 Trend Assessment | Tier 2 Trend Assessment | % Contribution to Trend | Cumulative Total |
|---|---|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Gas - Electricity Generation | $CO_2$ | 175.3 | 410.2 | 0.03 | 0.001 | 16.9 | 17 |
| $CO_2$ Emissions from Mobile Combustion: Road | $CO_2$ | 1,188.9 | 1,473.2 | 0.02 | 0.002 | 13.8 | 31 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.3 | 121.7 | 0.02 | 0.001 | 9.4 | 40 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Electricity Generation | $CO_2$ | 97.5 | 25.1 | 0.01 | 0.001 | 6.3 | 46 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Industrial | $CO_2$ | 155.3 | 90.0 | 0.01 | 0.002 | 6.1 | 52 |
| $CH_4$ Emissions from Landfills | $CH_4$ | 147.8 | 103.0 | 0.01 | 0.004 | 4.5 | 57 |
| $CO_2$ Emissions from Mobile Combustion: Aviation | $CO_2$ | 179.3 | 142.8 | 0.01 | 0.001 | 4.1 | 61 |
| $CO_2$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CO_2$ | 99.8 | 64.3 | 0.01 | 0.001 | 3.4 | 64 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Industrial | $CO_2$ | 408.9 | 409.7 | <0.01 | 0.001 | 2.8 | 67 |
| HFC-23 Emissions from HCFC-22 Production | HFCs | 36.4 | 6.9 | <0.01 | <0.001 | 2.5 | 70 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Electricity Generation | $CO_2$ | 1,547.6 | 1,718.0 | <0.01 | <0.001 | 2.5 | 72 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Industrial | $CO_2$ | 284.4 | 279.9 | <0.01 | 0.001 | 2.3 | 75 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Residential | $CO_2$ | 97.4 | 78.2 | <0.01 | <0.001 | 2.2 | 77 |
| $N_2O$ Emissions from Mobile Combustion: Road | $N_2O$ | 40.3 | 16.7 | <0.01 | 0.001 | 2.1 | 79 |
| $CO_2$ Emissions from Stationary Combustion - Oil - Commercial | $CO_2$ | 64.9 | 49.8 | <0.01 | <0.001 | 1.6 | 80 |
| Fugitive Emissions from Coal Mining | $CH_4$ | 84.1 | 72.6 | <0.01 | <0.001 | 1.5 | 82 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 31.7 | 52.3 | <0.01 | <0.001 | 1.4 | 83 |
| $SF_6$ Emissions from Electrical Transmission and | $SF_6$ | 26.7 | 11.7 | <0.01 | 0.001 | 1.3 | 85 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Distribution | | | | | | | |
| PFC Emissions from Aluminum Production | PFCs | 18.4 | 2.9 | <0.01 | 0.001 | 1.3 | 86 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Commercial | $CO_2$ | 142.1 | 171.1 | <0.01 | <0.001 | 1.3 | 87 |
| $CO_2$ Emissions from Stationary Combustion - Oil - U.S. Territories | $CO_2$ | 27.2 | 44.7 | <0.01 | <0.001 | 1.2 | 88 |
| $CO_2$ Emissions from Mobile Combustion: Marine | $CO_2$ | 44.5 | 36.5 | <0.01 | <0.001 | 0.9 | 89 |
| Direct $N_2O$ Emissions from Agricultural Soil Management | $N_2O$ | 272.1 | 285.6 | <0.01 | 0.001 | 0.8 | 90 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $N_2O$ | 7.4 | 17.9 | <0.01 | 0.002 | 0.8 | 91 |
| Fugitive Emissions from Natural Gas Systems | $CH_4$ | 189.6 | 215.4 | <0.01 | <0.001 | 0.7 | 92 |
| $CO_2$ Emissions from Natural Gas Systems | $CO_2$ | 37.6 | 32.3 | <0.01 | <0.001 | 0.7 | 92 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Commercial | $CO_2$ | 12.0 | 4.9 | <0.01 | <0.001 | 0.6 | 93 |
| Fugitive Emissions from Petroleum Systems | $CH_4$ | 35.2 | 31.5 | <0.01 | 0.001 | 0.5 | 93 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 15.8 | 10.6 | <0.01 | <0.001 | 0.5 | 94 |
| $CH_4$ Emissions from Enteric Fermentation | $CH_4$ | 133.8 | 139.3 | <0.01 | <0.001 | 0.5 | 94 |
| $CO_2$ Emissions from Ammonia Production | $CO_2$ | 13.0 | 8.8 | <0.01 | <0.001 | 0.4 | 95 |
| $SF_6$ Emissions from Magnesium Production and Processing | $SF_6$ | 5.4 | 1.3 | <0.01 | <0.001 | 0.4 | 95 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.3 | 31.6 | <0.01 | <0.001 | 0.4 | 96 |
| $CO_2$ Emissions from Limestone and Dolomite Use | $CO_2$ | 4.9 | 9.5 | <0.01 | <0.001 | 0.3 | 96 |
| $CO_2$ Emissions from Aluminum Production | $CO_2$ | 6.8 | 3.3 | <0.01 | <0.001 | 0.3 | 96 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Residential | $CO_2$ | 238.0 | 255.7 | <0.01 | <0.001 | 0.3 | 96 |
| $CO_2$ Emissions from Incineration of Waste | $CO_2$ | 8.0 | 12.0 | <0.01 | <0.001 | 0.3 | 96 |
| $CH_4$ Emissions from Mobile Combustion: Road | $CH_4$ | 4.2 | 1.4 | <0.01 | <0.001 | 0.3 | 97 |
| $CO_2$ Emissions from Stationary Combustion - Coal - U.S. Territories | $CO_2$ | 0.6 | 3.5 | <0.01 | <0.001 | 0.2 | 97 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Residential | $CO_2$ | 3.0 | 0.6 | <0.01 | <0.001 | 0.2 | 97 |
| $CO_2$ Emissions from Non-Energy Use of Fuels | $CO_2$ | 117.4 | 130.5 | <0.01 | <0.001 | 0.2 | 97 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.6 | 16.7 | <0.01 | <0.001 | 0.2 | 97 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 14.8 | 18.5 | <0.01 | <0.001 | 0.2 | 98 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacture | Several | 2.9 | 5.4 | <0.01 | <0.001 | 0.2 | 98 |
| Indirect $N_2O$ Emissions from Applied Nitrogen | $N_2O$ | 54.8 | 57.6 | <0.01 | <0.001 | 0.2 | 98 |
| Fugitive Emissions from Abandoned Underground Coal Mines | $CH_4$ | 6.0 | 5.0 | <0.01 | <0.001 | 0.1 | 98 |
| $CO_2$ Emissions from Stationary Combustion - Gas - U.S. Territories | $CO_2$ | + | 1.5 | <0.01 | <0.001 | 0.1 | 98 |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $CH_4$ | 4.6 | 3.6 | <0.01 | <0.001 | 0.1 | 98 |
| $N_2O$ Emissions from Wastewater Treatment | $N_2O$ | 3.5 | 5.2 | <0.01 | <0.001 | 0.1 | 98 |
| $N_2O$ Emissions from Composting | $N_2O$ | 0.4 | 1.7 | <0.01 | <0.001 | 0.1 | 99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.5 | 13.8 | <0.01 | <0.001 | 0.1 | 99 |
| $CH_4$ Emissions from Composting | $CH_4$ | 0.3 | 1.5 | <0.01 | <0.001 | 0.1 | 99 |
| $CH_4$ Emissions from Wastewater Treatment | $CH_4$ | 15.9 | 16.2 | <0.01 | <0.001 | 0.1 | 99 |
| $CH_4$ Emissions from Rice Cultivation | $CH_4$ | 7.1 | 6.6 | <0.01 | <0.001 | 0.1 | 99 |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $N_2O$ | 3.3 | 2.7 | <0.01 | <0.001 | 0.1 | 99 |
| $CO_2$ Emissions from Ferroalloy Production | $CO_2$ | 2.2 | 1.7 | <0.01 | <0.001 | 0.1 | 99 |
| $CO_2$ Emissions from Carbon Dioxide Consumption | $CO_2$ | 1.4 | 2.2 | <0.01 | <0.001 | 0.1 | 99 |
| $CH_4$ Emissions from Petrochemical Production | $CH_4$ | 2.3 | 3.1 | <0.01 | <0.001 | <0.1 | 99 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $CO_2$ Emissions from Mobile Combustion: Other | $CO_2$ | 73.3 | 79.2 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Titanium Dioxide Production | $CO_2$ | 1.2 | 1.9 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Zinc Production | $CO_2$ | 0.6 | 1.3 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Phosphoric Acid Production | $CO_2$ | 1.5 | 1.1 | <0.01 | <0.001 | <0.1 | 99 |
| $N_2O$ Emissions from Mobile Combustion: Aviation | $N_2O$ | 1.7 | 1.4 | <0.01 | <0.001 | <0.1 | 99 |
| $N_2O$ Emissions from Mobile Combustion: Other | $N_2O$ | 1.3 | 1.9 | <0.01 | <0.001 | <0.1 | 99 |
| $CH_4$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CH_4$ | 1.0 | 0.6 | <0.01 | <0.001 | <0.1 | 99 |
| $N_2O$ Emissions from Product Uses | $N_2O$ | 4.4 | 4.4 | <0.01 | <0.001 | <0.1 | 99 |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $CH_4$ | 1.6 | 1.3 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Soda Ash Production and Consumption | $CO_2$ | 2.8 | 2.7 | <0.01 | <0.001 | <0.1 | 99 |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $N_2O$ | 1.1 | 0.9 | <0.01 | <0.001 | <0.1 | 100 |
| $CO_2$ Emissions from Silicon Carbide Production and Consumption | $CO_2$ | 0.4 | 0.2 | <0.01 | <0.001 | <0.1 | 100 |
| $CO_2$ Emissions from Petrochemical Production | $CO_2$ | 3.4 | 3.5 | <0.01 | <0.001 | <0.1 | 100 |
| $CO_2$ Emissions from Urea Consumption for Non-Ag Purposes | $CO_2$ | 3.8 | 4.3 | <0.01 | <0.001 | <0.1 | 100 |
| $CO_2$ Emissions from Glass Production | $CO_2$ | 1.5 | 1.5 | <0.01 | <0.001 | <0.1 | 100 |
| $N_2O$ Emissions from Incineration of Waste | $N_2O$ | 0.5 | 0.4 | <0.01 | <0.001 | <0.1 | 100 |
| $N_2O$ Emissions from Mobile Combustion: Marine | $N_2O$ | 0.6 | 0.5 | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Mobile Combustion: Other | $CH_4$ | 0.3 | 0.4 | <0.01 | <0.001 | <0.1 | 100 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $CH_4$ | 0.3 | 0.4 | <0.01 | <0.001 | <0.1 | 100 |
| $CO_2$ Emissions from Petroleum Systems | $CO_2$ | 0.4 | 0.3 | <0.01 | <0.001 | <0.1 | 100 |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $N_2O$ | 0.4 | 0.3 | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Mobile Combustion: Aviation | $CH_4$ | 0.2 | 0.1 | <0.01 | <0.001 | <0.1 | 100 |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $N_2O$ | 0.1 | 0.1 | <0.01 | <0.001 | <0.1 | 100 |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $CH_4$ | 0.9 | 0.9 | <0.01 | <0.001 | <0.1 | 100 |
| $CO_2$ Emissions from Lead Production | $CO_2$ | 0.5 | 0.5 | <0.01 | <0.001 | <0.1 | 100 |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $CH_4$ | + | 0.1 | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Silicon Carbide Production and Consumption | $CH_4$ | + | + | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Field Burning of Agricultural Residues | $CH_4$ | 0.2 | 0.2 | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Ferroalloy Production | $CH_4$ | + | + | <0.01 | <0.001 | <0.1 | 100 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.4 | 0.4 | <0.01 | <0.001 | <0.1 | 100 |
| $N_2O$ Emissions from Field Burning of Agricultural Residues | $N_2O$ | 0.1 | 0.1 | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Mobile Combustion: Marine | $CH_4$ | + | + | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Incineration of Waste | $CH_4$ | + | + | <0.01 | <0.001 | <0.1 | 100 |

Note: LULUCF sources and sinks are not included in this analysis.
+ Does not exceed 0.05 Tg $CO_2$ Eq.

Table A- 9: 1990-2011 Key Source Category Tier 1 and 2 Analysis—Trend Assessment, with LULUCF

| IPCC Source Categories | Direct GHG | 1990 Estimate (Tg $CO_2$ Eq.) | 2011 Estimate (Tg $CO_2$ Eq.) | Tier 1 Trend Assessment | Tier 2 Trend Assessment | Percent Contribution to Trend (%) | Cumulative Contribution to Trend (%) |
|---|---|---|---|---|---|---|---|
| $CO_2$ Emissions from Stationary Combustion - Gas - Electricity Generation | $CO_2$ | 175.3 | 410.2 | 0.02 | 0.001 | 13.8 | 14 |
| $CO_2$ Emissions from Mobile Combustion: Road | $CO_2$ | 1,188.9 | 1,473.2 | 0.02 | 0.002 | 10.2 | 24 |
| $CO_2$ Emissions from Changes in Forest Carbon Stocks | $CO_2$ | 701.4 | 921.8 | 0.02 | 0.002 | 9.4 | 33 |
| Emissions from Substitutes for Ozone Depleting Substances | Several | 0.3 | 121.7 | 0.01 | 0.001 | 7.7 | 41 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Electricity Generation | $CO_2$ | 1,547.6 | 1,718.0 | <0.01 | <0.001 | 0.6 | 42 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Industrial | $CO_2$ | 155.3 | 90.0 | 0.01 | 0.002 | 5.2 | 47 |
| $CO_2$ Emissions from Stationary Combustion - Oi - Electricity Generation | $CO_2$ | 97.5 | 25.1 | 0.01 | 0.001 | 5.3 | 52 |
| $CO_2$ Emissions from Mobile Combustion: Aviation | $CO_2$ | 179.3 | 142.8 | 0.01 | 0.001 | 3.5 | 56 |
| $CH_4$ Emissions from Landfills | $CH_4$ | 147.8 | 103.0 | 0.01 | 0.004 | 3.8 | 60 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Industrial | $CO_2$ | 408.9 | 409.7 | <0.01 | 0.001 | 2.7 | 62 |
| $CO_2$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CO_2$ | 99.8 | 64.3 | 0.01 | 0.001 | 2.9 | 65 |
| HFC-23 Emissions from HCFC-22 Production | HFCs | 36.4 | 6.9 | <0.01 | <0.001 | 2.1 | 67 |
| $CO_2$ Emissions from Urban Trees | $CO_2$ | 57.1 | 98.0 | <0.01 | 0.001 | 2.2 | 70 |
| $CO_2$ Emissions from Stationary Combustion - Oi - Residential | $CO_2$ | 97.4 | 78.2 | <0.01 | <0.001 | 1.9 | 71 |
| $CO_2$ Emissions from Stationary Combustion - Oi - Industrial | $CO_2$ | 284.4 | 279.9 | <0.01 | 0.001 | 2.2 | 74 |
| $N_2O$ Emissions from Mobile Combustion: Road | $N_2O$ | 40.3 | 16.7 | <0.01 | 0.001 | 1.8 | 75 |
| $CO_2$ Emissions from Cropland Remaining Cropland | $CO_2$ | 17.0 | 2.4 | <0.01 | 0.004 | 1.0 | 76 |
| $CO_2$ Emissions from Stationary Combustion - Oi - Commercial | $CO_2$ | 64.9 | 49.8 | <0.01 | <0.001 | 1.4 | 78 |
| Fugitive Emissions from Coal Mining | $CH_4$ | 84.1 | 72.6 | <0.01 | <0.001 | 1.3 | 79 |
| $CO_2$ Emissions from Mobile Combustion: Marine | $CO_2$ | 44.5 | 36.5 | <0.01 | <0.001 | 0.8 | 80 |
| $CO_2$ Emissions from Grassland Remaining Grassland | $CO_2$ | 52.5 | 9.0 | 0.01 | 0.002 | 3.1 | 83 |
| PFC Emissions from Aluminum Production | PFCs | 18.4 | 2.9 | <0.01 | 0.001 | 1.1 | 84 |
| $CO_2$ Emissions from Land Converted to Cropland | $CO_2$ | 25.1 | 12.5 | <0.01 | 0.001 | 1.0 | 85 |
| $SF_6$ Emissions from Electrical Transmission and Distribution | $SF_6$ | 26.7 | 11.7 | <0.01 | <0.001 | 1.1 | 86 |
| $CH_4$ Emissions from Manure Management | $CH_4$ | 31.7 | 52.3 | <0.01 | <0.001 | 1.1 | 87 |
| $N_2O$ Emissions from Adipic Acid Production | $N_2O$ | 15.8 | 10.6 | <0.01 | <0.001 | 0.4 | 88 |
| $CO_2$ Emissions from Landfilled Yard Trimmings and Food Scraps | $CO_2$ | 24.2 | 13.0 | <0.01 | 0.001 | 0.9 | 89 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Commercial | $CO_2$ | 142.1 | 171.1 | <0.01 | <0.001 | 0.9 | 90 |
| $CO_2$ Emissions from Non-Energy Use of Fuels | $CO_2$ | 117.4 | 130.5 | <0.01 | <0.001 | 0.1 | 90 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $N_2O$ | 7.4 | 17.9 | <0.01 | 0.002 | 0.6 | 90 |
| $CO_2$ Emissions from Natural Gas Systems | $CO_2$ | 37.6 | 32.3 | <0.01 | <0.001 | 0.6 | 91 |
| $CH_4$ Emissions from Enteric Fermentation | $CH_4$ | 133.8 | 139.3 | <0.01 | <0.001 | 0.5 | 91 |
| $CO_2$ Emissions from Mobile Combustion: Other | $CO_2$ | 73.3 | 79.2 | <0.01 | <0.001 | 0.1 | 91 |
| Direct $N_2O$ Emissions from Agricultural Soil Management | $N_2O$ | 272.1 | 285.6 | <0.01 | 0.001 | 1.0 | 92 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Fugitive Emissions from Petroleum Systems | $CH_4$ | 35.2 | 31.5 | <0.01 | 0.001 | 0.5 | 93 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Commercial | $CO_2$ | 12.0 | 4.9 | <0.01 | <0.001 | 0.5 | 93 |
| $CO_2$ Emissions from Cement Production | $CO_2$ | 33.3 | 31.6 | <0.01 | <0.001 | 0.3 | 94 |
| $CO_2$ Emissions from Stationary Combustion - Oi - U.S. Territories | $CO_2$ | 27.2 | 44.7 | <0.01 | <0.001 | 0.9 | 95 |
| $CO_2$ Emissions from Ammonia Production | $CO_2$ | 13.0 | 8.8 | <0.01 | <0.001 | 0.4 | 95 |
| Indirect $N_2O$ Emissions from Applied Nitrogen | $N_2O$ | 54.8 | 57.6 | <0.01 | 0.001 | 0.2 | 95 |
| $SF_6$ Emissions from Magnesium Production and Processing | $SF_6$ | 5.4 | 1.3 | <0.01 | <0.001 | 0.3 | 95 |
| $CO_2$ Emissions from Aluminum Production | $CO_2$ | 6.8 | 3.3 | <0.01 | <0.001 | 0.3 | 96 |
| $CO_2$ Emissions from Limestone and Dolomite Use | $CO_2$ | 4.9 | 9.5 | <0.01 | <0.001 | 0.3 | 96 |
| $CO_2$ Emissions from Land Converted to Grassland | $CO_2$ | 11.4 | 14.6 | <0.01 | <0.001 | 0.1 | 96 |
| $CH_4$ Emissions from Mobile Combustion: Road | $CH_4$ | 4.2 | 1.4 | <0.01 | <0.001 | 0.2 | 96 |
| $CO_2$ Emissions from Incineration of Waste | $CO_2$ | 8.0 | 12.0 | <0.01 | <0.001 | 0.2 | 97 |
| $CO_2$ Emissions from Stationary Combustion - Coal - U.S. Territories | $CO_2$ | 0.6 | 3.5 | <0.01 | <0.001 | 0.2 | 97 |
| $N_2O$ Emissions from Nitric Acid Production | $N_2O$ | 17.6 | 16.7 | <0.01 | <0.001 | 0.2 | 97 |
| $CO_2$ Emissions from Stationary Combustion - Coal - Residential | $CO_2$ | 3.0 | 0.6 | <0.01 | <0.001 | 0.2 | 97 |
| Fugitive Emissions from Natural Gas Systems | $CH_4$ | 189.6 | 215.4 | <0.01 | <0.001 | 0.4 | 97 |
| PFC, HFC, and $SF_6$ Emissions from Semiconductor Manufacture | Several | 2.9 | 5.4 | <0.01 | <0.001 | 0.1 | 98 |
| $CH_4$ Emissions from Forest Fires | $CH_4$ | 2.5 | 4.8 | <0.01 | <0.001 | 0.1 | 98 |
| Fugitive Emissions from Abandoned Underground Coal Mines | $CH_4$ | 6.0 | 5.0 | <0.01 | <0.001 | 0.1 | 98 |
| $N_2O$ Emissions from Manure Management | $N_2O$ | 14.8 | 18.5 | <0.01 | <0.001 | 0.1 | 98 |
| $N_2O$ Emissions from Forest Fires | $N_2O$ | 2.1 | 4.0 | <0.01 | <0.001 | 0.1 | 98 |
| Non-$CO_2$ Emissions from Stationary Combustior - Residential | $CH_4$ | 4.6 | 3.6 | <0.01 | <0.001 | 0.1 | 98 |
| $CH_4$ Emissions from Wastewater Treatment | $CH_4$ | 15.9 | 16.2 | <0.01 | <0.001 | 0.1 | 98 |
| $CO_2$ Emissions from Stationary Combustion - Gas - U.S. Territories | $CO_2$ | + | 1.5 | <0.01 | <0.001 | 0.1 | 98 |
| $N_2O$ Emissions from Composting | $N_2O$ | 0.4 | 1.7 | <0.01 | <0.001 | 0.1 | 98 |
| $CO_2$ Emissions from Liming of Agricultural Soils | $CO_2$ | 4.7 | 4.5 | <0.01 | <0.001 | <0.1 | 99 |
| $CH_4$ Emissions from Composting | $CH_4$ | 0.3 | 1.5 | <0.01 | <0.001 | 0.1 | 99 |
| $N_2O$ Emissions from Wastewater Treatment | $N_2O$ | 3.5 | 5.2 | <0.01 | <0.001 | 0.1 | 99 |
| $CO_2$ Emissions from Ferroalloy Production | $CO_2$ | 2.2 | 1.7 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Soda Ash Production and Consumption | $CO_2$ | 2.8 | 2.7 | <0.01 | <0.001 | <0.1 | 99 |
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $N_2O$ | 3.3 | 2.7 | <0.01 | <0.001 | 0.1 | 99 |
| $CO_2$ Emissions from Urea Fertilization | $CO_2$ | 2.4 | 3.7 | <0.01 | <0.001 | 0.1 | 99 |
| $CO_2$ Emissions from Phosphoric Acid Production | $CO_2$ | 1.5 | 1.1 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Carbon Dioxide Consumption | $CO_2$ | 1.4 | 2.2 | <0.01 | <0.001 | <0.1 | 99 |
| $CH_4$ Emissions from Rice Cultivation | $CH_4$ | 7.1 | 6.6 | <0.01 | <0.001 | 0.1 | 99 |
| $N_2O$ Emissions from Mobile Combustion: Aviation | $N_2O$ | 1.7 | 1.4 | <0.01 | <0.001 | <0.1 | 99 |
| $CH_4$ Emissions from Iron and Steel Production & Metallurgical Coke Production | $CH_4$ | 1.0 | 0.6 | <0.01 | <0.001 | <0.1 | 99 |
| $N_2O$ Emissions from Product Uses | $N_2O$ | 4.4 | 4.4 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Titanium Dioxide Production | $CO_2$ | 1.2 | 1.9 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Zinc Production | $CO_2$ | 0.6 | 1.3 | <0.01 | <0.001 | <0.1 | 99 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Non-$CO_2$ Emissions from Stationary Combustion - Industrial | $CH_4$ | 1.6 | 1.3 | <0.01 | <0.001 | <0.1 | 99 |
| $N_2O$ Emissions from Settlement Soils | $N_2O$ | 1.0 | 1.5 | <0.01 | <0.001 | <0.1 | 99 |
| $N_2O$ Emissions from Mobile Combustion: Other | $N_2O$ | 1.3 | 1.9 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Petrochemical Production | $CO_2$ | 3.4 | 3.5 | <0.01 | <0.001 | <0.1 | 99 |
| Non-$CO_2$ Emissions from Stationary Combustion - Residential | $N_2O$ | 1.1 | 0.9 | <0.01 | <0.001 | <0.1 | 99 |
| $N_2O$ Emissions from Forest Soils | $N_2O$ | 0.1 | 0.4 | <0.01 | <0.001 | <0.1 | 99 |
| $N_2O$ Emissions from Mobile Combustion: Marine | $N_2O$ | 0.6 | 0.5 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Silicon Carbide Production and Consumption | $CO_2$ | 0.4 | 0.2 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Lime Production | $CO_2$ | 11.5 | 13.8 | <0.01 | <0.001 | 0.1 | 99 |
| $CO_2$ Emissions from Wetlands Remaining Wetlands | $CO_2$ | 1.0 | 1.0 | <0.01 | <0.001 | <0.1 | 99 |
| $N_2O$ Emissions from Incineration of Waste | $N_2O$ | 0.5 | 0.4 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Urea Consumption for Non-Ag Purposes | $CO_2$ | 3.8 | 4.3 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Petroleum Systems | $CO_2$ | 0.4 | 0.3 | <0.01 | <0.001 | <0.1 | 99 |
| Non-$CO_2$ Emissions from Stationary Combustion - Electricity Generation | $CH_4$ | 0.3 | 0.4 | <0.01 | <0.001 | <0.1 | 99 |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $N_2O$ | 0.4 | 0.3 | <0.01 | <0.001 | <0.1 | 99 |
| $CH_4$ Emissions from Mobile Combustion: Other | $CH_4$ | 0.3 | 0.4 | <0.01 | <0.001 | <0.1 | 99 |
| $CO_2$ Emissions from Stationary Combustion - Gas - Residential | $CO_2$ | 238.0 | 255.7 | <0.01 | <0.001 | 0.4 | 100 |
| $CH_4$ Emissions from Mobile Combustion: Aviation | $CH_4$ | 0.2 | 0.1 | <0.01 | <0.001 | <0.1 | 100 |
| Non-$CO_2$ Emissions from Stationary Combustion - Commercial | $CH_4$ | 0.9 | 0.9 | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Petrochemical Production | $CH_4$ | 2.3 | 3.1 | <0.01 | <0.001 | <0.1 | 100 |
| $CO_2$ Emissions from Stationary Combustion - Geothermal Energy | $CO_2$ | 0.4 | 0.4 | <0.01 | <0.001 | <0.1 | 100 |
| $CO_2$ Emissions from Lead Production | $CO_2$ | 0.5 | 0.5 | <0.01 | <0.001 | <0.1 | 100 |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $N_2O$ | 0.1 | 0.1 | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Silicon Carbide Production and Consumption | $CH_4$ | + | + | <0.01 | <0.001 | <0.1 | 100 |
| Non-$CO_2$ Emissions from Stationary Combustion - U.S. Territories | $CH_4$ | + | 0.1 | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Ferroalloy Production | $CH_4$ | + | + | <0.01 | <0.001 | <0.1 | 100 |
| $N_2O$ Emissions from Field Burning of Agricultural Residues | $N_2O$ | 0.1 | 0.1 | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Field Burning of Agricultural Residues | $CH_4$ | 0.2 | 0.2 | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Mobile Combustion: Marine | $CH_4$ | + | + | <0.01 | <0.001 | <0.1 | 100 |
| $N_2O$ Emissions from Wetlands Remaining Wetlands | $N_2O$ | + | + | <0.01 | <0.001 | <0.1 | 100 |
| $CO_2$ Emissions from Glass Production | $CO_2$ | 1.5 | 1.5 | <0.01 | <0.001 | <0.1 | 100 |
| $CH_4$ Emissions from Incineration of Waste | $CH_4$ | + | + | <0.01 | <0.001 | <0.1 | 100 |

+ Does not exceed 0.05 Tg $CO_2$ Eq.

## References

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

IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change, and Forestry*. National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, J. Penman, et al. (eds.). Available online at <http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.htm>. August 13, 2004.

IPCC (2000) *Good Practice Guidance* and Uncertainty Management in National Greenhouse Gas Inventories, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme.

# ANNEX 2 Methodology and Data for Estimating $CO_2$ Emissions from Fossil Fuel Combustion

## 2.1. Methodology for Estimating Emissions of $CO_2$ from Fossil Fuel Combustion

Carbon dioxide ($CO_2$) emissions from fossil fuel combustion were estimated using a "bottom-up" methodology characterized by seven steps. These steps are described below.

#### Step 1: Determine Total Fuel Consumption by Fuel Type and Sector

The bottom-up methodology used by the United States for estimating $CO_2$ emissions from fossil fuel combustion is conceptually similar to the approach recommended by the Intergovernmental Panel on Climate Change (IPCC) for countries that intend to develop detailed, sectoral-based emission estimates in line with a Tier 2 method in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). Total consumption data and adjustments to consumption are presented in Columns 2 through 13 of Table A- 10.

Adjusted consumption data are presented in Columns 2 through 8 of Table A- 11 through Table A- 32 with totals by fuel type in Column 8 and totals by end-use sector in the last rows. Fuel consumption data for the bottom-up approach were obtained directly from the Energy Information Administration (EIA) of the U.S. Department of Energy. These data were first gathered in physical units, and then converted to their energy equivalents (see the Constants, Units, and Conversions Annex). The EIA data were collected through a variety of consumption surveys at the point of delivery or use and qualified with survey data on fuel production, imports, exports, and stock changes. Individual data elements were supplied by a variety of sources within EIA. Most information was taken from published reports, although some data were drawn from unpublished energy studies and databases maintained by EIA.

Energy consumption data were aggregated by sector (i.e., residential, commercial, industrial, transportation, electricity generation, and U.S. territories), primary fuel type (e.g., coal, natural gas, and petroleum), and secondary fuel type (e.g., motor gasoline, distillate fuel, etc.). The 2011 total adjusted energy consumption across all sectors, including territories, and energy types was 73,227 trillion British thermal units (TBtu), as indicated in the last entry of Column 8 in Table A- 10. This total excludes fuel used for non-energy purposes and fuel consumed as international bunkers, both of which were deducted in earlier steps.

Electricity consumption information was allocated to each sector based on EIA's distribution of electricity retail sales to ultimate customers (i.e., residential, commercial, industrial, and other). Because the "other" fuel use includes sales to both the commercial and transportation sectors, EIA's limited transportation electricity use data were subtracted from "other" electricity use and also reported separately. This total was consequently combined with the commercial electricity data. Further information on these electricity end uses is described in EIA's *Annual Energy Review* (EIA 2012).

There are also three basic differences between the consumption data presented in Table A- 10 through Table A-32 and those recommended in the IPCC emission inventory methodology.

First, consumption data in the U.S. Inventory are presented using higher heating values (HHV)[1] rather than the lower heating values (LHV)[2] reflected in the IPCC emission inventory methodology. This convention is followed because data obtained from EIA are based on HHV. Of note, however, is that EIA renewable energy statistics are often published using LHV. The difference between the two conventions relates to the treatment of the heat energy that is consumed in the process of evaporating the water contained in the fuel. The simplified convention used by the International Energy

[1] Also referred to as Gross Calorific Values (GCV).

[2] Also referred to as Net Calorific Values (NCV).

Agency for converting from HHV to LHV is to multiply the energy content by 0.95 for petroleum and coal and by 0.9 for natural gas.

Second, while EIA's energy use data for the United States includes only the 50 U.S. states and the District of Columbia, the data reported to the UNFCCC are to include energy consumption within U.S. territories. Therefore, consumption estimates for U.S. territories[3] were added to domestic consumption of fossil fuels. Energy consumption data from U.S. territories are presented in Column 7 of Table A- 10 through Table A- 32. It is reported separately from domestic sectoral consumption, because it is collected separately by EIA with no sectoral disaggregation.

Third, there were a number of modifications made in this report that may cause consumption information herein to differ from figures given in the cited literature. These are (1) the reallocation of select amounts of coking coal, petroleum coke, natural gas, residual fuel oil, and other oil (>401 F) for processes accounted for in the Industrial Processes chapter, (2) corrections for synthetic natural gas production, (3) subtraction of other fuels used for non-energy purposes, and (4) subtraction of international bunker fuels. These adjustments are described in the following steps.

**Step 2: Subtract uses accounted for in the Industrial Processes chapter.**

Portions of the fuel consumption data for seven fuel categories—coking coal, distillate fuel, industrial other coal, petroleum coke, natural gas, residual fuel oil, and other oil (>401 F)—were reallocated to the Industrial Processes chapter, as these portions were consumed as raw materials during non-energy related industrial processes. Emissions from these fuels used as raw materials are presented in the Industrial Processes chapter, and are removed from the energy and non-energy consumption estimates within the Energy chapter.

- Coking coal is used as a raw material (specifically as a reducing agent) in the blast furnace process to produce iron and steel, lead, and zinc and therefore is not used as a fuel for this process.
- Similarly, petroleum coke is used in multiple processes as a raw material, and is thus not used as a fuel in those applications. The processes in which petroleum coke is used include (1) ferroalloy production, (2) aluminum production (for the production of C anodes and cathodes), (3) titanium dioxide production (in the chloride process), (4) ammonia production, and (5) silicon carbide.
- Natural gas consumption is used for the production of ammonia, and blast furnace and coke oven gas used in iron and steel production.
- Residual fuel oil and other oil (>401F) are both used in the production of C black.
- Natural gas, distillate fuel, coal, and metallurgical coke are used to produce pig iron through the reduction of iron ore in the production of iron and steel.

**Step 3: Adjust for Conversion of Fossil Fuels and Exports**

First, a portion of industrial "other" coal that is accounted for in EIA coal combustion statistics is actually used to make "synthetic natural gas" via coal gasification at the Dakota Gasification Plant, a synthetic natural gas plant. The plant produces synthetic natural gas and byproduct $CO_2$. The synthetic natural gas enters the natural gas distribution system. Since October 2000, a portion of the $CO_2$ produced by the coal gasification plant has been exported to Canada by pipeline. The remainder of the $CO_2$ byproduct from the plant is released to the atmosphere. The energy in this synthetic natural gas enters the natural gas distribution stream, and is accounted for in EIA natural gas combustion statistics. Because this energy of the synthetic natural gas is already accounted for as natural gas combustion, this amount of energy is deducted from the industrial coal consumption statistics to avoid double counting. The exported $CO_2$ is not emitted to the atmosphere in the United States, and therefore the energy used to produce this amount of $CO_2$ is subtracted from industrial other coal.

**Step 4: Subtract Consumption for Non-Energy Use**

U.S. aggregate energy statistics include consumption of fossil fuels for non-energy purposes. Depending on the end-use, non-energy uses of fossil fuels can result in long term storage of some or all of the C contained in the fuel. For example, asphalt made from petroleum can sequester up to 100 percent of the C contained in the petroleum feedstock for

[3] Fuel consumption by U.S. territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands) is included in this report

extended periods of time. Other non-energy fossil fuel products, such as lubricants or plastics also store C, but can lose or emit some of this C when they are used and/or burned as waste. As the emission pathways of C used for non-energy purposes are vastly different than fuel combustion, these emissions are estimated separately in the Carbon Emitted in Products from Non-Energy Uses of Fossil Fuels section in this chapter. Therefore, the amount of fuels used for non-energy purposes, shown in Table A-33, was subtracted from total fuel consumption.

#### Step 5: Subtract Consumption of International Bunker Fuels

Emissions from international transport activities, or international bunker fuel consumption, are not included in national totals, as required by the IPCC (IPCC/UNEP/OECD/IEA 1997). There is currently disagreement internationally as to how these emissions should be allocated, and until this issue is resolved, countries are asked to report them separately. EIA energy statistics, however, include these bunker fuels—jet fuel for aircraft, and distillate fuel oil and residual fuel oil for marine shipping—as part of fuel consumption by the transportation end-use sector. Therefore, the amount of consumption for international bunker fuels was estimated and subtracted from total fuel consumption (see Table A-34). Emissions from international bunker fuels have been estimated separately and not included in national totals.[4]

#### Step 6: Determine the C Content of All Fuels

The C content of combusted fossil fuels was estimated by multiplying adjusted energy consumption (Columns 2 through 8 of Table A- 11 through Table A- 32) by fuel-specific C content coefficients (see Table A- 35 and Table A- 36) that reflect the amount of C per unit of energy in each fuel. The C content coefficients used in the U.S. inventory were derived by EIA from detailed fuel information and are similar to the C content coefficients contained in the IPCC's default methodology (IPCC/UNEP/OECD/IEA 1997), with modifications reflecting fuel qualities specific to the United States.

#### Step 7: Estimate $CO_2$ Emissions

Actual $CO_2$ emissions in the United States were summarized by major fuel (i.e., coal, petroleum, natural gas, geothermal) and consuming sector (i.e., residential, commercial, industrial, transportation, electricity generation, and U.S. territories). Emission estimates are expressed in teragrams of carbon dioxide equivalents (Tg $CO_2$ Eq.). To convert from C content to $CO_2$ emissions, the fraction of C that is oxidized was applied. This fraction was 100 percent based on guidance in IPCC (2006).

To determine total emissions by final end-use sector, emissions from electricity generation were distributed to each end-use sector according to its share of aggregate electricity consumption (see Table A-37). This pro-rated approach to allocating emissions from electricity generation may overestimate or underestimate emissions for particular sectors due to differences in the average C content of fuel mixes burned to generate electricity.

[4] Refer to the International Bunker Fuels section of the Energy chapter for a description of the methodology for distinguishing between bunker and non-bunker fuel consumption.

Table A-10: 2011 Energy Consumption Data by Fuel Type (TBtu) and Adjusted Energy Consumption Data

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total Consumption (TBtu)[a] | | | | | | | Adjustments (TBtu)[b] | | | | |
| | | | | | | | | | Unadjusted NEU Consumption | | | |
| Fuel Type | Res. | Comm. | Ind. | Trans. | Elec. | Terr. | Total | Bunker Fuel | Ind. | Trans. | Terr. | Total Adjusted Consumption |
| **Total Coal** | **6.5** | **52.6** | **1,021.5** | **NE** | **18,035.2** | **37.6** | **19,153.5** | | **71.2** | | | **19,082.3** |
| Residential Coal | 6.5 | | | | | | 6.5 | | | | | 6.5 |
| Commercial Coal | | 52.6 | | | | | 52.6 | | | | | 52.6 |
| Industrial Coking Coal | | | 60.8 | | | | 60.8 | | 60.8 | | | |
| Industrial Other Coal | | | 960.7 | | | | 960.7 | | 10.3 | | | 950.4 |
| Transportation Coal | | | | NE | | | NE | | | | | |
| Electric Power Coal | | | | | 18,035.2 | | 18,035.2 | | | | | 18,035.2 |
| U.S. Territory Coal (bit) | | | | | | 37.6 | 37.6 | | | | | 37.6 |
| **Natural Gas** | **4,823.9** | **3,228.1** | **7,968.6** | **732.5** | **7,711.5** | **27.8** | **24,492.4** | | **233.6** | | | **24,258.8** |
| **Total Petroleum** | **1,086.4** | **654.2** | **7,956.1** | **25,345.6** | **303.0** | **738.0** | **36,083.3** | **1,586.0** | **4,410.6** | **133.9** | **123.6** | **29,829.1** |
| Asphalt & Road Oil | | | 859.5 | | | | 859.5 | | 859.5 | | | |
| Aviation Gasoline | | | | 27.1 | | | 27.1 | | | | | 27.1 |
| Distillate Fuel Oil | 514.2 | 408.2 | 1,212.6 | 5,993.1 | 64.2 | 132.9 | 8,325.3 | 101.9 | 17.5 | | | 8,205.9 |
| Jet Fuel | | | | 2,949.8 | NA | 56.4 | 3,006.2 | 965.8 | | | | 2,040.4 |
| Kerosene | 17.9 | 3.0 | 4.5 | | | 7.2 | 32.5 | | | | | 32.5 |
| LPG | 554.2 | 146.4 | 2,205.1 | 30.7 | | 11.9 | 2,948.4 | | 2,054.3 | | | 894.1 |
| Lubricants | | | 141.8 | 133.9 | | 1.0 | 276.8 | | 141.8 | 133.9 | 1.0 | |
| Motor Gasoline | | 27.1 | 124.2 | 15,424.4 | | 242.2 | 15,818.0 | | | | | 15,818.0 |
| Residual Fuel | | 69.4 | 46.2 | 786.5 | 93.1 | 163.8 | 1,159.0 | 518.4 | | | | 640.6 |
| Other Petroleum | | | | | | | | | | | | |
| AvGas Blend Components | | | (0.0) | | | | (0.0) | | | | | (0.0) |
| Crude Oil | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | |
| Misc. Products | | | 163.3 | | | 122.6 | 285.9 | | 163.3 | | 122.6 | |
| Naphtha (<401 deg. F) | | | 486.4 | | | | 486.4 | | 486.4 | | | |
| Other Oil (>401 deg. F) | | | 394.4 | | | | 394.4 | | 394.4 | | | |
| Pentanes Plus | | | 152.9 | | | | 152.9 | | 27.3 | | | 125.6 |
| Petroleum Coke | | 0.2 | 648.3 | | 145.7 | | 794.2 | | 62.4 | | | 731.8 |
| Still Gas | | | 1,479.9 | | | | 1,479.9 | | 167.6 | | | 1,312.2 |
| Special Naphtha | | | 21.4 | | | | 21.4 | | 21.4 | | | |
| Unfinished Oils | | | 0.9 | | | | 0.9 | | | | | 0.9 |
| Waxes | | | 14.6 | | | | 14.6 | | 14.6 | | | |
| **Geothermal** | | | | | **56.8** | | **56.8** | | | | | **56.8** |
| **TOTAL (All Fuels)** | **5,916.7** | **3,935.0** | **16,946.2** | **26,078.1** | **26,106.5** | **803.5** | **79,786.0** | **1,586.0** | **4,715.4** | **133.9** | **123.6** | **73,227.0** |

[a] Expressed as gross calorific values (i.e., higher heating values).
[b] Adjustments are subtracted from total consumption estimates and include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
NE (Not Estimated)

Table A- 11: 2011 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **6.5** | **52.6** | **950.4** | **NE** | **18,035.2** | **37.6** | **19,082.3** | **0.6** | **5.0** | **90.0** | **NE** | **1,722.7** | **3.5** | **1,821.7** |
| Residential Coal | 6.5 | | | | | | 6.5 | 0.6 | | | | | | 0.6 |
| Commercial Coal | | 52.6 | | | | | 52.6 | | 5.0 | | | | | 5.0 |
| Industrial Other Coal | | | 950.4 | | | | 950.4 | | | 90.0 | | | | 90.0 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 18,035.2 | | 18,035.2 | | | | | 1,722.7 | | 1,722.7 |
| U.S. Territory Coal (bit) | | | | | | 37.6 | 37.6 | | | | | | 3.5 | 3.5 |
| **Natural Gas** | **4,823.9** | **3,228.1** | **7,735.0** | **732.5** | **7,711.5** | **27.8** | **24,258.8** | **255.7** | **171.1** | **410.0** | **38.8** | **408.7** | **1.5** | **1,285.8** |
| **Total Petroleum** | **1,086.4** | **654.2** | **3,545.5** | **23,625.7** | **303.0** | **614.4** | **29,829.1** | **73.5** | **46.6** | **266.6** | **1,703.3** | **26.6** | **44.7** | **2,161.3** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 27.1 | | | 27.1 | | | | 1.9 | | | 1.9 |
| Distillate Fuel Oil | 514.2 | 408.2 | 1,195.1 | 5,891.3 | 64.2 | 132.9 | 8,205.9 | 38.0 | 30.2 | 88.4 | 435.7 | 4.7 | 9.8 | 606.9 |
| Jet Fuel | | | | 1,984.0 | NA | 56.4 | 2,040.4 | | | | 143.3 | | 4.1 | 147.4 |
| Kerosene | 17.9 | 3.0 | 4.5 | | | 7.2 | 32.5 | 1.3 | 0.2 | 0.3 | | | 0.5 | 2.4 |
| LPG | 554.2 | 146.4 | 150.8 | 30.7 | | 11.9 | 894.1 | 34.2 | 9.0 | 9.3 | 1.9 | | 0.7 | 55.2 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 27.1 | 124.2 | 15,424.4 | | 242.2 | 15,818.0 | | 1.9 | 8.9 | 1,100.4 | | 17.3 | 1,128.4 |
| Residual Fuel | | 69.4 | 46.2 | 268.1 | 93.1 | 163.8 | 640.6 | | 5.2 | 3.5 | 20.1 | 7.0 | 12.3 | 48.1 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | (0.0) | | | | (0.0) | | | (0.0) | | | | (0.0) |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 125.6 | | | | 125.6 | | | 8.8 | | | | 8.8 |
| Petroleum Coke | | 0.2 | 585.9 | | 145.7 | | 731.8 | | 0.0 | 59.8 | | 14.9 | | 74.7 |
| Still Gas | | | 1,312.2 | | | | 1,312.2 | | | 87.5 | | | | 87.5 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | 0.9 | | | | 0.9 | | | 0.1 | | | | 0.1 |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **56.8** | | **56.8** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **5,916.7** | **3,935.0** | **12,230.8** | **24,358.2** | **26,106.5** | **679.8** | **73,227.0** | **329.8** | **222.7** | **766.5** | **1,742.1** | **2,158.5** | **49.7** | **5,269.3** |

[a] Expressed as gross calorific values (i.e., higher heating values).
[b] Adjustments are subtracted from total consumption estimates and include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
NE (Not Estimated)

Table A-12: 2010 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **7.4** | **59.8** | **1,015.9** | **NE** | **19,133.5** | **36.9** | **20,253.4** | **0.7** | **5.6** | **96.2** | **NE** | **1,827.6** | **3.4** | **1,933.5** |
| Residential Coal | 7.4 | | | | | | 7.4 | 0.7 | | | | | | 0.7 |
| Commercial Coal | | 59.8 | | | | | 59.8 | | 5.6 | | | | | 5.6 |
| Industrial Other Coal | | | 1,015.9 | | | | 1,015.9 | | | 96.2 | | | | 96.2 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 19,133.5 | | 19,133.5 | | | | | 1,827.6 | | 1,827.6 |
| U.S. Territory Coal (bit) | | | | | | 36.9 | 36.9 | | | | | | 3.4 | 3.4 |
| **Natural Gas** | **4,882.9** | **3,163.6** | **7,437.9** | **715.6** | **7,527.3** | **27.8** | **23,755.2** | **258.8** | **167.7** | **394.2** | **37.9** | **399.0** | **1.5** | **1,259.1** |
| **Total Petroleum** | **1,131.9** | **678.7** | **3,669.9** | **23,738.4** | **378.3** | **614.4** | **30,211.5** | **77.2** | **48.4** | **276.6** | **1,710.7** | **32.2** | **44.7** | **2,189.9** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 27.0 | | | 27.0 | | | | 1.9 | | | 1.9 |
| Distillate Fuel Oil | 572.6 | 403.1 | 1,146.7 | 5,674.0 | 80.3 | 132.9 | 8,009.7 | 42.3 | 29.8 | 84.8 | 419.6 | 5.9 | 9.8 | 592.4 |
| Jet Fuel | | | | 1,981.7 | NA | 56.4 | 2,038.1 | | | | 143.1 | | 4.1 | 147.2 |
| Kerosene | 29.1 | 4.8 | 7.3 | | | 7.2 | 48.5 | 2.1 | 0.4 | 0.5 | | | 0.5 | 3.5 |
| LPG | 530.1 | 140.1 | 156.0 | 29.4 | | 11.9 | 867.6 | 32.7 | 8.6 | 9.6 | 1.8 | | 0.7 | 53.5 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 53.1 | 243.3 | 15,769.5 | | 242.2 | 16,308.1 | | 3.8 | 17.4 | 1,125.0 | | 17.3 | 1,163.4 |
| Residual Fuel | | 77.3 | 57.2 | 256.7 | 154.1 | 163.8 | 709.0 | | 5.8 | 4.3 | 19.3 | 11.6 | 12.3 | 53.2 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | (0.2) | | | | (0.2) | | | (0.0) | | | | (0.0) |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 77.8 | | | | 77.8 | | | 5.4 | | | | 5.4 |
| Petroleum Coke | | 0.4 | 620.9 | | 143.9 | | 765.2 | | 0.0 | 63.4 | | 14.7 | | 78.1 |
| Still Gas | | | 1,314.1 | | | | 1,314.1 | | | 87.7 | | | | 87.7 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | 46.7 | | | | 46.7 | | | 3.5 | | | | 3.5 |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **51.9** | | **51.9** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,022.2** | **3,902.2** | **12,123.7** | **24,454.0** | **27,091.0** | **679.1** | **74,272.1** | **336.7** | **221.8** | **767.0** | **1,748.6** | **2,259.2** | **49.6** | **5,382.9** |

[a] Expressed as gross calorific values (i.e., higher heating values).
[b] Adjustments are subtracted from total consumption estimates and include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
NE (Not Estimated)

Table A-13: 2009 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **7.8** | **63.0** | **880.4** | **NE** | **18,225.3** | **36.9** | **19,213.5** | **0.7** | **5.9** | **83.3** | **NE** | **1,740.9** | **3.4** | **1,834.3** |
| Residential Coal | 7.8 | | | | | | 7.8 | 0.7 | | | | | | 0.7 |
| Commercial Coal | | 63.0 | | | | | 63.0 | | 5.9 | | | | | 5.9 |
| Industrial Other Coal | | | 880.4 | | | | 880.4 | | | 83.3 | | | | 83.3 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 18,225.3 | | 18,225.3 | | | | | 1,740.9 | | 1,740.9 |
| U.S. Territory Coal (bit) | | | | | | 36.9 | 36.9 | | | | | | 3.4 | 3.4 |
| **Natural Gas** | **4,883.1** | **3,186.6** | **7,119.4** | **714.9** | **7,022.4** | **27.4** | **22,953.7** | **258.8** | **168.9** | **377.3** | **37.9** | **372.2** | **1.5** | **1,216.6** |
| **Total Petroleum** | **1,164.9** | **697.0** | **3,524.2** | **23,620.6** | **389.9** | **535.5** | **29,932.2** | **79.4** | **49.7** | **265.4** | **1,701.6** | **33.0** | **39.0** | **2,168.1** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 26.6 | | | 26.6 | | | | 1.8 | | | 1.8 |
| Distillate Fuel Oil | 590.2 | 405.3 | 1,065.4 | 5,449.6 | 70.1 | 83.4 | 7,664.0 | 43.6 | 30.0 | 78.8 | 403.0 | 5.2 | 6.2 | 566.8 |
| Jet Fuel | | | | 2,092.6 | NA | 61.5 | 2,154.1 | | | | 151.1 | | 4.4 | 155.6 |
| Kerosene | 27.7 | 4.2 | 4.4 | | | 8.0 | 44.3 | 2.0 | 0.3 | 0.3 | | | 0.6 | 3.2 |
| LPG | 547.1 | 138.9 | 162.5 | 28.0 | | 15.0 | 891.4 | 33.8 | 8.6 | 10.0 | 1.7 | | 0.9 | 55.0 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 72.8 | 333.7 | 15,818.3 | | 202.0 | 16,426.9 | | 5.2 | 23.8 | 1,128.5 | | 14.4 | 1,171.9 |
| Residual Fuel | | 75.6 | 43.3 | 205.4 | 181.0 | 165.7 | 670.9 | | 5.7 | 3.3 | 15.4 | 13.6 | 12.4 | 50.4 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | (0.8) | | | | (0.8) | | | (0.1) | | | | (0.1) |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 54.4 | | | | 54.4 | | | 3.8 | | | | 3.8 |
| Petroleum Coke | | 0.3 | 618.0 | | 138.9 | | 757.2 | | 0.0 | 63.1 | | 14.2 | | 77.3 |
| Still Gas | | | 1,321.1 | | | | 1,321.1 | | | 88.1 | | | | 88.1 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (77.8) | | | | (77.8) | | | (5.8) | | | | (5.8) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **51.2** | | **51.2** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,055.8** | **3,946.6** | **11,524.0** | **24,335.5** | **25,688.9** | **599.8** | **72,150.6** | **339.0** | **224.6** | **726.1** | **1,739.5** | **2,146.4** | **43.8** | **5,219.4** |

[a] Expressed as gross calorific values (i.e., higher heating values).
[b] Adjustments are subtracted from total consumption estimates and include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
NE (Not Estimated)

Table A-14: 2008 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **7.7** | **69.1** | **1,083.9** | **NE** | **20,513.0** | **36.9** | **21,710.4** | **0.7** | **6.5** | **102.6** | **NE** | **1,959.4** | **3.4** | **2,072.6** |
| Residential Coal | 7.7 | | | | | | 7.7 | 0.7 | | | | | | 0.7 |
| Commercial Coal | | 69.1 | | | | | 69.1 | | 6.5 | | | | | 6.5 |
| Industrial Other Coal | | | 1,083.9 | | | | 1,083.9 | | | 102.6 | | | | 102.6 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 20,513.0 | | 20,513.0 | | | | | 1,959.4 | | 1,959.4 |
| U.S. Territory Coal (bit) | | | | | | 36.9 | 36.9 | | | | | | 3.4 | 3.4 |
| **Natural Gas** | **5,010.1** | **3,228.4** | **7,566.3** | **692.1** | **6,828.9** | **29.3** | **23,355.1** | **265.5** | **171.1** | **401.0** | **36.7** | **361.9** | **1.6** | **1,237.9** |
| **Total Petroleum** | **1,214.7** | **669.2** | **4,037.6** | **24,442.7** | **467.7** | **492.3** | **31,324.2** | **83.1** | **47.4** | **302.9** | **1,762.0** | **39.2** | **36.0** | **2,270.6** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 28.3 | | | 28.3 | | | | 2.0 | | | 2.0 |
| Distillate Fuel Oil | 640.7 | 355.9 | 1,197.9 | 5,996.5 | 73.1 | 110.3 | 8,374.4 | 47.4 | 26.3 | 88.6 | 443.5 | 5.4 | 8.2 | 619.3 |
| Jet Fuel | | | | 2,268.9 | NA | 35.0 | 2,303.9 | | | | 163.9 | | 2.5 | 166.4 |
| Kerosene | 21.3 | 4.3 | 4.0 | | | 5.9 | 35.4 | 1.6 | 0.3 | 0.3 | | | 0.4 | 2.6 |
| LPG | 552.7 | 158.0 | 176.8 | 40.1 | | 15.7 | 943.4 | 34.1 | 9.7 | 10.9 | 2.5 | | 1.0 | 58.2 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 77.7 | 424.5 | 15,843.9 | | 136.1 | 16,482.1 | | 5.5 | 30.3 | 1,130.3 | | 9.7 | 1,175.8 |
| Residual Fuel | | 73.2 | 135.6 | 265.0 | 240.4 | 189.3 | 903.5 | | 5.5 | 10.2 | 19.9 | 18.1 | 14.2 | 67.8 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 0.1 | | | | 0.1 | | | 0.0 | | | | 0.0 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 86.8 | | | | 86.8 | | | 6.1 | | | | 6.1 |
| Petroleum Coke | | 0.3 | 642.6 | | 154.2 | | 797.1 | | 0.0 | 65.6 | | 15.7 | | 81.4 |
| Still Gas | | | 1,423.0 | | | | 1,423.0 | | | 94.9 | | | | 94.9 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (53.7) | | | | (53.7) | | | (4.0) | | | | (4.0) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **50.6** | | **50.6** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,232.4** | **3,966.7** | **12,687.8** | **25,134.8** | **27,860.2** | **558.4** | **76,440.4** | **349.3** | **225.1** | **806.5** | **1,798.6** | **2,360.9** | **41.0** | **5,581.5** |

[a] Expressed as gross calorific values (i.e., higher heating values).
[b] Adjustments are subtracted from total consumption estimates and include biofuels, conversion of fossil fuels, non-energy use (seeTable A-33 ), and international bunker fuel consumption (see Table A-34).
NE (Not Estimated)

Table A-15: 2007 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **7.8** | **70.0** | **1,130.8** | **NE** | **20,807.7** | **36.9** | **22,053.2** | **0.7** | **6.7** | **107.0** | **NE** | **1,987.3** | **3.4** | **2,105.1** |
| Residential Coal | 7.8 | | | | | | 7.8 | 0.7 | | | | | | 0.7 |
| Commercial Coal | | 70.0 | | | | | 70.0 | | 6.7 | | | | | 6.7 |
| Industrial Other Coal | | | 1,130.8 | | | | 1,130.8 | | | 107.0 | | | | 107.0 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 20,807.7 | | 20,807.7 | | | | | 1,987.3 | | 1,987.3 |
| U.S. Territory Coal (bit) | | | | | | 36.9 | 36.9 | | | | | | 3.4 | 3.4 |
| **Natural Gas** | **4,835.4** | **3,085.1** | **7,521.3** | **663.5** | **7,005.2** | **26.7** | **23,137.2** | **256.3** | **163.5** | **398.6** | **35.2** | **371.3** | **1.4** | **1,226.3** |
| **Total Petroleum** | **1,224.9** | **680.6** | **4,530.9** | **25,764.5** | **657.1** | **551.7** | **33,409.7** | **84.6** | **48.7** | **338.7** | **1,864.4** | **53.9** | **40.4** | **2,430.8** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 31.6 | | | 31.6 | | | | 2.2 | | | 2.2 |
| Distillate Fuel Oil | 697.3 | 368.7 | 1,185.5 | 6,439.7 | 89.3 | 136.5 | 8,917.0 | 51.6 | 27.3 | 87.7 | 476.3 | 6.6 | 10.1 | 659.5 |
| Jet Fuel | | | | 2,414.7 | NA | 55.5 | 2,470.2 | | | | 174.4 | | 4.0 | 178.4 |
| Kerosene | 43.9 | 9.2 | 13.4 | | | 5.2 | 71.8 | 3.2 | 0.7 | 1.0 | | | 0.4 | 5.3 |
| LPG | 483.7 | 121.4 | 334.3 | 21.9 | | 11.6 | 973.0 | 29.8 | 7.5 | 20.6 | 1.4 | | 0.7 | 60.0 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 105.6 | 528.4 | 16,470.5 | | 157.0 | 17,261.4 | | 7.6 | 37.9 | 1,181.2 | | 11.3 | 1,238.0 |
| Residual Fuel | | 75.4 | 130.4 | 386.1 | 396.6 | 185.9 | 1,174.4 | | 5.7 | 9.8 | 29.0 | 29.8 | 14.0 | 88.2 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 1.8 | | | | 1.8 | | | 0.1 | | | | 0.1 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 84.5 | | | | 84.5 | | | 5.9 | | | | 5.9 |
| Petroleum Coke | | 0.4 | 704.7 | | 171.2 | | 876.3 | | 0.0 | 72.0 | | 17.5 | | 89.5 |
| Still Gas | | | 1,482.6 | | | | 1,482.6 | | | 98.9 | | | | 98.9 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | 65.2 | | | | 65.2 | | | 4.8 | | | | 4.8 |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **49.9** | | **49.9** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,068.1** | **3,835.7** | **13,183.0** | **26,428.0** | **28,520.0** | **615.3** | **78,650.0** | **341.6** | **218.9** | **844.4** | **1,899.6** | **2,412.8** | **45.2** | **5,762.6** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-16: 2006 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **6.4** | **64.8** | **1,188.8** | **NE** | **20,461.9** | **36.9** | **21,758.7** | **0.6** | **6.2** | **112.6** | **NE** | **1,953.7** | **3.4** | **2,076.6** |
| Residential Coal | 6.4 | | | | | | 6.4 | 0.6 | | | | | | 0.6 |
| Commercial Coal | | 64.8 | | | | | 64.8 | | 6.2 | | | | | 6.2 |
| Industrial Other Coal | | | 1,188.8 | | | | 1,188.8 | | | 112.6 | | | | 112.6 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 20,461.9 | | 20,461.9 | | | | | 1,953.7 | | 1,953.7 |
| U.S. Territory Coal (bit) | | | | | | 36.9 | 36.9 | | | | | | 3.4 | 3.4 |
| **Natural Gas** | **4,475.9** | **2,901.7** | **7,323.2** | **625.0** | **6,375.1** | **26.14** | **21,727.0** | **237.3** | **153.8** | **388.2** | **33.1** | **338.0** | **1.4** | **1,151.8** |
| **Total Petroleum** | **1,204.9** | **677.7** | **4,641.1** | **25,643.7** | **648.1** | **620.9** | **33,436.4** | **83.6** | **48.5** | **347.3** | **1,848.9** | **54.4** | **45.5** | **2,428.1** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 33.4 | | | 33.4 | | | | 2.3 | | | 2.3 |
| Distillate Fuel Oil | 693.0 | 390.5 | 1,199.4 | 6,358.6 | 73.7 | 90.2 | 8,805.3 | 51.3 | 28.9 | 88.7 | 470.3 | 5.4 | 6.7 | 651.2 |
| Jet Fuel | | | | 2,400.8 | NA | 76.1 | 2,476.9 | | | | 173.4 | | 5.5 | 178.9 |
| Kerosene | 66.4 | 15.2 | 29.6 | | | 4.4 | 115.5 | 4.9 | 1.1 | 2.2 | | | 0.3 | 8.5 |
| LPG | 445.5 | 123.2 | 316.9 | 27.5 | | 6.6 | 919.6 | 27.5 | 7.6 | 19.6 | 1.7 | | 0.4 | 56.8 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 73.3 | 566.7 | 16,517.0 | | 188.8 | 17,345.9 | | 5.2 | 40.4 | 1,178.2 | | 13.5 | 1,237.4 |
| Residual Fuel | | 75.3 | 176.4 | 306.3 | 360.5 | 254.8 | 1,173.3 | | 5.7 | 13.2 | 23.0 | 27.1 | 19.1 | 88.1 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 0.6 | | | | 0.6 | | | 0.0 | | | | 0.0 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 64.6 | | | | 64.6 | | | 4.5 | | | | 4.5 |
| Petroleum Coke | | 0.3 | 720.5 | | 213.9 | | 934.6 | | 0.0 | 73.6 | | 21.8 | | 95.4 |
| Still Gas | | | 1,496.1 | | | | 1,496.1 | | | 99.8 | | | | 99.8 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | 70.3 | | | | 70.3 | | | 5.2 | | | | 5.2 |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **49.7** | | **49.7** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **5,687.2** | **3,644.2** | **13,153.1** | **26,268.7** | **27,534.8** | **683.9** | **76,971.8** | **321.5** | **208.6** | **848.1** | **1,882.0** | **2,346.4** | **50.3** | **5,656.9** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-17: 2005 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **8.4** | **97.0** | **1,219.1** | **NE** | **20,737.2** | **32.7** | **22,094.5** | **0.8** | **9.3** | **115.3** | **NE** | **1,983.8** | **3.0** | **2,112.3** |
| Residential Coal | 8.4 | | | | | | 8.4 | 0.8 | | | | | | 0.8 |
| Commercial Coal | | 97.0 | | | | | 97.0 | | 9.3 | | | | | 9.3 |
| Industrial Other Coal | | | 1,219.1 | | | | 1,219.1 | | | 115.3 | | | | 115.3 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 20,737.2 | | 20,737.2 | | | | | 1,983.8 | | 1,983.8 |
| U.S. Territory Coal (bit) | | | | | | 32.7 | 32.7 | | | | | | 3.0 | 3.0 |
| **Natural Gas** | **4,946.4** | **3,073.2** | **7,329.7** | **623.9** | **6,014.5** | **24.3** | **22,012.0** | **262.2** | **162.9** | **388.5** | **33.1** | **318.8** | **1.3** | **1,166.7** |
| **Total Petroleum** | **1,369.2** | **716.0** | **4,257.4** | **25,592.4** | **1,234.5** | **623.3** | **33,792.8** | **94.9** | **51.3** | **319.6** | **1,839.0** | **99.2** | **45.7** | **2,449.6** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 35.4 | | | 35.4 | | | | 2.4 | | | 2.4 |
| Distillate Fuel Oil | 772.6 | 404.7 | 1,128.9 | 6,193.8 | 114.6 | 121.3 | 8,735.9 | 57.1 | 29.9 | 83.5 | 458.1 | 8.5 | 9.0 | 646.1 |
| Jet Fuel | | | | 2,348.8 | NA | 66.0 | 2,414.8 | | | | 169.6 | | 4.8 | 174.4 |
| Kerosene | 83.8 | 21.6 | 39.1 | | | 5.8 | 150.2 | 6.1 | 1.6 | 2.9 | | | 0.4 | 11.0 |
| LPG | 512.9 | 131.4 | 292.8 | 28.2 | | 0.8 | 966.0 | 31.7 | 8.1 | 18.1 | 1.7 | | 0.0 | 59.6 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 42.2 | 328.2 | 16,729.7 | | 194.3 | 17,294.4 | | 3.0 | 23.3 | 1,187.8 | | 13.8 | 1,227.9 |
| Residual Fuel | | 115.8 | 237.4 | 256.4 | 876.5 | 235.2 | 1,721.3 | | 8.7 | 17.8 | 19.3 | 65.8 | 17.7 | 129.3 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 8.3 | | | | 8.3 | | | 0.6 | | | | 0.6 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 88.4 | | | | 88.4 | | | 6.2 | | | | 6.2 |
| Petroleum Coke | | 0.3 | 702.1 | | 243.5 | | 945.9 | | 0.0 | 71.7 | | 24.9 | | 96.6 |
| Still Gas | | | 1,429.4 | | | | 1,429.4 | | | 95.4 | | | | 95.4 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | 2.8 | | | | 2.8 | | | 0.2 | | | | 0.2 |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **50.1** | | **50.1** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,324.0** | **3,886.2** | **12,806.2** | **26,216.3** | **28,036.4** | **680.4** | **77,949.5** | **357.9** | **223.5** | **823.4** | **1,872.0** | **2,402.1** | **50.0** | **5,729.0** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-18: 2004 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **11.4** | **102.9** | **1,262.0** | **NE** | **20,305.0** | **32.0** | **21,713.3** | **1.1** | **9.8** | **118.3** | **NE** | **1,943.1** | **2.9** | **2,075.1** |
| Residential Coal | 11.4 | | | | | | 11.4 | 1.1 | | | | | | 1.1 |
| Commercial Coal | | 102.9 | | | | | 102.9 | | 9.8 | | | | | 9.8 |
| Industrial Other Coal | | | 1,262.0 | | | | 1,262.0 | | | 118.3 | | | | 118.3 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 20,305.0 | | 20,305.0 | | | | | 1,943.1 | | 1,943.1 |
| U.S. Territory Coal (bit) | | | | | | 32.0 | 32.0 | | | | | | 2.9 | 2.9 |
| **Natural Gas** | **4,980.8** | **3,201.0** | **7,913.5** | **602.0** | **5,594.9** | **24.6** | **22,316.9** | **264.1** | **169.7** | **419.6** | **31.9** | **296.7** | **1.3** | **1,183.4** |
| **Total Petroleum** | **1,474.6** | **766.7** | **4,109.4** | **25,245.3** | **1,212.4** | **653.6** | **33,461.9** | **102.7** | **54.9** | **308.7** | **1,814.4** | **96.9** | **47.9** | **2,425.6** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 31.2 | | | 31.2 | | | | 2.2 | | | 2.2 |
| Distillate Fuel Oil | 878.1 | 447.0 | 1,139.6 | 5,917.7 | 111.3 | 134.4 | 8,628.1 | 64.9 | 33.1 | 84.3 | 437.7 | 8.2 | 9.9 | 638.1 |
| Jet Fuel | | | | 2,240.4 | NA | 68.8 | 2,309.1 | | | | 161.8 | | 5.0 | 166.8 |
| Kerosene | 84.8 | 20.5 | 28.2 | | | 6.0 | 139.5 | 6.2 | 1.5 | 2.1 | | | 0.4 | 10.2 |
| LPG | 511.7 | 152.0 | 305.3 | 19.1 | | 0.8 | 989.0 | 31.6 | 9.4 | 18.9 | 1.2 | | 0.0 | 61.1 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 24.4 | 203.2 | 16,850.4 | | 198.6 | 17,276.7 | | 1.7 | 14.4 | 1,197.6 | | 14.1 | 1,227.9 |
| Residual Fuel | | 122.5 | 204.7 | 186.4 | 879.0 | 245.0 | 1,637.6 | | 9.2 | 15.4 | 14.0 | 66.0 | 18.4 | 123.0 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 10.6 | | | | 10.6 | | | 0.7 | | | | 0.7 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 94.7 | | | | 94.7 | | | 6.6 | | | | 6.6 |
| Petroleum Coke | | 0.3 | 715.3 | | 222.1 | | 937.6 | | 0.0 | 73.0 | | 22.7 | | 95.7 |
| Still Gas | | | 1,483.3 | | | | 1,483.3 | | | 99.0 | | | | 99.0 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (75.6) | | | | (75.6) | | | (5.6) | | | | (5.6) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **50.5** | | **50.5** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,466.9** | **4,070.6** | **13,284.9** | **25,847.2** | **27,162.9** | **710.2** | **77,542.7** | **367.9** | **234.4** | **846.6** | **1,846.3** | **2,337.0** | **52.2** | **5,684.5** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-19: 2003 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **12.2** | **82.0** | **1,248.8** | **NE** | **20,184.7** | **33.9** | **21,561.7** | **1.2** | **7.8** | **117.0** | **NE** | **1,931.0** | **3.1** | **2,060.1** |
| Residential Coal | 12.2 | | | | | | 12.2 | 1.2 | | | | | | 1.2 |
| Commercial Coal | | 82.0 | | | | | 82.0 | | 7.8 | | | | | 7.8 |
| Industrial Other Coal | | | 1,248.8 | | | | 1,248.8 | | | 117.0 | | | | 117.0 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 20,184.7 | | 20,184.7 | | | | | 1,931.0 | | 1,931.0 |
| U.S. Territory Coal (bit) | | | | | | 33.9 | 33.9 | | | | | | 3.1 | 3.1 |
| **Natural Gas** | **5,209.4** | **3,260.9** | **7,845.1** | **627.4** | **5,246.2** | **26.9** | **22,216.0** | **275.9** | **172.7** | **415.4** | **33.2** | **277.8** | **1.4** | **1,176.4** |
| **Total Petroleum** | **1,466.1** | **762.0** | **3,852.3** | **24,621.3** | **1,205.0** | **621.8** | **32,528.5** | **101.8** | **54.5** | **290.4** | **1,767.5** | **95.0** | **45.3** | **2,354.5** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 30.2 | | | 30.2 | | | | 2.1 | | | 2.1 |
| Distillate Fuel Oil | 851.3 | 453.1 | 1,055.5 | 5,710.9 | 161.0 | 120.5 | 8,352.3 | 63.0 | 33.5 | 78.1 | 422.4 | 11.9 | 8.9 | 617.7 |
| Jet Fuel | | | | 2,164.1 | NA | 76.1 | 2,240.2 | | | | 156.3 | | 5.5 | 161.8 |
| Kerosene | 70.3 | 18.6 | 24.1 | | | 10.7 | 123.7 | 5.1 | 1.4 | 1.8 | | | 0.8 | 9.1 |
| LPG | 544.5 | 156.9 | 245.6 | 16.5 | | 10.5 | 974.0 | 33.7 | 9.7 | 15.2 | 1.0 | | 0.7 | 60.2 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 22.0 | 119.1 | 16,600.4 | | 210.1 | 16,951.6 | | 1.6 | 8.5 | 1,178.3 | | 14.9 | 1,203.2 |
| Residual Fuel | | 111.1 | 176.4 | 99.1 | 869.4 | 193.9 | 1,450.0 | | 8.3 | 13.2 | 7.4 | 65.3 | 14.6 | 108.9 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 7.5 | | | | 7.5 | | | 0.5 | | | | 0.5 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 95.3 | | | | 95.3 | | | 6.7 | | | | 6.7 |
| Petroleum Coke | | 0.3 | 701.9 | | 174.7 | | 876.8 | | 0.0 | 71.7 | | 17.8 | | 89.5 |
| Still Gas | | | 1,477.3 | | | | 1,477.3 | | | 98.6 | | | | 98.6 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (50.4) | | | | (50.4) | | | (3.7) | | | | (3.7) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **49.2** | | **49.2** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,687.8** | **4,104.9** | **12,946.2** | **25,248.7** | **26,685.2** | **682.6** | **76,355.4** | **378.8** | **235.0** | **822.8** | **1,800.8** | **2,304.2** | **49.9** | **5,591.4** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-20: 2002 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **12.2** | **89.8** | **1,243.7** | **NE** | **19,782.8** | **10.8** | **21,139.3** | **1.2** | **8.6** | **116.6** | **NE** | **1,889.9** | **1.0** | **2,017.2** |
| Residential Coal | 12.2 | | | | | | 12.2 | 1.2 | | | | | | 1.2 |
| Commercial Coal | | 89.8 | | | | | 89.8 | | 8.6 | | | | | 8.6 |
| Industrial Other Coal | | | 1,243.7 | | | | 1,243.7 | | | 116.6 | | | | 116.6 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 19,782.8 | | 19,782.8 | | | | | 1,889.9 | | 1,889.9 |
| U.S. Territory Coal (bit) | | | | | | 10.8 | 10.8 | | | | | | 1.0 | 1.0 |
| **Natural Gas** | **4,995.0** | **3,212.5** | **8,086.3** | **698.9** | **5,766.8** | **22.8** | **22,782.3** | **264.7** | **170.3** | **428.6** | **37.0** | **305.7** | **1.2** | **1,207.5** |
| **Total Petroleum** | **1,358.9** | **645.4** | **3,703.7** | **24,536.1** | **961.3** | **556.8** | **31,762.2** | **93.9** | **46.1** | **278.8** | **1,762.9** | **76.8** | **40.6** | **2,299.1** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 33.7 | | | 33.7 | | | | 2.3 | | | 2.3 |
| Distillate Fuel Oil | 761.8 | 393.4 | 1,048.4 | 5,595.9 | 127.4 | 92.8 | 8,019.7 | 56.3 | 29.1 | 77.5 | 413.9 | 9.4 | 6.9 | 593.1 |
| Jet Fuel | | | | 2,140.5 | NA | 61.8 | 2,202.2 | | | | 154.6 | | 4.5 | 159.1 |
| Kerosene | 59.9 | 15.9 | 13.8 | | | 8.2 | 97.9 | 4.4 | 1.2 | 1.0 | | | 0.6 | 7.2 |
| LPG | 537.1 | 140.8 | 317.7 | 14.3 | | 11.2 | 1,021.1 | 33.2 | 8.7 | 19.6 | 0.9 | | 0.7 | 63.1 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 15.2 | 104.1 | 16,523.8 | | 189.4 | 16,832.5 | | 1.1 | 7.4 | 1,174.1 | | 13.5 | 1,196.0 |
| Residual Fuel | | 79.8 | 146.1 | 227.9 | 658.7 | 193.6 | 1,306.1 | | 6.0 | 11.0 | 17.1 | 49.5 | 14.5 | 98.1 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 7.5 | | | | 7.5 | | | 0.5 | | | | 0.5 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 102.2 | | | | 102.2 | | | 7.2 | | | | 7.2 |
| Petroleum Coke | | 0.2 | 696.3 | | 175.2 | | 871.7 | | 0.0 | 71.1 | | 17.9 | | 89.0 |
| Still Gas | | | 1,403.3 | | | | 1,403.3 | | | 93.6 | | | | 93.6 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (135.7) | | | | (135.7) | | | (10.1) | | | | (10.1) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **49.4** | | **49.4** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,366.1** | **3,947.7** | **13,033.7** | **25,235.0** | **26,560.4** | **590.4** | **75,733.2** | **359.8** | **224.9** | **824.0** | **1,799.9** | **2,272.7** | **42.8** | **5,524.1** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-21: 2001 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **12.0** | **96.9** | **1,358.4** | **NE** | **19,613.7** | **3.8** | **21,084.8** | **1.1** | **9.2** | **127.8** | **NE** | **1,869.8** | **0.4** | **2,008.4** |
| Residential Coal | 12.0 | | | | | | 12.0 | 1.1 | | | | | | 1.1 |
| Commercial Coal | | 96.9 | | | | | 96.9 | | 9.2 | | | | | 9.2 |
| Industrial Other Coal | | | 1,358.4 | | | | 1,358.4 | | | 127.8 | | | | 127.8 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 19,613.7 | | 19,613.7 | | | | | 1,869.8 | | 1,869.8 |
| U.S. Territory Coal (bit) | | | | | | 3.8 | 3.8 | | | | | | 0.4 | 0.4 |
| **Natural Gas** | **4,889.0** | **3,097.3** | **7,949.0** | **658.0** | **5,458.1** | **22.9** | **22,074.3** | **259.1** | **164.2** | **421.3** | **34.9** | **289.3** | **1.2** | **1,170.0** |
| **Total Petroleum** | **1,463.0** | **718.6** | **3,826.8** | **24,041.6** | **1,276.6** | **632.2** | **31,958.8** | **101.8** | **51.5** | **287.9** | **1,724.8** | **98.5** | **46.2** | **2,310.6** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 34.9 | | | 34.9 | | | | 2.4 | | | 2.4 |
| Distillate Fuel Oil | 842.2 | 471.4 | 1,181.8 | 5,417.0 | 170.5 | 109.4 | 8,192.3 | 62.3 | 34.9 | 87.4 | 400.6 | 12.6 | 8.1 | 605.9 |
| Jet Fuel | | | | 2,218.2 | NA | 98.9 | 2,317.0 | | | | 160.2 | | 7.1 | 167.3 |
| Kerosene | 95.1 | 31.4 | 23.2 | | | 0.9 | 150.6 | 7.0 | 2.3 | 1.7 | | | 0.1 | 11.0 |
| LPG | 525.7 | 142.7 | 292.4 | 13.7 | | 7.0 | 981.5 | 32.5 | 8.8 | 18.1 | 0.8 | | 0.4 | 60.7 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 3.1 | 24.2 | 16,198.3 | | 187.6 | 16,413.2 | | 0.2 | 1.7 | 1,148.7 | | 13.3 | 1,164.0 |
| Residual Fuel | | 69.9 | 146.7 | 159.5 | 1,002.8 | 228.4 | 1,607.2 | | 5.2 | 11.0 | 12.0 | 75.3 | 17.2 | 120.7 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 6.1 | | | | 6.1 | | | 0.4 | | | | 0.4 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 114.0 | | | | 114.0 | | | 8.0 | | | | 8.0 |
| Petroleum Coke | | 0.2 | 683.3 | | 103.2 | | 786.7 | | 0.0 | 69.8 | | 10.5 | | 80.3 |
| Still Gas | | | 1,430.7 | | | | 1,430.7 | | | 95.5 | | | | 95.5 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (75.4) | | | | (75.4) | | | (5.6) | | | | (5.6) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **46.9** | | **46.9** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,364.0** | **3,912.7** | **13,134.3** | **24,699.7** | **26,395.2** | **658.9** | **75,164.7** | **362.0** | **224.9** | **837.0** | **1,759.7** | **2,257.9** | **47.8** | **5,489.3** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-22: 2000 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **11.4** | **91.9** | **1,348.8** | **NE** | **20,220.2** | **10.3** | **21,682.4** | **1.1** | **8.8** | **127.3** | **NE** | **1,927.4** | **0.9** | **2,065.5** |
| Residential Coal | 11.4 | | | | | | 11.4 | 1.1 | | | | | | 1.1 |
| Commercial Coal | | 91.9 | | | | | 91.9 | | 8.8 | | | | | 8.8 |
| Industrial Other Coal | | | 1,348.8 | | | | 1,348.8 | | | 127.3 | | | | 127.3 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 20,220.2 | | 20,220.2 | | | | | 1,927.4 | | 1,927.4 |
| U.S. Territory Coal (bit) | | | | | | 10.3 | 10.3 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | **5,104.6** | **3,251.5** | **8,656.0** | **672.0** | **5,293.4** | **12.7** | **22,990.2** | **270.7** | **172.5** | **459.1** | **35.6** | **280.8** | **0.7** | **1,219.4** |
| **Total Petroleum** | **1,427.5** | **694.0** | **3,425.7** | **24,358.3** | **1,144.3** | **471.7** | **31,521.4** | **98.8** | **49.6** | **257.9** | **1,748.1** | **88.4** | **34.2** | **2,277.0** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 36.3 | | | 36.3 | | | | 2.5 | | | 2.5 |
| Distillate Fuel Oil | 778.0 | 422.2 | 1,003.7 | 5,442.4 | 174.8 | 71.3 | 7,892.5 | 57.5 | 31.2 | 74.2 | 402.5 | 12.9 | 5.3 | 583.7 |
| Jet Fuel | | | | 2,409.5 | NA | 74.1 | 2,483.5 | | | | 174.0 | | 5.3 | 179.4 |
| Kerosene | 94.6 | 29.7 | 15.6 | | | 2.4 | 142.2 | 6.9 | 2.2 | 1.1 | | | 0.2 | 10.4 |
| LPG | 554.9 | 150.4 | 361.4 | 11.9 | | 8.0 | 1,086.6 | 34.4 | 9.3 | 22.4 | 0.7 | | 0.5 | 67.3 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | | | 16,014.8 | | 185.1 | 16,199.8 | | | | 1,135.0 | | 13.1 | 1,148.1 |
| Residual Fuel | | 91.6 | 184.1 | 443.5 | 870.8 | 130.9 | 1,720.8 | | 6.9 | 13.8 | 33.3 | 65.4 | 9.8 | 129.2 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 3.8 | | | | 3.8 | | | 0.3 | | | | 0.3 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 125.2 | | | | 125.2 | | | 8.8 | | | | 8.8 |
| Petroleum Coke | | 0.2 | 697.3 | | 98.6 | | 796.2 | | 0.0 | 71.2 | | 10.1 | | 81.3 |
| Still Gas | | | 1,435.6 | | | | 1,435.6 | | | 95.8 | | | | 95.8 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (401.2) | | | | (401.2) | | | (29.7) | | | | (29.7) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **48.1** | | **48.1** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,543.4** | **4,037.4** | **13,430.5** | **25,030.3** | **26,706.0** | **494.6** | **76,242.1** | **370.7** | **230.8** | **844.3** | **1,783.7** | **2,296.9** | **35.9** | **5,562.2** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-23: 1999 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **14.0** | **102.5** | **1,372.8** | **NE** | **19,279.5** | **10.2** | **20,779.0** | **1.3** | **9.8** | **129.9** | **NE** | **1,836.4** | **0.9** | **1,978.3** |
| Residential Coal | 14.0 | | | | | | 14.0 | 1.3 | | | | | | 1.3 |
| Commercial Coal | | 102.5 | | | | | 102.5 | | 9.8 | | | | | 9.8 |
| Industrial Other Coal | | | 1,372.8 | | | | 1,372.8 | | | 129.9 | | | | 129.9 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 19,279.5 | | 19,279.5 | | | | | 1,836.4 | | 1,836.4 |
| U.S. Territory Coal (bit) | | | | | | 10.2 | 10.2 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | **4,834.9** | **3,115.0** | **8,424.6** | **675.3** | **4,902.1** | | **21,952.0** | **256.3** | **165.1** | **446.6** | **35.8** | **259.9** | | **1,163.8** |
| **Total Petroleum** | **1,342.1** | **613.9** | **3,562.2** | **23,722.1** | **1,211.4** | **461.0** | **30,912.8** | **92.8** | **43.8** | **268.1** | **1,700.7** | **93.8** | **33.5** | **2,232.8** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 39.2 | | | 39.2 | | | | 2.7 | | | 2.7 |
| Distillate Fuel Oil | 705.0 | 373.4 | 983.4 | 5,251.3 | 140.1 | 79.4 | 7,532.6 | 52.1 | 27.6 | 72.7 | 388.4 | 10.4 | 5.9 | 557.1 |
| Jet Fuel | | | | 2,328.5 | NA | 59.5 | 2,388.1 | | | | 168.2 | | 4.3 | 172.5 |
| Kerosene | 111.2 | 26.9 | 12.8 | | | 3.7 | 154.7 | 8.1 | 2.0 | 0.9 | | | 0.3 | 11.3 |
| LPG | 526.0 | 140.2 | 395.9 | 14.3 | | 8.3 | 1,084.6 | 32.5 | 8.7 | 24.5 | 0.9 | | 0.5 | 67.1 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | | | 15,913.1 | | 164.0 | 16,077.2 | | | | 1,127.4 | | 11.6 | 1,139.0 |
| Residual Fuel | | 73.3 | 150.9 | 175.7 | 958.7 | 146.0 | 1,504.6 | | 5.5 | 11.3 | 13.2 | 72.0 | 11.0 | 113.0 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 6.4 | | | | 6.4 | | | 0.4 | | | | 0.4 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 159.9 | | | | 159.9 | | | 11.2 | | | | 11.2 |
| Petroleum Coke | | 0.1 | 719.8 | | 112.5 | | 832.4 | | 0.0 | 73.5 | | 11.5 | | 85.0 |
| Still Gas | | | 1,421.1 | | | | 1,421.1 | | | 94.8 | | | | 94.8 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (287.9) | | | | (287.9) | | | (21.3) | | | | (21.3) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **50.6** | | **50.6** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,191.0** | **3,831.5** | **13,359.6** | **24,397.4** | **25,443.6** | **471.2** | **73,694.3** | **350.5** | **218.7** | **844.6** | **1,736.5** | **2,190.5** | **34.5** | **5,375.3** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-24: 1998 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **11.5** | **93.4** | **1,470.8** | **NE** | **19,215.7** | **10.5** | **20,802.0** | **1.1** | **8.9** | **139.1** | **NE** | **1,828.2** | **1.0** | **1,978.3** |
| Residential Coal | 11.5 | | | | | | 11.5 | 1.1 | | | | | | 1.1 |
| Commercial Coal | | 93.4 | | | | | 93.4 | | 8.9 | | | | | 8.9 |
| Industrial Other Coal | | | 1,470.8 | | | | 1,470.8 | | | 139.1 | | | | 139.1 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 19,215.7 | | 19,215.7 | | | | | 1,828.2 | | 1,828.2 |
| U.S. Territory Coal (bit) | | | | | | 10.5 | 10.5 | | | | | | 1.0 | 1.0 |
| **Natural Gas** | **4,646.1** | **3,083.0** | **8,826.0** | **666.1** | **4,674.9** | | **21,896.1** | **246.0** | **163.3** | **467.4** | **35.3** | **247.6** | | **1,159.5** |
| **Total Petroleum** | **1,207.3** | **609.1** | **3,469.9** | **22,834.1** | **1,306.2** | **445.4** | **29,872.1** | **84.0** | **43.7** | **262.3** | **1,638.8** | **101.3** | **32.4** | **2,162.5** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 35.5 | | | 35.5 | | | | 2.5 | | | 2.5 |
| Distillate Fuel Oil | 675.1 | 375.1 | 1,027.9 | 4,955.2 | 135.7 | 71.9 | 7,240.8 | 49.9 | 27.7 | 76.0 | 366.5 | 10.0 | 5.3 | 535.5 |
| Jet Fuel | | | | 2,163.5 | NA | 59.9 | 2,223.3 | | | | 156.3 | | 4.3 | 160.6 |
| Kerosene | 108.3 | 31.2 | 22.1 | | | 6.3 | 167.8 | 7.9 | 2.3 | 1.6 | | | 0.5 | 12.3 |
| LPG | 423.9 | 117.6 | 271.6 | 17.6 | | 5.9 | 836.7 | 26.1 | 7.2 | 16.7 | 1.1 | | 0.4 | 51.6 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | | | 15,583.4 | | 160.3 | 15,743.8 | | | | 1,106.6 | | 11.4 | 1,118.0 |
| Residual Fuel | | 85.2 | 173.3 | 78.9 | 1,047.0 | 141.1 | 1,525.5 | | 6.4 | 13.0 | 5.9 | 78.6 | 10.6 | 114.6 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 4.0 | | | | 4.0 | | | 0.3 | | | | 0.3 |
| Crude Oil | | | | | | | | | | | | | | |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 140.0 | | | | 140.0 | | | 9.8 | | | | 9.8 |
| Petroleum Coke | | 0.1 | 707.7 | | 123.6 | | 831.4 | | 0.0 | 72.3 | | 12.6 | | 84.9 |
| Still Gas | | | 1,437.3 | | | | 1,437.3 | | | 95.9 | | | | 95.9 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (313.9) | | | | (313.9) | | | (23.3) | | | | (23.3) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **50.4** | | **50.4** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **5,865.0** | **3,785.5** | **13,766.7** | **23,500.2** | **25,247.2** | **456.0** | **72,620.6** | **331.1** | **215.9** | **868.8** | **1,674.1** | **2,177.4** | **33.4** | **5,300.6** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-25: 1997 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **16.0** | **129.4** | **1,457.6** | **NE** | **18,904.5** | **10.4** | **20,518.0** | **1.5** | **12.3** | **137.6** | **NE** | **1,797.0** | **1.0** | **1,949.5** |
| Residential Coal | 16.0 | | | | | | 16.0 | 1.5 | | | | | | 1.5 |
| Commercial Coal | | 129.4 | | | | | 129.4 | | 12.3 | | | | | 12.3 |
| Industrial Other Coal | | | 1,457.6 | | | | 1,457.6 | | | 137.6 | | | | 137.6 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 18,904.5 | | 18,904.5 | | | | | 1,797.0 | | 1,797.0 |
| U.S. Territory Coal (bit) | | | | | | 10.4 | 10.4 | | | | | | 1.0 | 1.0 |
| **Natural Gas** | **5,092.9** | **3,285.3** | **9,032.5** | **780.3** | **4,125.5** | | **22,316.6** | **270.1** | **174.2** | **479.0** | **41.4** | **218.8** | | **1,183.4** |
| **Total Petroleum** | **1,333.5** | **655.1** | **3,903.5** | **22,320.6** | **926.8** | **445.3** | **29,584.9** | **93.0** | **47.1** | **290.6** | **1,601.5** | **72.2** | **32.4** | **2,136.8** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 39.7 | | | 39.7 | | | | 2.7 | | | 2.7 |
| Distillate Fuel Oil | 785.9 | 398.9 | 1,057.3 | 4,802.2 | 110.6 | 81.6 | 7,236.4 | 58.1 | 29.5 | 78.2 | 355.2 | 8.2 | 6.0 | 535.2 |
| Jet Fuel | | | | 2,180.5 | NA | 62.1 | 2,242.6 | | | | 157.5 | | 4.5 | 162.0 |
| Kerosene | 92.9 | 24.6 | 18.8 | | | 4.0 | 140.3 | 6.8 | 1.8 | 1.4 | | | 0.3 | 10.3 |
| LPG | 454.8 | 120.2 | 429.9 | 14.2 | | 6.5 | 1,025.7 | 28.1 | 7.4 | 26.5 | 0.9 | | 0.4 | 63.3 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | | | 15,147.5 | | 160.0 | 15,307.5 | | | | 1,075.0 | | 11.4 | 1,086.4 |
| Residual Fuel | | 111.2 | 240.1 | 136.5 | 714.6 | 131.1 | 1,333.5 | | 8.4 | 18.0 | 10.3 | 53.7 | 9.8 | 100.1 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 9.1 | | | | 9.1 | | | 0.6 | | | | 0.6 |
| Crude Oil | | | 4.6 | | | | 4.6 | | | 0.3 | | | | 0.3 |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 161.7 | | | | 161.7 | | | 11.3 | | | | 11.3 |
| Petroleum Coke | | 0.1 | 639.9 | | 101.6 | | 741.6 | | 0.0 | 65.3 | | 10.4 | | 75.7 |
| Still Gas | | | 1,445.1 | | | | 1,445.1 | | | 96.4 | | | | 96.4 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (102.9) | | | | (102.9) | | | (7.6) | | | | (7.6) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | 50.2 | | 50.2 | | | | | 0.4 | | 0.4 |
| **TOTAL (All Fuels)** | **6,442.5** | **4,069.8** | **14,393.7** | **23,100.9** | **24,007.1** | **455.7** | **72,469.7** | **364.6** | **233.6** | **907.2** | **1,642.9** | **2,088.4** | **33.4** | **5,270.0** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-26: 1996 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **16.6** | **121.6** | **1,454.9** | **NE** | **18,429.0** | **10.3** | **20,032.4** | **1.6** | **11.6** | **137.4** | **NE** | **1,752.4** | **1.0** | **1,903.9** |
| Residential Coal | 16.6 | | | | | | 16.6 | 1.6 | | | | | | 1.6 |
| Commercial Coal | | 121.6 | | | | | 121.6 | | 11.6 | | | | | 11.6 |
| Industrial Other Coal | | | 1,454.9 | | | | 1,454.9 | | | 137.4 | | | | 137.4 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 18,429.0 | | 18,429.0 | | | | | 1,752.4 | | 1,752.4 |
| U.S. Territory Coal (bit) | | | | | | 10.3 | 10.3 | | | | | | 1.0 | 1.0 |
| **Natural Gas** | **5,354.4** | **3,226.3** | **9,020.3** | **736.9** | **3,862.4** | | **22,200.4** | **283.9** | **171.1** | **478.3** | **39.1** | **204.8** | | **1,177.2** |
| **Total Petroleum** | **1,396.6** | **718.3** | **3,904.1** | **22,088.6** | **817.4** | **434.6** | **29,359.6** | **97.5** | **51.8** | **291.0** | **1,585.1** | **63.4** | **31.6** | **2,120.3** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 37.4 | | | 37.4 | | | | 2.6 | | | 2.6 |
| Distillate Fuel Oil | 839.0 | 437.6 | 1,049.1 | 4,599.0 | 109.4 | 76.5 | 7,110.5 | 62.1 | 32.4 | 77.6 | 340.1 | 8.1 | 5.7 | 525.9 |
| Jet Fuel | | | | 2,142.3 | NA | 78.5 | 2,220.8 | | | | 154.7 | | 5.7 | 160.4 |
| Kerosene | 88.8 | 21.0 | 18.3 | | | 3.0 | 131.1 | 6.5 | 1.5 | 1.3 | | | 0.2 | 9.6 |
| LPG | 468.7 | 122.4 | 401.7 | 15.6 | | 7.3 | 1,015.8 | 28.9 | 7.5 | 24.8 | 1.0 | | 0.5 | 62.6 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | | | 14,979.4 | | 151.4 | 15,130.8 | | | | 1,063.0 | | 10.7 | 1,073.8 |
| Residual Fuel | | 137.2 | 284.7 | 314.9 | 628.4 | 118.0 | 1,483.1 | | 10.3 | 21.4 | 23.6 | 47.2 | 8.9 | 111.4 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 7.0 | | | | 7.0 | | | 0.5 | | | | 0.5 |
| Crude Oil | | | 13.7 | | | | 13.7 | | | 1.0 | | | | 1.0 |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 167.2 | | | | 167.2 | | | 11.7 | | | | 11.7 |
| Petroleum Coke | | 0.1 | 638.2 | | 79.6 | | 717.9 | | 0.0 | 65.2 | | 8.1 | | 73.3 |
| Still Gas | | | 1,437.1 | | | | 1,437.1 | | | 95.9 | | | | 95.9 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (112.8) | | | | (112.8) | | | (8.4) | | | | (8.4) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | 48.9 | | 48.9 | | | | | 0.4 | | 0.4 |
| **TOTAL (All Fuels)** | **6,767.5** | **4,066.2** | **14,379.3** | **22,825.5** | **23,157.7** | **445.0** | **71,641.3** | **383.0** | **234.5** | **906.6** | **1,624.2** | **2,021.0** | **32.5** | **5,201.8** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34Table A-33).

[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

NE (Not Estimated)

Table A-27: 1995 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **17.5** | **116.8** | **1,526.9** | **NE** | **17,466.3** | **10.2** | **19,137.7** | **1.7** | **11.2** | **144.4** | **NE** | **1,660.7** | **0.9** | **1,819.0** |
| Residential Coal | 17.5 | | | | | | 17.5 | 1.7 | | | | | | 1.7 |
| Commercial Coal | | 116.8 | | | | | 116.8 | | 11.2 | | | | | 11.2 |
| Industrial Other Coal | | | 1,526.9 | | | | 1,526.9 | | | 144.4 | | | | 144.4 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 17,466.3 | | 17,466.3 | | | | | 1,660.7 | | 1,660.7 |
| U.S. Territory Coal (bit) | | | | | | 10.2 | 10.2 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | **4,954.2** | **3,096.0** | **8,722.5** | **724.0** | **4,302.0** | | **21,798.6** | **262.7** | **164.2** | **462.5** | **38.4** | **228.1** | | **1,155.9** |
| **Total Petroleum** | **1,260.9** | **694.0** | **3,541.6** | **21,607.6** | **754.6** | **461.8** | **28,320.5** | **88.3** | **50.1** | **263.4** | **1,547.9** | **58.7** | **33.6** | **2,042.1** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 39.6 | | | 39.6 | | | | 2.7 | | | 2.7 |
| Distillate Fuel Oil | 791.8 | 419.1 | 967.9 | 4,383.3 | 108.1 | 89.5 | 6,759.6 | 58.6 | 31.0 | 71.6 | 324.2 | 8.0 | 6.6 | 499.9 |
| Jet Fuel | | | | 2,101.2 | NA | 75.7 | 2,177.0 | | | | 149.0 | | 5.4 | 154.4 |
| Kerosene | 74.3 | 22.1 | 15.4 | | | 3.6 | 115.4 | 5.4 | 1.6 | 1.1 | | | 0.3 | 8.4 |
| LPG | 394.8 | 108.7 | 403.4 | 17.7 | | 5.6 | 930.2 | 24.4 | 6.7 | 24.9 | 1.1 | | 0.3 | 57.4 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 2.5 | 27.2 | 14,678.5 | | 146.7 | 14,854.9 | | 0.2 | 1.9 | 1,041.8 | | 10.4 | 1,054.3 |
| Residual Fuel | | 141.5 | 286.2 | 387.3 | 566.0 | 140.7 | 1,521.6 | | 10.6 | 21.5 | 29.1 | 42.5 | 10.6 | 114.3 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 5.3 | | | | 5.3 | | | 0.4 | | | | 0.4 |
| Crude Oil | | | 14.5 | | | | 14.5 | | | 1.1 | | | | 1.1 |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 164.6 | | | | 164.6 | | | 11.5 | | | | 11.5 |
| Petroleum Coke | | 0.1 | 600.7 | | 80.6 | | 681.4 | | 0.0 | 61.3 | | 8.2 | | 69.6 |
| Still Gas | | | 1,377.3 | | | | 1,377.3 | | | 91.9 | | | | 91.9 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (320.9) | | | | (320.9) | | | (23.8) | | | | (23.8) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **45.6** | | **45.6** | | | | | **0.3** | | **0.3** |
| **TOTAL (All Fuels)** | **6,232.5** | **3,906.8** | **13,791.1** | **22,331.6** | **22,568.5** | **472.0** | **69,302.5** | **352.7** | **225.5** | **870.4** | **1,586.3** | **1,947.9** | **34.5** | **5,017.4** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (seeTable A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-28: 1994 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **20.8** | **118.1** | **1,594.9** | **NE** | **17,260.9** | **10.0** | **19,004.7** | **2.0** | **11.3** | **150.7** | **NE** | **1,638.8** | **0.9** | **1,803.7** |
| Residential Coal | 20.8 | | | | | | 20.8 | 2.0 | | | | | | 2.0 |
| Commercial Coal | | 118.1 | | | | | 118.1 | | 11.3 | | | | | 11.3 |
| Industrial Other Coal | | | 1,594.9 | | | | 1,594.9 | | | 150.7 | | | | 150.7 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 17,260.9 | | 17,260.9 | | | | | 1,638.8 | | 1,638.8 |
| U.S. Territory Coal (bit) | | | | | | 10.0 | 10.0 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | **4,959.8** | **2,962.0** | **8,290.3** | **708.5** | **3,977.3** | | **20,897.9** | **262.9** | **157.0** | **439.4** | **37.6** | **210.8** | | **1,107.6** |
| **Total Petroleum** | **1,305.3** | **745.9** | **3,728.3** | **21,078.0** | **1,058.8** | **506.3** | **28,422.7** | **91.8** | **54.0** | **276.7** | **1,509.9** | **81.3** | **36.9** | **2,050.6** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 38.1 | | | 38.1 | | | | 2.6 | | | 2.6 |
| Distillate Fuel Oil | 856.7 | 447.1 | 975.8 | 4,187.0 | 120.1 | 118.8 | 6,705.5 | 63.4 | 33.1 | 72.2 | 309.7 | 8.9 | 8.8 | 495.9 |
| Jet Fuel | | | | 2,059.5 | NA | 65.8 | 2,125.3 | | | | 146.1 | | 4.7 | 150.8 |
| Kerosene | 64.9 | 19.5 | 16.9 | | | 3.0 | 104.3 | 4.8 | 1.4 | 1.2 | | | 0.2 | 7.6 |
| LPG | 383.7 | 107.3 | 423.1 | 34.0 | | 7.3 | 955.3 | 23.7 | 6.6 | 26.1 | 2.1 | | 0.4 | 59.0 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | | | 14,401.3 | | 147.4 | 14,548.7 | | | | 1,022.5 | | 10.5 | 1,033.0 |
| Residual Fuel | | 171.9 | 368.4 | 358.1 | 869.0 | 164.1 | 1,931.5 | | 12.9 | 27.7 | 26.9 | 65.3 | 12.3 | 145.0 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 6.1 | | | | 6.1 | | | 0.4 | | | | 0.4 |
| Crude Oil | | | 18.7 | | | | 18.7 | | | 1.4 | | | | 1.4 |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 190.6 | | | | 190.6 | | | 13.3 | | | | 13.3 |
| Petroleum Coke | | 0.1 | 594.9 | | 69.7 | | 664.7 | | 0.0 | 60.7 | | 7.1 | | 67.9 |
| Still Gas | | | 1,413.2 | | | | 1,413.2 | | | 94.3 | | | | 94.3 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (279.2) | | | | (279.2) | | | (20.7) | | | | (20.7) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **53.0** | | **53.0** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,286.0** | **3,826.0** | **13,613.5** | **21,786.6** | **22,350.0** | **516.3** | **68,378.3** | **356.7** | **222.3** | **866.8** | **1,547.5** | **1,931.2** | **37.8** | **4,962.3** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-29: 1993 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **25.7** | **117.3** | **1,585.0** | **NE** | **17,195.9** | **9.6** | **18,933.5** | **2.5** | **11.3** | **149.8** | **NE** | **1,632.5** | **0.9** | **1,796.9** |
| Residential Coal | 25.7 | | | | | | 25.7 | 2.5 | | | | | | 2.5 |
| Commercial Coal | | 117.3 | | | | | 117.3 | | 11.3 | | | | | 11.3 |
| Industrial Other Coal | | | 1,585.0 | | | | 1,585.0 | | | 149.8 | | | | 149.8 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 17,195.9 | | 17,195.9 | | | | | 1,632.5 | | 1,632.5 |
| U.S. Territory Coal (bit) | | | | | | 9.6 | 9.6 | | | | | | 0.9 | 0.9 |
| **Natural Gas** | **5,063.3** | **2,923.3** | **8,272.5** | **644.7** | **3,537.5** | | **20,441.3** | **268.4** | **155.0** | **438.6** | **34.2** | **187.5** | | **1,083.7** |
| **Total Petroleum** | **1,348.5** | **743.4** | **3,626.9** | **20,571.4** | **1,123.8** | **459.9** | **27,873.8** | **94.9** | **53.8** | **270.0** | **1,477.3** | **86.4** | **33.6** | **2,016.0** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 38.4 | | | 38.4 | | | | 2.7 | | | 2.7 |
| Distillate Fuel Oil | 883.3 | 447.2 | 989.9 | 3,889.4 | 86.5 | 104.9 | 6,401.1 | 65.3 | 33.1 | 73.2 | 287.6 | 6.4 | 7.8 | 473.4 |
| Jet Fuel | | | | 2,018.8 | NA | 62.1 | 2,080.9 | | | | 143.4 | | 4.4 | 147.8 |
| Kerosene | 75.6 | 14.0 | 13.1 | | | 3.8 | 106.5 | 5.5 | 1.0 | 1.0 | | | 0.3 | 7.8 |
| LPG | 389.6 | 109.2 | 412.2 | 20.2 | | 4.9 | 936.2 | 24.0 | 6.7 | 25.4 | 1.2 | | 0.3 | 57.8 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | | | 14,237.0 | | 128.3 | 14,365.3 | | | | 1,014.8 | | 9.1 | 1,023.9 |
| Residual Fuel | | 172.7 | 382.9 | 367.5 | 958.6 | 155.9 | 2,037.7 | | 13.0 | 28.8 | 27.6 | 72.0 | 11.7 | 153.0 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 0.1 | | | | 0.1 | | | 0.0 | | | | 0.0 |
| Crude Oil | | | 21.2 | | | | 21.2 | | | 1.6 | | | | 1.6 |
| MoGas Blend Components | | | | | | | | | | | | | | |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 187.2 | | | | 187.2 | | | 13.1 | | | | 13.1 |
| Petroleum Coke | | 0.2 | 614.6 | | 78.6 | | 693.4 | | 0.0 | 62.8 | | 8.0 | | 70.8 |
| Still Gas | | | 1,401.8 | | | | 1,401.8 | | | 93.5 | | | | 93.5 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (396.0) | | | | (396.0) | | | (29.3) | | | | (29.3) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **57.3** | | **57.3** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,437.5** | **3,783.9** | **13,484.4** | **21,216.1** | **21,914.5** | **469.5** | **67,305.9** | **365.8** | **220.1** | **858.3** | **1,511.5** | **1,906.9** | **34.5** | **4,897.0** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-30: 1992 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **25.6** | **116.6** | **1,554.6** | **NE** | **16,465.6** | **8.8** | **18,171.2** | **2.5** | **11.3** | **147.4** | **NE** | **1,569.6** | **0.8** | **1,731.6** |
| Residential Coal | 25.6 | | | | | | 25.6 | 2.5 | | | | | | 2.5 |
| Commercial Coal | | 116.6 | | | | | 116.6 | | 11.3 | | | | | 11.3 |
| Industrial Other Coal | | | 1,554.6 | | | | 1,554.6 | | | 147.4 | | | | 147.4 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 16,465.6 | | 16,465.6 | | | | | 1,569.6 | | 1,569.6 |
| U.S. Territory Coal (bit) | | | | | | 8.8 | 8.8 | | | | | | 0.8 | 0.8 |
| **Natural Gas** | **4,804.6** | **2,871.2** | **8,125.3** | **608.1** | **3,511.5** | | **19,920.7** | **254.5** | **152.1** | **430.5** | **32.2** | **186.0** | | **1,055.4** |
| **Total Petroleum** | **1,365.8** | **788.9** | **3,789.1** | **20,087.2** | **990.7** | **444.9** | **27,466.6** | **96.5** | **57.3** | **281.5** | **1,445.2** | **75.5** | **32.5** | **1,988.4** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 41.1 | | | 41.1 | | | | 2.8 | | | 2.8 |
| Distillate Fuel Oil | 931.4 | 481.7 | 1,028.5 | 3,665.7 | 73.5 | 91.8 | 6,272.6 | 68.9 | 35.6 | 76.1 | 271.1 | 5.4 | 6.8 | 463.9 |
| Jet Fuel | | | | 1,988.4 | NA | 61.3 | 2,049.6 | | | | 141.4 | | 4.4 | 145.7 |
| Kerosene | 65.0 | 11.1 | 9.8 | | | 3.3 | 89.2 | 4.8 | 0.8 | 0.7 | | | 0.2 | 6.5 |
| LPG | 369.4 | 106.9 | 441.8 | 19.4 | | 11.9 | 949.4 | 22.8 | 6.6 | 27.3 | 1.2 | | 0.7 | 58.7 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | | | 13,972.5 | | 122.1 | 14,094.7 | | | | 998.6 | | 8.7 | 1,007.4 |
| Residual Fuel | | 189.1 | 323.9 | 400.1 | 872.2 | 154.6 | 1,939.8 | | 14.2 | 24.3 | 30.0 | 65.5 | 11.6 | 145.7 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 0.2 | | | | 0.2 | | | 0.0 | | | | 0.0 |
| Crude Oil | | | 27.4 | | | | 27.4 | | | 2.0 | | | | 2.0 |
| MoGas Blend Components | | | 75.7 | | | | 75.7 | | | 5.4 | | | | 5.4 |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 174.4 | | | | 174.4 | | | 12.2 | | | | 12.2 |
| Petroleum Coke | | 0.1 | 626.7 | | 45.0 | | 671.8 | | 0.0 | 64.0 | | 4.6 | | 68.6 |
| Still Gas | | | 1,435.7 | | | | 1,435.7 | | | 95.8 | | | | 95.8 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (354.8) | | | | (354.8) | | | (26.3) | | | | (26.3) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **55.1** | | **55.1** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,196.0** | **3,776.7** | **13,469.0** | **20,695.3** | **21,022.9** | **453.7** | **65,613.5** | **353.5** | **220.6** | **859.4** | **1,477.4** | **1,831.5** | **33.3** | **4,775.8** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-31: 1991 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **25.4** | **115.5** | **1,602.7** | **NE** | **16,249.7** | **7.7** | **18,001.0** | **2.4** | **11.1** | **152.1** | **NE** | **1,548.2** | **0.7** | **1,714.6** |
| Residential Coal | 25.4 | | | | | | 25.4 | 2.4 | | | | | | 2.4 |
| Commercial Coal | | 115.5 | | | | | 115.5 | | 11.1 | | | | | 11.1 |
| Industrial Other Coal | | | 1,602.7 | | | | 1,602.7 | | | 152.1 | | | | 152.1 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 16,249.7 | | 16,249.7 | | | | | 1,548.2 | | 1,548.2 |
| U.S. Territory Coal (bit) | | | | | | 7.7 | 7.7 | | | | | | 0.7 | 0.7 |
| **Natural Gas** | **4,667.2** | **2,795.4** | **7,827.8** | **620.3** | **3,377.4** | | **19,288.1** | **247.3** | **148.1** | **414.7** | **32.9** | **178.9** | | **1,021.8** |
| **Total Petroleum** | **1,381.5** | **903.6** | **3,513.8** | **19,397.6** | **1,198.3** | **425.4** | **26,820.2** | **97.5** | **65.6** | **261.5** | **1,392.1** | **90.7** | **30.9** | **1,938.2** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 41.7 | | | 41.7 | | | | 2.9 | | | 2.9 |
| Distillate Fuel Oil | 931.0 | 517.7 | 1,050.8 | 3,449.7 | 83.6 | 71.4 | 6,104.1 | 68.9 | 38.3 | 77.7 | 255.1 | 6.2 | 5.3 | 451.4 |
| Jet Fuel | | | | 2,055.4 | NA | 78.2 | 2,133.6 | | | | 146.2 | | 5.6 | 151.8 |
| Kerosene | 72.3 | 12.1 | 11.4 | | | 2.8 | 98.6 | 5.3 | 0.9 | 0.8 | | | 0.2 | 7.2 |
| LPG | 378.1 | 108.2 | 342.2 | 21.1 | | 13.8 | 863.5 | 23.3 | 6.7 | 21.1 | 1.3 | | 0.9 | 53.3 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 53.7 | 122.0 | 13,605.3 | | 124.7 | 13,905.6 | | 3.8 | 8.7 | 969.7 | | 8.9 | 991.1 |
| Residual Fuel | | 211.9 | 270.9 | 224.4 | 1,085.3 | 134.6 | 1,927.2 | | 15.9 | 20.3 | 16.9 | 81.5 | 10.1 | 144.7 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | (0.1) | | | | (0.1) | | | (0.0) | | | | (0.0) |
| Crude Oil | | | 38.9 | | | | 38.9 | | | 2.9 | | | | 2.9 |
| MoGas Blend Components | | | (25.9) | | | | (25.9) | | | (1.8) | | | | (1.8) |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 161.6 | | | | 161.6 | | | 11.3 | | | | 11.3 |
| Petroleum Coke | | | 587.6 | | 29.3 | | 616.9 | | | 60.0 | | 3.0 | | 63.0 |
| Still Gas | | | 1,404.5 | | | | 1,404.5 | | | 93.7 | | | | 93.7 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (450.2) | | | | (450.2) | | | (33.3) | | | | (33.3) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **54.5** | | **54.5** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **6,074.0** | **3,814.5** | **12,944.3** | **20,017.9** | **20,879.8** | **433.2** | **64,163.8** | **347.2** | **224.8** | **828.3** | **1,425.0** | **1,818.2** | **31.6** | **4,675.0** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33Table A-33), and international bunker fuel consumption (see Table A-34).

[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.

NE (Not Estimated)

Table A- 32: 1990 Energy Consumption Data and $CO_2$ Emissions from Fossil Fuel Combustion by Fuel Type

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Adjusted Consumption (TBtu)[a] | | | | | | | Emissions[b] (Tg $CO_2$ Eq.) from Energy Use | | | | | | |
| **Fuel Type** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** | **Res.** | **Comm.** | **Ind.** | **Trans.** | **Elec.** | **Terr.** | **Total** |
| **Total Coal** | **31.1** | **124.5** | **1,640.5** | **NE** | **16,261.0** | **7.0** | **18,064.0** | **3.0** | **12.0** | **155.3** | **NE** | **1,547.6** | **0.6** | **1,718.4** |
| Residential Coal | 31.1 | | | | | | 31.1 | 3.0 | | | | | | 3.0 |
| Commercial Coal | | 124.5 | | | | | 124.5 | | 12.0 | | | | | 12.0 |
| Industrial Other Coal | | | 1,640.5 | | | | 1,640.5 | | | 155.3 | | | | 155.3 |
| Transportation Coal | | | | NE | | | | | | | | | | NE |
| Electric Power Coal | | | | | 16,261.0 | | 16,261.0 | | | | | 1,547.6 | | 1,547.6 |
| U.S. Territory Coal (bit) | | | | | | 7.0 | 7.0 | | | | | | 0.6 | 0.6 |
| **Natural Gas** | **4,490.9** | **2,682.2** | **7,716.4** | **679.9** | **3,308.5** | | **18,877.9** | **238.0** | **142.1** | **408.9** | **36.0** | **175.3** | | **1,000.3** |
| **Total Petroleum** | **1,375.2** | **891.4** | **3,830.7** | **19,919.1** | **1,289.4** | **374.8** | **27,680.7** | **97.4** | **64.9** | **284.4** | **1,429.0** | **97.5** | **27.2** | **2,000.4** |
| Asphalt & Road Oil | | | | | | | | | | | | | | |
| Aviation Gasoline | | | | 45.0 | | | 45.0 | | | | 3.1 | | | 3.1 |
| Distillate Fuel Oil | 959.2 | 525.4 | 1,098.5 | 3,554.8 | 96.5 | 74.0 | 6,308.4 | 70.9 | 38.9 | 81.2 | 262.9 | 7.1 | 5.5 | 466.5 |
| Jet Fuel | | | | 2,183.1 | NA | 61.0 | 2,244.1 | | | | 155.3 | | 4.3 | 159.6 |
| Kerosene | 63.9 | 11.8 | 12.3 | | | 2.6 | 90.6 | 4.7 | 0.9 | 0.9 | | | 0.2 | 6.6 |
| LPG | 352.1 | 102.3 | 380.2 | 22.9 | | 14.4 | 871.9 | 21.8 | 6.3 | 23.5 | 1.4 | | 0.9 | 53.9 |
| Lubricants | | | | | | | | | | | | | | |
| Motor Gasoline | | 22.1 | 36.7 | 13,813.0 | | 101.0 | 13,972.8 | | 1.6 | 2.6 | 983.7 | | 7.2 | 995.1 |
| Residual Fuel | | 229.8 | 364.1 | 300.3 | 1,162.6 | 121.8 | 2,178.7 | | 17.3 | 27.3 | 22.6 | 87.3 | 9.2 | 163.6 |
| Other Petroleum | | | | | | | | | | | | | | |
| AvGas Blend Components | | | 0.2 | | | | 0.2 | | | 0.0 | | | | 0.0 |
| Crude Oil | | | 50.9 | | | | 50.9 | | | 3.8 | | | | 3.8 |
| MoGas Blend Components | | | 53.7 | | | | 53.7 | | | 3.8 | | | | 3.8 |
| Misc. Products | | | | | | | | | | | | | | |
| Naphtha (<401 deg. F) | | | | | | | | | | | | | | |
| Other Oil (>401 deg. F) | | | | | | | | | | | | | | |
| Pentanes Plus | | | 160.0 | | | | 160.0 | | | 11.2 | | | | 11.2 |
| Petroleum Coke | | | 591.2 | | 30.4 | | 621.5 | | | 60.4 | | 3.1 | | 63.5 |
| Still Gas | | | 1,451.9 | | | | 1,451.9 | | | 96.9 | | | | 96.9 |
| Special Naphtha | | | | | | | | | | | | | | |
| Unfinished Oils | | | (369.0) | | | | (369.0) | | | (27.3) | | | | (27.3) |
| Waxes | | | | | | | | | | | | | | |
| **Geothermal** | | | | | **52.7** | | **52.7** | | | | | **0.4** | | **0.4** |
| **TOTAL (All Fuels)** | **5,897.2** | **3,698.1** | **13,187.5** | **20,599.0** | **20,911.6** | **381.9** | **64,675.3** | **338.3** | **219.0** | **848.6** | **1,465.0** | **1,820.8** | **27.9** | **4,719.6** |

[a] Expressed as gross calorific values (i.e., higher heating values). Adjustments include biofuels, conversion of fossil fuels, non-energy use (see Table A-33), and international bunker fuel consumption (see Table A-34).
[b] Consumption and/or emissions of select fuels are shown as negative due to differences in EIA energy balancing accounting. These are designated with parentheses.
NE (Not Estimated)

Table A-33: Unadjusted Non-Energy Fuel Consumption (TBtu)

| Sector/Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Industry** | **4,493.8** | **5,086.3** | **5,159.2** | **5,368.9** | **5,633.4** | **5,859.3** | **5,726.1** | **5,347.6** | **5,507.2** | **5,440.6** | **5,931.7** | **5,549.9** | **5,528.3** | **5,275.1** | **4,809.9** | **4,558.8** | **4,753.6** | **4,715.4** |
| Industrial Coking Coal | + | 37.8 | 24.1 | + | 10.9 | 40.1 | 53.6 | 24.8 | 40.3 | 51.9 | 167.8 | 80.5 | 62.9 | 2.3 | 29.2 | 6.4 | 64.8 | 60.8 |
| Industrial Other Coal | 8.2 | 11.3 | 11.4 | 11.2 | 10.4 | 11.1 | 12.4 | 11.3 | 12.0 | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 | 11.9 | 10.3 | 10.3 |
| Natural Gas to Chemical Plants, Other Uses | 305.9 | 371.0 | 388.7 | 406.4 | 426.6 | 413.5 | 401.7 | 391.8 | 380.7 | 345.3 | 306.6 | 270.4 | 233.4 | 233.6 | 233.6 | 233.6 | 233.6 | 233.6 |
| Asphalt & Road Oil | 1,170.2 | 1,178.2 | 1,175.9 | 1,223.6 | 1,262.6 | 1,324.4 | 1,275.7 | 1,256.9 | 1,240.0 | 1,219.5 | 1,303.8 | 1,323.2 | 1,261.2 | 1,197.0 | 1,012.0 | 873.1 | 877.8 | 859.5 |
| LPG | 1,201.4 | 1,586.9 | 1,652.0 | 1,670.4 | 1,744.4 | 1,820.7 | 1,866.6 | 1,722.1 | 1,841.9 | 1,784.1 | 1,835.9 | 1,716.3 | 1,787.4 | 1,771.5 | 1,646.5 | 1,787.3 | 1,965.3 | 2,054.3 |
| Lubricants | 186.3 | 177.8 | 172.5 | 182.3 | 190.8 | 192.8 | 189.9 | 174.0 | 171.9 | 159.0 | 161.0 | 160.2 | 156.1 | 161.2 | 149.6 | 134.5 | 149.5 | 141.8 |
| Pentanes Plus | 90.3 | 173.3 | 187.8 | 167.2 | 154.0 | 205.1 | 218.0 | 149.2 | 121.7 | 125.5 | 127.7 | 107.9 | 75.5 | 94.9 | 66.2 | 73.2 | 77.7 | 27.3 |
| Naphtha (<401 deg. F) | 347.8 | 373.0 | 479.3 | 536.4 | 584.0 | 502.1 | 613.5 | 493.7 | 582.6 | 613.0 | 749.4 | 698.7 | 628.9 | 562.5 | 477.2 | 471.9 | 490.4 | 486.4 |
| Other Oil (>401 deg. F) | 753.9 | 801.0 | 729.6 | 861.3 | 818.7 | 811.1 | 722.2 | 662.4 | 632.1 | 699.4 | 779.5 | 708.0 | 790.6 | 744.1 | 647.8 | 424.8 | 452.7 | 394.4 |
| Still Gas | 21.3 | 40.1 | 0.0 | 2.1 | 0.0 | 16.1 | 12.6 | 35.8 | 57.8 | 59.0 | 62.9 | 67.7 | 57.2 | 44.2 | 47.3 | 133.9 | 152.5 | 167.6 |
| Petroleum Coke | 123.1 | 120.6 | 118.6 | 87.5 | 150.8 | 216.0 | 98.7 | 174.3 | 145.8 | 122.8 | 218.3 | 186.9 | 213.6 | 201.2 | 225.1 | 180.7 | 61.0 | 62.4 |
| Special Naphtha | 107.1 | 70.8 | 74.5 | 72.3 | 107.3 | 145.4 | 97.4 | 78.5 | 102.4 | 80.5 | 51.0 | 62.5 | 70.1 | 78.0 | 84.9 | 46.2 | 26.5 | 21.4 |
| Other (Wax/Misc.) | | | | | | | | | | | | | | | | | | |
| Distillate Fuel Oil | 7.0 | 6.8 | 6.8 | 6.8 | 11.7 | 11.7 | 11.7 | 11.7 | 11.7 | 11.7 | 11.7 | 11.7 | 17.5 | 17.5 | 17.5 | 17.5 | 17.5 | 17.5 |
| Waxes | 33.3 | 40.6 | 48.7 | 43.7 | 42.4 | 37.4 | 33.1 | 36.3 | 32.2 | 31.0 | 30.8 | 31.4 | 26.1 | 21.9 | 19.1 | 12.2 | 15.4 | 14.6 |
| Miscellaneous Products | 137.8 | 97.1 | 89.0 | 97.8 | 119.0 | 111.9 | 119.2 | 124.9 | 134.2 | 126.0 | 113.4 | 112.8 | 136.0 | 133.5 | 142.0 | 151.8 | 158.8 | 163.3 |
| **Transportation** | **176.0** | **167.9** | **163.0** | **172.1** | **180.2** | **182.1** | **179.4** | **164.3** | **162.4** | **150.1** | **152.1** | **151.3** | **147.4** | **152.2** | **141.3** | **127.1** | **141.2** | **133.9** |
| Lubricants | 176.0 | 167.9 | 163.0 | 172.1 | 180.2 | 182.1 | 179.4 | 164.3 | 162.4 | 150.1 | 152.1 | 151.3 | 147.4 | 152.2 | 141.3 | 127.1 | 141.2 | 133.9 |
| **U.S. Territories** | **86.7** | **90.8** | **121.7** | **131.6** | **135.0** | **139.3** | **152.2** | **80.3** | **140.2** | **123.5** | **110.8** | **121.9** | **133.4** | **108.4** | **132.1** | **59.6** | **123.6** | **123.6** |
| Lubricants | 0.7 | 2.0 | 1.5 | 2.5 | 1.3 | 1.4 | 3.1 | + | 3.0 | 4.9 | 5.1 | 4.6 | 6.2 | 5.9 | 2.7 | 1.0 | 1.0 | 1.0 |
| Other Petroleum (Misc. Prod.) | 86.0 | 88.8 | 120.2 | 129.1 | 133.8 | 138.0 | 149.1 | 80.3 | 137.2 | 118.6 | 105.7 | 117.3 | 127.2 | 102.5 | 129.4 | 58.5 | 122.6 | 122.6 |
| **Total** | **4,756.5** | **5,345.0** | **5,443.9** | **5,672.7** | **5,948.7** | **6,180.8** | **6,057.6** | **5,592.2** | **5,809.8** | **5,714.2** | **6,194.6** | **5,823.2** | **5,809.1** | **5,535.8** | **5,083.3** | **4,745.5** | **5,018.4** | **4,972.9** |

Note: These values are unadjusted non-energy fuel use provided by EIA. They have not yet been adjusted to remove petroleum feedstock exports and processes accounted for in the Industrial Processes Chapter.
+ Does not exceed 0.05 TBtu.

Table A-34: International Bunker Fuel Consumption (TBtu)

| Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Marine Residual Fuel Oil | 715.7 | 523.2 | 536.4 | 575.2 | 594.8 | 489.7 | 444.1 | 426.0 | 448.9 | 471.8 | 553.1 | 581.0 | 599.4 | 607.5 | 654.6 | 604.8 | 619.8 | 518.4 |
| Marine Distillate Fuel Oil & Other | 158.0 | 125.7 | 114.1 | 125.5 | 158.8 | 113.6 | 85.9 | 72.4 | 82.6 | 103.9 | 143.6 | 126.9 | 119.3 | 111.3 | 122.2 | 111.0 | 128.2 | 101.9 |
| Aviation Jet Fuel | 946.4 | 1,031.0 | 1,131.9 | 1,127.6 | 1,193.3 | 1,133.3 | 1,170.9 | 1,207.8 | 1,199.9 | 1,101.3 | 1,142.1 | 1,126.0 | 978.6 | 942.9 | 924.0 | 790.6 | 981.1 | 965.8 |
| **Total** | **1,820.0** | **1,679.9** | **1,782.4** | **1,828.4** | **1,946.9** | **1,736.6** | **1,700.8** | **1,706.3** | **1,731.3** | **1,677.0** | **1,838.8** | **1,833.9** | **1,697.3** | **1,661.8** | **1,700.8** | **1,506.4** | **1,729.2** | **1,586.0** |

Table A- 35: Key Assumptions for Estimating $CO_2$ Emissions

| Fuel Type | C Content Coefficient (Tg C/QBtu) |
|---|---|
| **Coal** | |
| Residential Coal | [a] |
| Commercial Coal | [a] |
| Industrial Coking Coal | [a] |
| Industrial Other Coal | [a] |
| Electric Power Coal | [a] |
| U.S. Territory Coal (bit) | 25.14 |
| **Pipeline Natural Gas** | **[a]** |
| Flare Gas [a] | 14.92 |
| **Petroleum** | |
| Asphalt & Road Oil | 20.55 |
| Aviation Gasoline | 18.86 |
| Distillate Fuel Oil No. 1 | 19.98 |
| Distillate Fuel Oil No. 2[b] | 20.17 |
| Distillate Fuel Oil No. 4 | 20.47 |
| Jet Fuel | [a] |
| Kerosene | 19.96 |
| LPG (energy use) | [a] |
| LPG (non-energy use) | [a] |
| Lubricants | 20.20 |
| Motor Gasoline | [a] |
| Residual Fuel Oil No. 5 | 19.89 |
| Residual Fuel Oil No. 6 [b] | 20.48 |
| **Other Petroleum** | |
| AvGas Blend Components | 18.87 |
| Crude Oil | [a] |
| MoGas Blend Components | [a] |
| Misc. Products | [a] |
| Misc. Products (Territories) | [a] |
| Naphtha (<401 deg. F) | 18.55 |
| Other Oil (>401 deg. F) | 20.17 |
| Pentanes Plus | 19.10 |
| Petroleum Coke | 27.85 |
| Still Gas | 18.20 |
| Special Naphtha | 19.74 |
| Unfinished Oils | [a] |
| Waxes | 19.80 |
| **Geothermal** | **2.05** |

[a] Flare gas is not used in the $CO_2$ from fossil fuel combustion calculations and is presented for informational purposes only.
[b] Distillate fuel oil No.2 and residual fuel oil No. 6 are used in the $CO_2$ from fossil fuel combustion calculations, and other oil types are presented for informational purposes only. An additional discussion on the derivation of these carbon content coefficients is presented in Annex 2.2.
Sources: C coefficients from EIA (2009b) and EPA 2010a.
[a] These coefficients vary annually due to fluctuations in fuel quality (see Table A- 36 )

Table A- 36: Annually Variable C Content Coefficients by Year (Tg C/QBtu)

| Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Residential Coal | 26.20 | 26.13 | 26.04 | 25.90 | 26.07 | 25.98 | 26.01 | 26.00 | 25.98 | 26.04 | 25.91 | 26.09 | 26.29 | 25.94 | 25.71 | 25.71 | 25.71 | 25.71 |
| Commercial Coal | 26.20 | 26.13 | 26.04 | 25.90 | 26.07 | 25.98 | 26.01 | 26.00 | 25.98 | 26.04 | 25.91 | 26.09 | 26.29 | 25.94 | 25.71 | 25.71 | 25.71 | 25.71 |
| Industrial Coking Coal | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 | 31.00 |
| Industrial Other Coal | 25.82 | 25.80 | 25.75 | 25.75 | 25.79 | 25.80 | 25.74 | 25.66 | 25.57 | 25.55 | 25.56 | 25.80 | 25.84 | 25.82 | 25.82 | 25.82 | 25.82 | 25.82 |
| Electric Power Coal | 25.96 | 25.93 | 25.93 | 25.93 | 25.95 | 25.98 | 26.00 | 26.00 | 26.05 | 26.09 | 26.10 | 26.09 | 26.04 | 26.05 | 26.05 | 26.05 | 26.05 | 26.05 |
| Pipeline Natural Gas | 14.45 | 14.46 | 14.46 | 14.46 | 14.44 | 14.46 | 14.47 | 14.46 | 14.46 | 14.44 | 14.46 | 14.46 | 14.46 | 14.46 | 14.46 | 14.46 | 14.46 | 14.46 |
| LPG (energy use) | 16.86 | 16.99 | 16.99 | 16.99 | 16.99 | 16.99 | 16.98 | 16.99 | 16.98 | 17.00 | 16.98 | 16.98 | 16.96 | 16.94 | 16.95 | 16.90 | 16.91 | 16.87 |
| LPG (non-energy use) | 17.06 | 16.82 | 16.82 | 16.84 | 16.81 | 16.86 | 16.89 | 16.87 | 16.85 | 16.86 | 16.84 | 16.84 | 16.83 | 16.82 | 16.83 | 16.83 | 16.83 | 16.83 |
| Motor Gasoline | 19.42 | 17.09 | 17.10 | 17.08 | 17.08 | 17.07 | 17.09 | 17.10 | 17.09 | 17.09 | 17.07 | 17.06 | 17.06 | 17.05 | 17.06 | 17.06 | 17.06 | 17.06 |
| Jet Fuel | 19.40 | 19.36 | 19.35 | 19.36 | 19.37 | 19.32 | 19.33 | 19.34 | 19.38 | 19.36 | 19.38 | 19.36 | 19.45 | 19.56 | 19.46 | 19.46 | 19.46 | 19.46 |
| MoGas Blend Components | 19.42 | 19.34 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 |
| Misc. Products | 20.15 | 19.36 | 19.35 | 19.36 | 19.37 | 19.32 | 19.33 | 19.34 | 19.38 | 19.36 | 19.38 | 19.36 | 19.45 | 19.56 | 19.46 | 19.46 | 19.46 | 19.46 |
| Unfinished Oils | 20.15 | 20.21 | 20.23 | 20.22 | 20.22 | 20.17 | 20.22 | 20.27 | 20.28 | 20.25 | 20.31 | 20.31 | 20.28 | 20.28 | 20.31 | 20.31 | 20.31 | 20.31 |
| Crude Oil | 20.15 | 20.21 | 20.23 | 20.22 | 20.22 | 20.17 | 20.22 | 20.27 | 20.28 | 20.25 | 20.31 | 20.31 | 20.28 | 20.28 | 20.31 | 20.31 | 20.31 | 20.31 |

*U.S. EIA discontinued collection of residential sector coal consumption data in 2008, because consumption of coal in the residential sector is extremely limited. Therefore, the number cited here is developed from commercial/institutional consumption.
Source: EPA (2010a)

Table A-37: Electricity Consumption by End-Use Sector (Billion Kilowatt-Hours)

| End-Use Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Residential | 924 | 1,043 | 1,083 | 1,076 | 1,130 | 1,145 | 1,192 | 1,202 | 1,265 | 1,276 | 1,292 | 1,359 | 1,352 | 1,392 | 1,380 | 1,364 | 1,446 | 1,424 |
| Commercial | 838 | 953 | 980 | 1,027 | 1,078 | 1,104 | 1,159 | 1,191 | 1,205 | 1,199 | 1,230 | 1,275 | 1,300 | 1,336 | 1,336 | 1,307 | 1,330 | 1,319 |
| Industrial | 1,070 | 1,163 | 1,186 | 1,194 | 1,212 | 1,230 | 1,235 | 1,159 | 1,156 | 1,181 | 1,186 | 1,169 | 1,158 | 1,154 | 1,141 | 1,044 | 1,103 | 1,106 |
| Transportation | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 7 | 8 | 8 | 8 | 8 | 8 |
| **Total** | **2,837** | **3,164** | **3,254** | **3,302** | **3,425** | **3,484** | **3,592** | **3,557** | **3,632** | **3,662** | **3,716** | **3,811** | **3,817** | **3,890** | **3,865** | **3,724** | **3,886** | **3,856** |

Note: Does not include the U.S. territories.
Source: EIA (2012)

## 2.2. Methodology for Estimating the Carbon Content of Fossil Fuels

This sub-annex presents the background and methodology for estimating the carbon (C) content of fossil fuels combusted in the United States. The C content of a particular fossil fuel represents the maximum potential emissions to the atmosphere if all C in the fuel is oxidized during combustion. The C content coefficients used in past editions of this report were developed using methods first outlined in the U.S. Energy Information Administration's (EIA) *Emissions of Greenhouse Gases in the United States: 1987-1992* (1994) and were developed primarily by EIA. For this report, EPA has updated many of the C content coefficients based on carbon dioxide emission factors developed for the Mandatory Reporting of Greenhouse Gases Rule, signed in September 2009 (EPA, 2009b, 2010). This sub-annex describes an updated methodology for estimating the C content of natural gas, and presents a time-series analysis of changes in U.S. C content coefficients for coal, petroleum products and natural gas. A summary of C content coefficients used in this report appears in Table A- 38.

Though the methods for estimating C contents for coal, natural gas, and petroleum products differ in their details, they each follow the same basic approach. First, because C coefficients are presented in terms of mass per unit energy (i.e., teragrams C per quadrillion Btu or Tg C/QBtu), those fuels that are typically described in volumetric units (petroleum products and natural gas) are converted to units of mass using an estimated density. Second, C contents are derived from fuel sample data, using descriptive statistics to estimate the C share of the fuel by weight. The heat content of the fuel is then estimated based on the sample data, or where sample data are unavailable or unrepresentative, by default values that reflect the characteristics of the fuel as defined by market requirements. A discussion of each fuel appears below.

The C content of coal is described first because approximately one-third of all U.S. C emissions from fossil fuel combustion are associated with coal consumption. The methods and sources for estimating the C content of natural gas are provided next. Approximately one-fifth of U.S. greenhouse gas emissions from fossil fuel combustion are attributable to natural gas consumption. Finally, this sub-annex examines C contents of petroleum products. U.S. energy consumption statistics account for more than 20 different petroleum products.

Table A- 38: Carbon Content Coefficients Used in this Report (Tg Carbon/QBtu)

| Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Coal** | | | | | | | | | | | | | | | | | | |
| Residential Coal[a] | 26.20 | 26.13 | 26.04 | 25.90 | 26.07 | 25.98 | 26.01 | 26.00 | 25.98 | 26.04 | 25.91 | 26.09 | 26.29 | 25.94 | 25.71* | 25.71* | 25.71* | 25.71* |
| Commercial Coal[a] | 26.20 | 26.13 | 26.04 | 25.90 | 26.07 | 25.98 | 26.01 | 26.00 | 25.98 | 26.04 | 25.91 | 26.09 | 26.29 | 25.94 | 25.71 | 25.71 | 25.71 | 25.71 |
| Industrial Coking Coal[a] | 25.53 | 25.57 | 25.56 | 25.59 | 25.62 | 25.59 | 25.63 | 25.63 | 25.65 | 25.63 | 25.63 | 25.60 | 25.60 | 25.61 | 25.61 | 25.61 | 25.61 | 25.61 |
| Industrial Other Coal[a] | 25.82 | 25.80 | 25.75 | 25.75 | 25.79 | 25.80 | 25.74 | 25.66 | 25.57 | 25.55 | 25.56 | 25.80 | 25.84 | 25.82 | 25.82 | 25.82 | 25.82 | 25.82 |
| Utility Coal[a,b] | 25.96 | 25.93 | 25.93 | 25.93 | 25.95 | 25.98 | 26.00 | 26.00 | 26.05 | 26.09 | 26.10 | 26.09 | 26.04 | 26.05 | 26.05 | 26.05 | 26.05 | 26.05 |
| **Pipeline Natural Gas[c]** | **14.45** | **14.46** | **14.46** | **14.46** | **14.44** | **14.46** | **14.47** | **14.46** | **14.46** | **14.44** | **14.46** | **14.46** | **14.46** | **14.46** | **14.46** | **14.46** | **14.46** | **14.46** |
| **Flare Gas** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** | **15.31** |
| **Petroleum** | | | | | | | | | | | | | | | | | | |
| Asphalt and Road Oil | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 | 20.55 |
| Aviation Gasoline | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 | 18.86 |
| Distillate Fuel Oil No. 1 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 | 19.98 |
| Distillate Fuel Oil No. 2 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 |
| Distillate Fuel Oil No. 4 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 | 20.47 |
| Jet Fuel[a] | 19.40 | 19.34 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 |
| Kerosene | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 | 19.96 |
| LPG (energy use)[c] | 16.86 | 16.82 | 16.82 | 16.84 | 16.81 | 16.86 | 16.89 | 16.87 | 16.85 | 16.86 | 16.84 | 16.84 | 16.83 | 16.82 | 16.83 | 16.83 | 16.83 | 16.83 |
| LPG (non-energy use)[c] | 17.06 | 17.09 | 17.10 | 17.08 | 17.08 | 17.07 | 17.09 | 17.10 | 17.09 | 17.09 | 17.07 | 17.06 | 17.06 | 17.05 | 17.06 | 17.06 | 17.06 | 17.06 |
| Lubricants | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 | 20.20 |
| Motor Gasoline[c] | 19.42 | 19.36 | 19.35 | 19.36 | 19.37 | 19.32 | 19.33 | 19.34 | 19.38 | 19.36 | 19.38 | 19.36 | 19.45 | 19.56 | 19.46 | 19.46 | 19.46 | 19.46 |
| Residual Fuel No. 5 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 | 19.89 |
| Residual Fuel No. 6 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 | 20.48 |
| **Other Petroleum** | | | | | | | | | | | | | | | | | | |
| Av Gas Blend Comp. | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 |
| Mo Gas Blend Comp[c] | 19.42 | 19.36 | 19.35 | 19.36 | 19.37 | 19.32 | 19.33 | 19.34 | 19.38 | 19.36 | 19.38 | 19.36 | 19.45 | 19.56 | 19.46 | 19.46 | 19.46 | 19.46 |
| Crude Oil[c] | 20.15 | 20.21 | 20.23 | 20.22 | 20.22 | 20.17 | 20.22 | 20.27 | 20.28 | 20.25 | 20.31 | 20.31 | 20.28 | 20.28 | 20.31 | 20.31 | 20.31 | 20.31 |
| Misc. Products[c] | 20.15 | 20.21 | 20.23 | 20.22 | 20.22 | 20.17 | 20.22 | 20.27 | 20.28 | 20.25 | 20.31 | 20.31 | 20.28 | 20.28 | 20.31 | 20.31 | 20.31 | 20.31 |
| Misc. Products (Terr.) | 20.15 | 20.21 | 20.23 | 20.22 | 20.22 | 20.17 | 20.22 | 20.27 | 20.28 | 20.25 | 20.31 | 20.31 | 20.28 | 20.28 | 20.31 | 20.31 | 20.31 | 20.31 |
| Naphtha (<401 deg. F) | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 | 18.55 |
| Other oil (>401 deg. F) | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 | 20.17 |
| Pentanes Plus | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 | 19.10 |
| Petroleum Coke | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 |
| Still Gas | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 | 18.20 |
| Special Naphtha | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 | 19.74 |
| Unfinished Oils[c] | 20.15 | 20.21 | 20.23 | 20.22 | 20.22 | 20.17 | 20.22 | 20.27 | 20.28 | 20.25 | 20.31 | 20.31 | 20.28 | 20.28 | 20.31 | 20.31 | 20.31 | 20.31 |
| Waxes | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 |
| Other Wax and Misc. | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 | 19.80 |
| **Geothermal** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** | **2.05** |

*U.S. EIA discontinued collection of residential sector coal consumption data in 2008, because consumption of coal in the residential sector is extremely limited. Therefore, the number cited here is developed from commercial/institutional consumption.

[a]C contents vary annually based on changes in annual mix of production and end-use consumption of coal from each producing state.

[b]C content for utility coal used in the electric power calculations. All coefficients based on higher heating value. Higher heating value (gross heating value) is the total amount of heat released when a fuel is burned. Coal, crude oil, and natural gas all include chemical compounds of carbon and hydrogen. When those fuels are burned, the carbon and hydrogen combine with oxygen in the air to produce $CO_2$ and water. Some of the energy released in burning goes into transforming the water into steam and is usually lost. The amount of heat spent in transforming the water into steam is counted as part of gross heat content. Lower heating value (net heating value), in contrast, does not include the heat spent in transforming the water into steam. Using a simplified methodology based on International Energy Agency defaults, higher heating value can be converted to lower heating value for coal and petroleum products by multiplying by 0.95 and for natural gas by multiplying by 0.90. Carbon content coefficients are presented in higher heating value because U.S. energy statistics are reported by higher heating value.

[c]C contents vary annually based on changes in fuel composition.

## Coal

Approximately one-third of all U.S. $CO_2$ emissions from fossil fuel combustion are associated with coal consumption. Although the IPCC guidelines provide C contents for coal according to rank, it was necessary to develop C content coefficients by consuming sector to match the format in which coal consumption is reported by EIA. Because the C content of coal varies by the state in which it was mined and by coal rank, and because the sources of coal for each consuming sector vary by year, the weighted average C content for coal combusted in each consuming sector also varies over time. A time series of C contents by coal rank and consuming sector appears in Table A- 39.[5]

### Methodology

The methodology for developing C contents for coal by consuming sector consists of four steps. An additional step has been taken to calculate C contents by coal rank to facilitate comparison with IPCC default values.

#### *Step 1. Determine carbon contents by rank and by state of origin*

C contents by rank and state of origin are estimated on the basis of 7,092 coal samples, 6,588 of which were collected by the U.S. Geological Survey (USGS 1998) and 504 samples that come from the Pennsylvania State University database (PSU 2010). These coal samples are classified according to rank and state of origin. For each rank in each state, the average heat content and C content of the coal samples are calculated based on the proximate (heat) and ultimate (percent carbon) analyses of the samples. Dividing the C content (reported in pounds $CO_2$) by the heat content (reported in million Btu or MMBtu) yields an average C content coefficient. This coefficient is then converted into units of Tg C/QBtu.

#### *Step 2. Determine weighted average carbon content by state*

C contents by rank and origin calculated in Step 1 are then weighted by the annual share of state production that was each rank. State production by rank is obtained from the EIA. This step yields a single carbon content per state that varies annually based on production. However, most coal-producing states produce only one rank of coal. For these states the weighted factor equals the carbon content calculated in Step 1 and is constant across the time series.

#### *Step 3. Allocate sectoral consumption by state of origin*

U.S. energy statistics[6] through 2007 provide data on the origin of coal used in four areas: 1) the electric power industry, 2) industrial coking, 3) all other industrial uses, and 4) the residential and commercial end-use sectors.[7] Because U.S. energy statistics do not provide the distribution of coal rank consumed by each consuming sector, it is assumed that each sector consumes a representative mixture of coal ranks from a particular state that matches the mixture of all coal produced in that state during the year. Thus, the weighted state-level factor developed in Step 2 is applied.

#### *Step 4. Weight sectoral carbon contents to reflect the rank and state of origin of coal consumed*

Sectoral C contents are calculated by multiplying the share of coal purchased from each state by the state's weighted C content estimated in Step 2. The resulting partial C contents are then totaled across all states to generate a national sectoral C content.

$$C_{sector} = S_{state1} \times C_{state1} + S_{state2} \times C_{state2} + \ldots + S_{state50} \times C_{state50}$$

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[5] For a comparison to earlier estimated carbon contents please see *Chronology and Explanation of Changes in Individual Carbon Content Coefficients of Fossil Fuels* near the end of this annex.

[6] U.S. Energy Information Administration (EIA). *Coal Distribution – Annual* (2001-2008); and *Coal Industry Annual* (1990-2000).

[7] Beginning in 2008, the EIA collects and reports data on commercial and institutional coal consumption, rather than residential and commercial consumption. Thus, the residential / commercial coal coefficient reported in Table A- 38 for 2009 represents the mix of coal consumed by commercial and institutional users. Currently, only an extremely small amount of coal is consumed in the U.S. Residential Sector.

Where,

$C_{sector}$ = The C content by consuming sector;
$S_{state}$ = The portion of consuming sector coal consumption attributed to production from a given state;
$C_{state}$ = The estimated weighted C content of all ranks produced in a given state.

Table A- 39: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank (Tg C/QBtu) (1990-2011)

| Consuming Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electric Power | 25.96 | 25.93 | 25.93 | 25.93 | 25.95 | 25.98 | 26.00 | 26.00 | 26.05 | 26.09 | 26.10 | 26.09 | 26.04 | 26.05 | 26.05 | 26.05 | 26.05 | 26.05 |
| Industrial Coking | 25.53 | 25.57 | 25.56 | 25.59 | 25.62 | 25.59 | 25.63 | 25.63 | 25.65 | 25.63 | 25.63 | 25.60 | 25.60 | 25.61 | 25.61 | 25.61 | 25.61 | 25.61 |
| Other Industrial | 25.82 | 25.80 | 25.75 | 25.75 | 25.79 | 25.80 | 25.74 | 25.66 | 25.57 | 25.55 | 25.56 | 25.80 | 25.84 | 25.82 | 25.82 | 25.82 | 25.82 | 25.82 |
| Residential/ Commercial | 26.20 | 26.13 | 26.04 | 25.90 | 26.07 | 25.98 | 26.01 | 26.00 | 25.98 | 26.04 | 25.91 | 26.09 | 26.29 | 25.94 | 25.71 | 25.71 | 25.71 | 25.71 |
| **Coal Rank** | | | | | | | | | | | | | | | | | | |
| Anthracite | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 | 28.28 |
| Bituminous | 25.38 | 25.42 | 25.43 | 25.43 | 25.43 | 25.44 | 25.45 | 25.46 | 25.46 | 25.45 | 25.45 | 25.45 | 25.45 | 25.45 | 25.44 | 25.44 | 25.44 | 25.44 |
| Sub-bituminous | 26.50 | 26.50 | 26.50 | 26.50 | 26.50 | 26.50 | 26.49 | 26.50 | 26.50 | 26.50 | 26.50 | 26.50 | 26.50 | 26.50 | 26.50 | 26.50 | 26.50 | 26.50 |
| Lignite | 26.58 | 26.59 | 26.58 | 26.59 | 26.59 | 26.60 | 26.61 | 26.62 | 26.63 | 26.62 | 26.62 | 26.62 | 26.62 | 26.64 | 26.65 | 26.65 | 26.65 | 26.65 |

[a] In 2008, the EIA began collecting consumption data for commercial and institutional consumption rather than commercial and residential consumption.

Sources: C content coefficients calculated from USGS (1998) and PSU (2010); data presented in EPA (2010b).

***Step 5. Develop national-level carbon contents by rank for comparison to IPCC defaults***

Although not used to calculate emissions, national-level C contents by rank are more easily compared to C contents of other countries than are sectoral C contents. This step requires weighting the state-level C contents by rank developed under Step 1 by overall coal production by state and rank. Each state-level C content by rank is multiplied by the share of national production of that rank that each state represents. The resulting partial C contents are then summed across all states to generate an overall C content for each rank.

$$N_{rank} = P_{rank1} \times C_{rank1} + P_{rank2} \times C_{rank2} + \ldots + P_{rankn} \times C_{rankn}$$

Where,

$N_{rank}$ = The national C content by rank;
$P_{rank}$ = The portion of U.S. coal production of a given rank attributed to each state; and
$C_{rank}$ = The estimated C content of a given rank in each state.

**Data Sources**

The ultimate analysis of coal samples was based on the 7,092 coal samples, 6,588 of which are from USGS (1998) and 504 that come from the Pennsylvania State University Coal Database (PSU 2010). Data contained in the USGS's CoalQual Database are derived primarily from samples taken between 1973 and 1989, and were largely reported in State Geological Surveys. Data in the PSU Coal Database are mainly from samples collected by PSU since 1967 and are housed at the PSU Sample Bank. Only the subset of PSU samples that are whole-seam channel samples are included in the development of carbon factors in order to increase data accuracy.

Data on coal consumption by sector and state of origin, as well as coal production by state and rank, were obtained from EIA. The EIA's *Annual Coal Report* is the source for state coal production by rank from 2001-2008. In prior years, the EIA reported this data in its *Coal Industry Annual*. Data for coal consumption by state of origin and consuming sector for 2001 to 2008 was obtained from the EIA's *Coal Distribution – Annual*. For 1990-2000, end-use data was obtained from the *Coal Industry Annual*.

**Uncertainty**

C contents vary considerably by state. Bituminous coal production and sub-bituminous coal production represented 47.3 percent and 46.1 percent of total U.S. supply in 2008, respectively. State average C content coefficients for bituminous coal vary from a low of 85.59 kg $CO_2$ per MMBtu in Texas to a high of 105.21 kg $CO_2$ per MMBtu in Montana. However, Texas bituminous coal is considered anomalous,[8] has not been produced since 2004 and production since 1990 peaked at just 446,000 short tons in 1996. The next lowest average emission factor for bituminous coal is found in Western Kentucky (91.36 kg $CO_2$ per MMBtu). In 2000, Montana produced no bituminous coal and Western Kentucky production accounted for just 4.5 percent of overall bituminous production. In 2008, more than 60 percent of bituminous coal was produced in three states: West Virginia, Kentucky (predominantly from the Eastern production region), and Pennsylvania, and this share has remained fairly constant since 1990. These three states show a variation in C content for bituminous coals of ±0.7 percent, based on more than 2,000 samples (see Table A-40).

Similarly, the C content coefficients for sub-bituminous coal range from 91.29 kg $CO_2$ per MMBtu in Utah to 98.10 kg $CO_2$ per MMBtu in Alaska. However, Utah has no recorded production of sub-bituminous coal since 1990. Production of sub-bituminous coal in Alaska has made up less than 0.7 percent of total sub-bituminous production since 1990, with even this small share declining over time. Wyoming has represented between 75 percent and 87 percent of total sub-bituminous coal production in the United States in each year since 1990. Thus, the C content coefficient for Wyoming (97.22 kg $CO_2$ per MMBtu), based on 455 samples, dominates the national average.

The interquartile range of C content coefficients among samples of sub-bituminous coal in Wyoming was ±1.5 percent from the mean. Similarly, this range among samples of bituminous coal from West Virginia, Kentucky, and Pennsylvania was ±1.2 percent or less for each state. The large number of samples and the low variability within the sample set of the states that represent the predominant source of supply of U.S. coal suggest that the uncertainty in this factor is very low, on the order of ±1.0 percent.

[8] See, for example: San Filipo, 1999. USGS. (U.S. Geological Survey Open-File Report 99-301), Ch. 4.

For comparison, J. Quick (2010) completed an analysis similar in methodology to that used here, in order to generate national average carbon emission factors as well as county-level factors. This study's rank-based national average factors have a maximum deviation from the factors developed in this Inventory report of -0.55 percent, which is for lignite (range: -0.55 to +0.1 percent). This corroboration further supports the assertion of minimal uncertainty in the application of the rank-based factors derived for the purposes of this Inventory.

Table A-40: Variability in Carbon Content Coefficients by Rank Across States (Kilograms $CO_2$ Per MMBtu)

| State | Number of Samples | Bituminous | Sub-bituminous | Anthracite | Lignite |
|---|---|---|---|---|---|
| Alabama | 951 | 92.84 | - | - | 99.10 |
| Alaska | 91 | 98.33 | 98.10 | - | 98.65 |
| Arizona | 15 | 93.94 | 97.34 | - | - |
| Arkansas | 80 | 96.36 | - | - | 94.97 |
| Colorado | 318 | 94.37 | 96.52 | - | 101.10 |
| Georgia | 35 | 95.01 | - | - | - |
| Idaho | 1 | - | 94.90 | - | - |
| Illinois | 57 | 92.33 | - | - | - |
| Indiana | 146 | 92.65 | - | - | - |
| Iowa | 100 | 91.87 | - | - | - |
| Kansas | 29 | 90.91 | - | - | - |
| Kentucky | 897 | 92.61 | - | - | - |
| Louisiana | 1 | - | - | - | 96.01 |
| Maryland | 47 | 94.29 | - | - | - |
| Massachusetts | 3 | - | - | 114.82 | - |
| Michigan | 3 | 92.88 | - | - | - |
| Mississippi | 8 | - | - | - | 98.19 |
| Missouri | 111 | 91.71 | - | - | - |
| Montana | 309 | 105.21 | 97.73 | 103.60 | 99.40 |
| Nevada | 2 | 94.41 | - | - | 99.86 |
| New Mexico | 185 | 94.29 | 94.89 | 103.92 | - |
| North Dakota | 202 | - | 93.97 | - | 99.48 |
| Ohio | 674 | 91.84 | - | - | - |
| Oklahoma | 63 | 92.33 | - | - | - |
| Pennsylvania | 861 | 93.33 | - | 103.68 | - |
| Tennessee | 61 | 92.82 | - | - | - |
| Texas | 64 | 85.59 | 94.19 | - | 94.47 |
| Utah | 169 | 95.75 | 91.29 | - | - |
| Virginia | 470 | 93.51 | - | 98.54 | - |
| Washington | 18 | 94.53 | 97.36 | 102.53 | 106.55 |
| West Virginia | 612 | 93.84 | - | - | - |
| Wyoming | 503 | 94.80 | 97.22 | - | - |
| **U.S. Average** | **7,092** | **93.13** | **96.94** | **104.29** | **98.63** |

Notes: - Indicates No Sample Data Available.
Sources: Calculated from USGS (1998), and PSU (2010); data presented in EPA (2010).

## Natural Gas

Natural gas is predominantly composed of methane, which is 75 percent C by weight and contains 14.2 Tg C/QBtu (higher heating value), but it may also contain many other compounds that can lower or raise its overall C content. These other compounds may be divided into two classes: 1) natural gas liquids (NGLs), and 2) non-hydrocarbon gases. The most common NGLs are ethane ($C_2H_6$), propane ($C_3H_8$), butane ($C_4H_{10}$), and, to a lesser extent, pentane ($C_5H_{12}$) and hexane ($C_6H_{14}$). Because the NGLs have more C atoms than $CH_4$ (which has only one), their presence increases the overall C content of natural gas. NGLs have a commercial value greater than that of $CH_4$, and therefore are usually separated from raw natural gas at gas processing plants and sold as separate products. Ethane is typically used as a

petrochemical feedstock, propane and butane have diverse uses, and natural gasoline[9] contributes to the gasoline/naphtha "octane pool," used primarily to make motor gasoline.

Raw natural gas can also contain varying amounts of non-hydrocarbon gases, such as $CO_2$, nitrogen, helium and other noble gases, and hydrogen sulfide. The share of non-hydrocarbon gases is usually less than 5 percent of the total, but there are individual natural gas reservoirs where the share can be much larger. The treatment of non-hydrocarbon gases in raw gas varies. Hydrogen sulfide is always removed. Inert gases are removed if their presence is substantial enough to reduce the energy content of the gas below pipeline specifications (see Step 1, below). Otherwise, inert gases will usually be left in the natural gas. Because the raw gas that is usually flared (see Step 2, below) contains NGLs and $CO_2$, it will typically have a higher overall C content than gas that has been processed and moved to end-use customers via transmission and distribution pipelines.

### Methodology

The methodology for estimating the C contents of pipeline and flared natural gas can be described in five steps.

#### *Step 1. Define pipeline-quality natural gas*

In the United States, pipeline-quality natural gas is required to have an energy content greater than 970 Btu per cubic foot, but less than 1,100 Btu per cubic foot. Hydrogen sulfide content must be negligible. Typical pipeline-quality natural gas is about 95 percent $CH_4$, 3 percent NGLs, and 2 percent non-hydrocarbon gases, of which approximately half is $CO_2$.

However, there remains a range of gas compositions that are consistent with pipeline specifications. The minimum C content coefficient for natural gas would match that for pure $CH_4$, which equates to an energy content of 1,005 Btu per standard cubic foot. Gas compositions with higher or lower Btu content tend to have higher C emission factors, because the "low" Btu gas has a higher content of inert gases (including $CO_2$ offset with more NGLs), while "high" Btu gas tends to have more NGLs.

#### *Step 2. Define flared gas*

Every year, a certain amount of natural gas is flared in the United States. There are several reasons that gas is flared:

- There may be no market for some batches of natural gas, the amount may be too small or too variable, or the quality might be too poor to justify treating the gas and transporting it to market (such is the case when gas contains large shares of $CO_2$). Most natural gas that is flared for these reasons is "rich" associated gas, with relatively high energy content, high NGL content, and a high C content.
- Gas treatment plants may flare substantial volumes of natural gas because of "process upsets," because the gas is "off spec," or possibly as part of an emissions control system. Gas flared at processing plants may be of variable quality.

Data on the energy content of flare gas, as reported by states to EIA, indicate an average energy content of 1,130 Btu per standard cubic foot (EIA 1994). Flare gas may have an even higher energy content than reported by EIA since rich associated gas can have energy contents as high as 1,300 to 1,400 Btu per cubic foot.

#### *Step 3. Determine a relationship between carbon content and heat content*

A relationship between C content and heat content may be used to develop a C content coefficient for natural gas consumed in the United States. In 1994, EIA examined the composition (including C contents) of 6,743 samples of pipeline-quality natural gas from utilities and/or pipeline companies in 26 cities located in 19 states. To demonstrate that these samples were representative of actual natural gas "as consumed" in the United States, their heat content was compared to that of the national average. For the most recent year, the average heat content of natural gas consumed in the United States was 1,029 Btu per cubic foot, and has varied by less than 1 percent (1,027 to 1,029 Btu per cubic foot) over the past 5 years. Meanwhile, the average heat content of the 6,743 samples was 1,027 Btu per cubic foot, and the median heat content was 1,031 Btu per cubic foot. Thus, the average heat content of the sample set falls well within the typical

[9] A term used in the gas processing industry to refer to a mixture of liquid hydrocarbons (mostly pentanes and heavier hydrocarbons) extracted from natural gas.

range of natural gas consumed in the United States, suggesting that these samples continue to be representative of natural gas "as consumed" in the United States. The average and median composition of these samples appear inTable A-41.

Table A-41: Composition of Natural Gas (Percent)

| Compound | Average | Median |
|---|---|---|
| Methane | 93.07 | 95.00 |
| Ethane | 3.21 | 2.79 |
| Propane | 0.59 | 0.48 |
| Higher Hydrocarbons | 0.32 | 0.30 |
| Non-hydrocarbons | 2.81 | 1.43 |
| Higher Heating Value (Btu per cubic foot) | 1,027 | 1,031 |

Source: Gas Technology Institute (1992).

Carbon contents were calculated for a series of sub-samples based on their $CO_2$ content and heat content. Carbon contents were calculated for the groups of samples with less than 1.0 percent (n=5,181) and less than 1.5 percent $CO_2$ only (n=6,522) and those with less than 1.0 or 1.5 percent $CO_2$ and less than 1,050 Btu/cf (n= 4,888 and 6,166, respectively). These stratifications were chosen to exclude samples with $CO_2$ content and heat contents outside the range of pipeline-quality natural gas. In addition, hexane was removed from the samples since it is usually stripped out of raw natural gas before delivery because it is a valuable natural gas liquid used as a feedstock for gasoline. The average carbon contents for the four separate sub-samples are shown below in Table A-42.

Table A-42: Carbon Content of Pipeline-Quality Natural Gas by $CO_2$ and Heat Content (Tg C/QBtu)

| Sample | Average Carbon Content |
|---|---|
| Full Sample | 14.48 |
| < 1.0% $CO_2$ | 14.43 |
| < 1.5% $CO_2$ | 14.47 |
| < 1.0 % $CO_2$ and <1,050 Btu/cf | 14.42 |
| < 1.5 % $CO_2$ and <1,050 Btu/cf | 14.47 |

Source: EPA (2010).

***Step 4. Apply carbon content coefficients developed in Step 3 to pipeline natural gas***

A regression analysis was performed on the sub-samples in to further examine the relationship between carbon content and heat content. The regression used carbon content as the dependent variable and heat content as the independent variable. The resulting R-squared values[10] for each of the sub-samples ranged from 0.79 for samples with less than 1.5% $CO_2$ and under 1,050 Btu/cf to 0.91 for samples containing less than 1.0 percent $CO_2$ only. However, the sub-sample with less than 1.5% $CO_2$ and 1,050 Btu/cf was chosen as the representative sample for two reasons. First, it most accurately reflects the range of $CO_2$ content and heat content of pipeline quality natural gas. Secondly, the R-squared value, although it is the lowest of the sub-groups tested, remains relatively high. This high R-squared indicates a low percentage of variation in C content as related to heat content. The regression for this sub-sample resulted in the following equation:

$$\text{C Content} = (0.011 \times \text{Heat Content}) + 3.5341$$

This equation was used to estimate the annual predicted carbon content of natural gas from 1990 to 2010 based on the EIA's national average pipeline-quality gas heat content for each year. The table of average C contents for each year is shown below in Table A-43.

Table A-43: Carbon Content Coefficients for Natural Gas (Tg Carbon/QBtu)

| Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Natural Gas | 14.45 | 14.46 | 14.46 | 14.46 | 14.44 | 14.46 | 14.47 | 14.46 | 14.46 | 14.44 | 14.46 | 14.46 | 14.46 | 14.46 | 14.46 | 14.46 | 14.46 | 14.46 |

Source: EPA (2010)

[10] R-squared represents the percentage of variation in the dependent variable (in this case carbon content) explained by variation in the independent variables.

***Step 5. Apply carbon content coefficients developed in Step 3 to flare gas***

Selecting a C content coefficient for flare gas was much more difficult than for pipeline natural gas, because of the uncertainty of its composition and of the combustion efficiency of the flare. Because EIA estimates the heat content of flare gas at 1,130 Btu per cubic foot, the average C content for samples with more than 1,100 Btu per cubic foot (n=18) was chosen as the relevant sub-sample from which to calculate a flare gas carbon content. It should be noted that the sample dataset did not include any samples with more than 1,130 Btu per cubic foot.

Hexane was not removed from flare gas samples since it is assumed that natural gas liquids are present in samples with higher heat contents. Carbon contents were calculated for each sample with a heat content of more than 1,100 Btu per cubic foot. The simple average carbon content for the sample sub-set representing flare gas is shown below in Table A-44.

Table A-44: Carbon Content of Flare Gas (Tg C/QBtu)

| Relevant Sub-Sample | Average Carbon Content |
|---|---|
| >1,100 Btu/cf | 15.31 |

Source: EPA (2010)

**Data Sources**

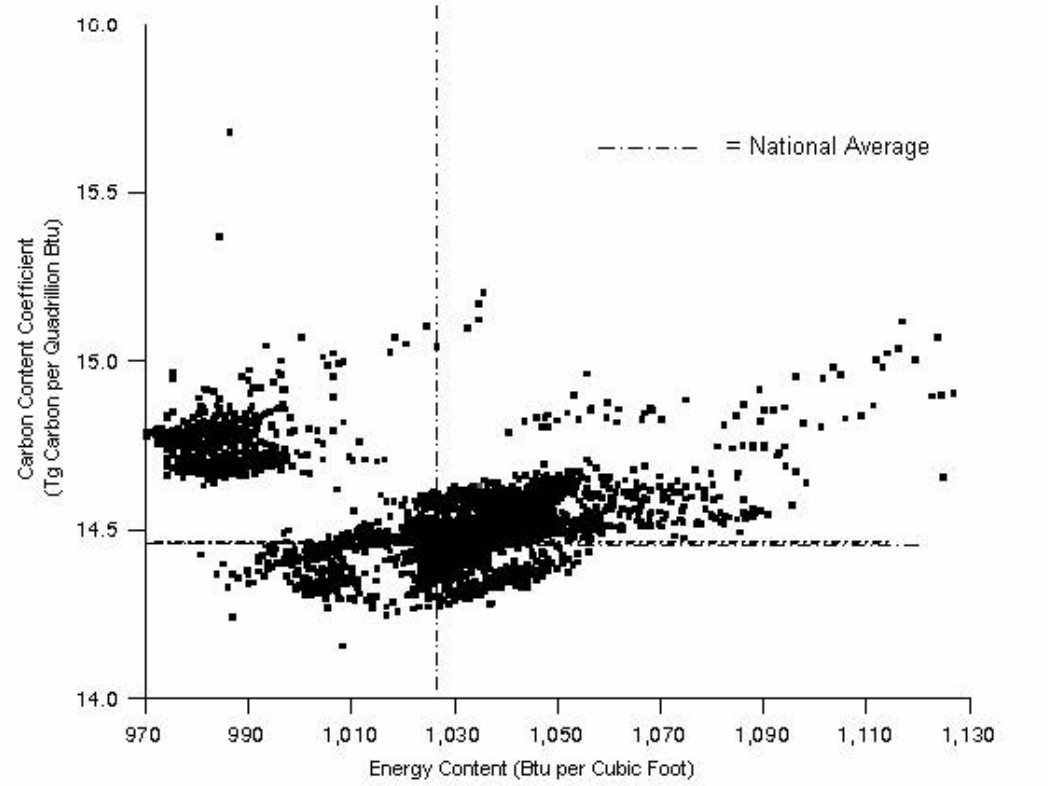
Natural gas samples were obtained from the Gas Technology Institute (1992). Average heat content data for natural gas consumed in the United States was taken from EIA (2009a).

**Uncertainty**

The assignment of C content coefficients for natural gas, and particularly for flare gas, requires more subjective judgment than the methodology used for coal. This subjective judgment may introduce additional uncertainty.

Figure A-1 shows the relationship between the calculated C content for each natural gas sample and its energy content. This figure illustrates the relatively restricted range of variation in both the energy content (which varies by about 6 percent from average) and the C emission coefficient of natural gas (which varies by about 5 percent). Thus, the knowledge that gas has been sold via pipeline to an end-use consumer allows its C emission coefficient to be predicted with an accuracy of ±5.0 percent.

Figure A-1: Carbon Content for Samples of Pipeline-Quality Natural Gas Included in the Gas Technology Institute Database




Source: EIA (1994) Energy Information Administration, Emissions of Greenhouse Gases in the United States 1987-1992, U.S. Department of Energy, Washington, DC, November, 1994, DOE/EIA 0573, Appendix A.

Natural gas suppliers may achieve the same overall energy content from a wide variety of methane, higher hydrocarbon, and non-hydrocarbon gas combinations. Thus, the plot reveals large variations in C content for a single Btu value. In fact, the variation in C content for a single Btu value may be nearly as great as the variation for the whole sample. As a result, while energy content has some predictive value, the specific energy content does not substantially improve the accuracy of an estimated C content coefficient beyond the ±5.0 percent offered with the knowledge that it is of pipeline-quality.

The plot of C content also reveals other interesting anomalies. Samples with the lowest emissions coefficients tend to have energy contents of about 1,000 Btu per cubic foot. They are composed of almost pure $CH_4$. Samples with a greater proportion of NGLs (e.g., ethane, propane, and butane) tend to have energy contents greater than 1,000 Btu per cubic foot, along with higher emissions coefficients. Samples with a greater proportion of inert gases tend to have lower energy content, but they usually contain $CO_2$ as one of the inert gases and, consequently, also tend to have higher emission coefficients (see left side of Figure A-1).

For the full sample (n=6,743), the average C content of a cubic foot of gas was 14.48 Tg C/QBtu (see Table A-43). Additionally, a regression analysis using the full sample produced a predicted C content of 14.49 Tg C/QBtu based on a heat content of 1,029 Btu/cf (the average heat content in the U.S. for the most recent year). However, these two values include an upward influence on the resulting carbon content that is caused by inclusion in the sample set of the samples that contain large amounts of inert carbon dioxide and those samples with more than 1,050 Btu per cubic foot that contain an unusually large amount of NGLs. Because typical gas consumed in the United States does not contain such a large amount of carbon dioxide or natural gas liquids, a carbon content of 14.47 Tg C/QBtu, based on samples with less

than 1.5 percent carbon dioxide and less than 1,050 Btu per cubic foot, better represents the pipeline-quality fuels typically consumed.

## Petroleum

There are four critical determinants of the C content coefficient for a petroleum-based fuel:

- The density of the fuel (e.g., the weight in kilograms of one barrel of fuel);
- The fraction by mass of the product that consists of hydrocarbons, and the fraction of non-hydrocarbon impurities;
- The specific types of "families" of hydrocarbons that make up the hydrocarbon portion of the fuel; and
- The heat content of the fuel.

$$C_{fuel} = (D_{fuel} \times S_{fuel}) / E_{fuel}$$

Where,

$C_{fuel}$ = The C content coefficient of the fuel;
$D_{fuel}$ = The density of the fuel;
$S_{fuel}$ = The share of the fuel that is C; and
$E_{fuel}$ = The heat content of the fuel.

Most of the density, carbon share or heat contents applied to calculate the carbon coefficients for petroleum products that are described in this sub-Annex and applied to this emissions inventory have been updated for this edition of the report. These changes have been made where necessary to increase the accuracy of the underlying data or to align the petroleum properties data used in this report with that developed for use in the Mandatory Reporting of Greenhouse Gases Rule (EPA 2009b).

Petroleum products vary between 5.6 degrees API gravity (dense products such as asphalt and road oil) and 247 degrees (ethane).[11] This is a range in density of 60 to 150 kilograms per barrel, or ±50 percent. The variation in C content, however, is much smaller (±5 to 7 percent) for products produced by standard distillation refining: ethane is 80 percent C by weight, while petroleum coke is 90 to 92 percent C. This tightly bound range of C contents can be explained by basic petroleum chemistry (see below). Additional refining can increase carbon contents. Calcined coke, for example, is formed by heat treating petroleum coke to about 1600 degrees Kelvin (calcining), to expel volatile materials and increase the percentage of elemental carbon. This product can contain as much as 97 to 99 percent carbon. Calcined coke is mainly used in the aluminum and steel industry to produce C anodes.

### Petroleum Chemistry

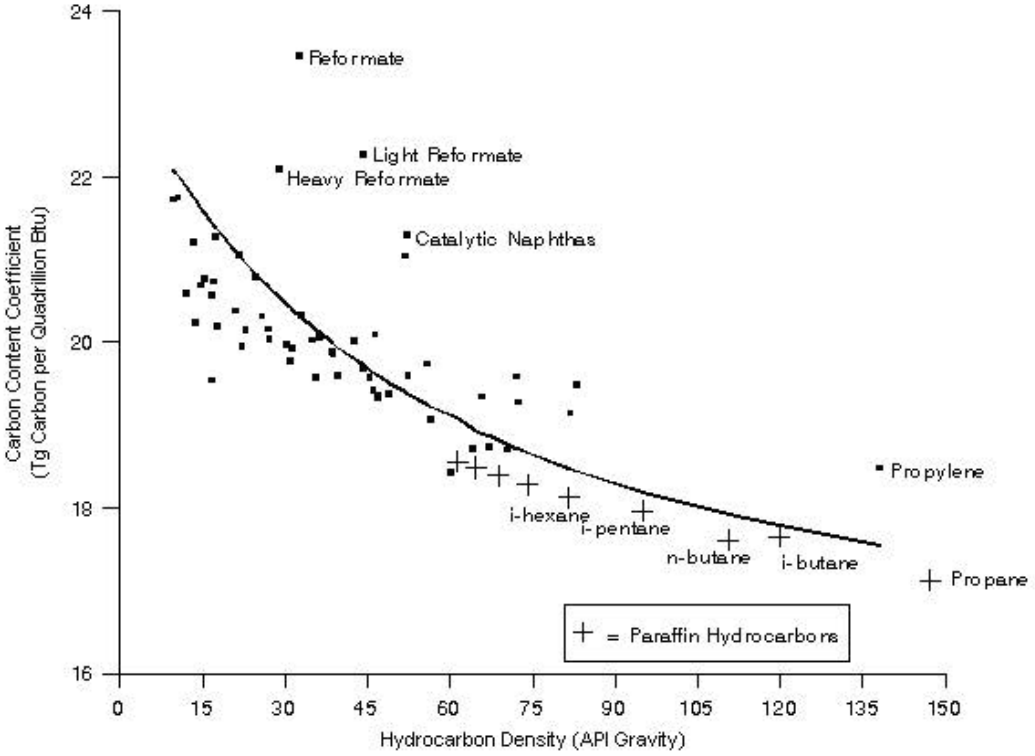
Crude oil and petroleum products are typically mixtures of several hundred distinct compounds, predominantly hydrocarbons. All hydrocarbons contain hydrogen and C in various proportions. When crude oil is distilled into petroleum products, it is sorted into fractions by the boiling temperature of these hundreds of organic compounds. Boiling temperature is strongly correlated with the number of C atoms in each molecule. Petroleum products consisting of relatively simple molecules and few C atoms have low boiling temperatures, while larger molecules with more C atoms have higher boiling temperatures.

Products that boil off at higher temperatures are usually more dense, which implies greater C content as well. Petroleum products with higher C contents, in general, have lower energy content per unit mass and higher energy content per unit volume than products with lower C contents. Empirical research led to the establishment of a set of quantitative relationships between density, energy content per unit weight and volume, and C and hydrogen content. Figure A-2 compares C content coefficients calculated on the basis of the derived formula with actual C content coefficients for a

[11] API gravity is an arbitrary scale expressing the gravity or density of liquid petroleum products, as established by the American Petroleum Institute (API). The measuring scale is calibrated in terms of degrees API. The higher the API gravity, the lighter the compound. Light crude oils generally exceed 38 degrees API and heavy crude oils are all crude oils with an API gravity of 22 degrees or below. Intermediate crude oils fall in the range of 22 degrees to 38 degrees API gravity. API gravity can be calculated with the following formula: API Gravity = (141.5/Specific Gravity) – 131.5. Specific gravity is the density of a material relative to that of water. At standard temperature and pressure, there are 62.36 pounds of water per cubic foot, or 8.337 pounds water per gallon.

range of crude oils, fuel oils, petroleum products, and pure hydrocarbons. The actual fuel samples were drawn from the sources described below in the discussions of individual petroleum products.

Figure A-2: Estimated and Actual Relationships Between Petroleum Carbon Content Coefficients and Hydrocarbon Density




Source: Carbon content factors for paraffins are calculated based on the properties of hydrocarbons in V. Guthrie (ed.), *Petroleum Products Handbook* (New York: McGraw Hill, 1960) p. 33. Carbon content factors from other petroleum products are drawn from sources described below. Relationship between density and emission factors based on the relationship between density and energy content in U.S. Department of Commerce, National Bureau of Standards, *Thermal Properties of Petroleum Products*, Miscellaneous Publication, No. 97 (Washington, D.C., 1929), pp.16-21, and relationship between energy content and fuel composition in S. Ringen, J. Lanum, and F.P. Miknis, "Calculating Heating Values from the Elemental Composition of Fossil Fuels," *Fuel*, Vol. 58 (January 1979), p.69.

The derived empirical relationship between C content per unit heat and density is based on the types of hydrocarbons most frequently encountered. Petroleum fuels can vary from this relationship due to non-hydrocarbon impurities and variations in molecular structure among classes of hydrocarbons. In the absence of more exact information, this empirical relationship offers a good indication of C content.

***Non-hydrocarbon Impurities***

Most fuels contain a certain share of non-hydrocarbon material. This is also primarily true of crude oils and fuel oils. The most common impurity is sulfur, which typically accounts for between 0.5 and 4 percent of the mass of most crude oils, and can form an even higher percentage of heavy fuel oils. Some crude oils and fuel oils also contain appreciable quantities of oxygen and nitrogen, typically in the form of asphaltenes or various acids. The nitrogen and oxygen content of crude oils can range from near zero to a few percent by weight. Lighter petroleum products have much lower levels of impurities, because the refining process tends to concentrate all of the non-hydrocarbons in the residual oil

fraction. Light products usually contain less than 0.5 percent non-hydrocarbons by mass. Thus, the C content of heavy fuel oils can often be several percent lower than that of lighter fuels, due entirely to the presence of non-hydrocarbons.

#### *Variations in Hydrocarbon Classes*

Hydrocarbons can be divided into five general categories, each with a distinctive relationship between density and C content and physical properties. Refiners tend to control the mix of hydrocarbon types in particular products in order to give petroleum products distinct properties. The main classes of hydrocarbons are described below.

*Paraffins***.** Paraffins are the most common constituent of crude oil, usually comprising 60 percent by mass. Paraffins are straight-chain hydrocarbons with the general formula $C_nH_{2n+2}$. Paraffins include ethane ($C_2H_6$), propane ($C_3H_8$), butane ($C_4H_{10}$), and octane ($C_8H_{18}$). As the chemical formula suggests, the C content of the paraffins increases with their C number: ethane is 79.89 percent C by weight, octane 84.12 percent. As the size of paraffin molecules increases, the C content approaches the limiting value of 85.7 percent asymptotical (see Figure A-3).

*Cycloparaffins.* Cycloparaffins are similar to paraffins, except that the C molecules form ring structures rather than straight chains, and consequently require two fewer hydrogen molecules than paraffins. Cycloparaffins always have the general formula $C_nH_{2n}$ and are 85.63 percent C by mass, regardless of molecular size.

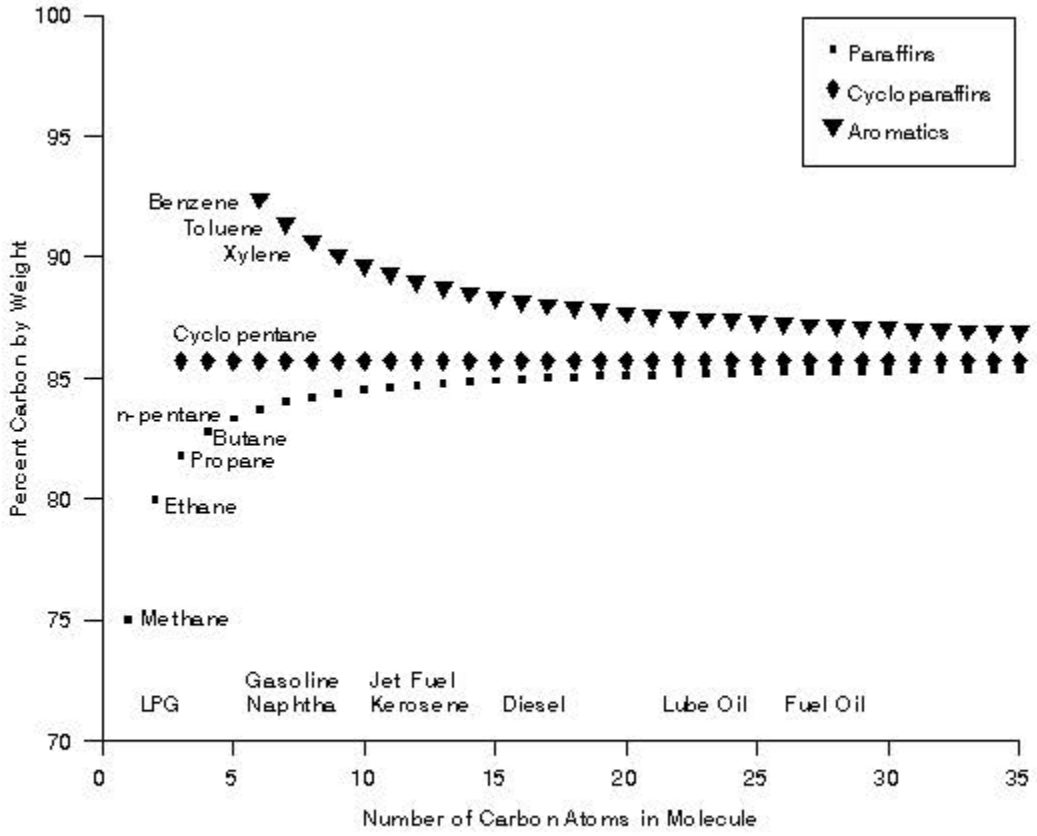
*Olefins.* Olefins are a very reactive and unstable form of paraffin: a straight chain with two carbon atoms double bonded together (thus are unsaturated) compared to the carbon atoms in a paraffin (which are saturated with hydrogen).. They are never found in crude oil but are created in moderate quantities by the refining process. Gasoline, for example, may contain between 2 and 20 percent olefins. They also have the general formula $C_nH_{2n}$, and hence are also always 85.63 percent C by weight. Propylene ($C_3H_6$), a common intermediate petrochemical product, is an olefin.

*Aromatics.* Aromatics are very reactive hydrocarbons that are relatively uncommon in crude oil (10 percent or less). Light aromatics increase the octane level in gasoline, and consequently are deliberately created by catalytic reforming of heavy naphtha. Aromatics also take the form of ring structures with some double bonds between C atoms. The most common aromatics are benzene ($C_6H_6$), toluene ($C_7H_8$), and xylene ($C_8H_{10}$). The general formula for aromatics is $C_nH_{2n-6}$. Benzene is 92.26 percent C by mass, while xylene is 90.51 percent C by mass and toluene is 91.25 percent C by mass. Unlike the other hydrocarbon families, the C content of aromatics declines asymptotically toward 85.7 percent with increasing C number and density (see Figure A-3).

*Polynuclear Aromatics.* Polynuclear aromatics are large molecules with a multiple ring structure and few hydrogen atoms, such as naphthalene ($C_{10}H_8$ and 93.71 percent C by mass) and anthracene ($C_{14}H_{10}$ and 97.7 percent C). They are relatively rare but do appear in heavier petroleum products.

Figure A-3 illustrates the share of C by weight for each class of hydrocarbon. Hydrocarbon molecules containing 2 to 4 C atoms are all natural gas liquids; hydrocarbons with 5 to 10 C atoms are predominantly found in naphtha and gasoline; and hydrocarbon compounds with 12 to 20 C atoms comprise "middle distillates," which are used to make diesel fuel, kerosene and jet fuel. Larger molecules which can be vacuum distilled may be used as lubricants, waxes, and residual fuel oil or cracked and blended into the gasoline or distillate pools.

Figure A-3: Carbon Content of Pure Hydrocarbons as a Function of Carbon Number




Source: J.M. Hunt, *Petroleum Geochemistry and Geology* (San Francisco, CA, W.H. Freeman and Company, 1979), pp. 31-37.

If one knows nothing about the composition of a particular petroleum product, assuming that it is 85.7 percent C by mass is not an unreasonable first approximation. Since denser products have higher C numbers, this guess would be most likely to be correct for crude oils and fuel oils. The C content of lighter products is more affected by the shares of paraffins and aromatics in the blend.

### Energy Content of Petroleum Products

The exact energy content (gross heat of combustion) of petroleum products is not generally known. EIA estimates energy consumption in Btu on the basis of a set of industry-standard conversion factors. These conversion factors are generally accurate to within 3 to 5 percent.

#### *Individual Petroleum Products*

The United States maintains data on the consumption of more than 20 separate petroleum products and product categories. The C contents, heat contents, and density for each product are provided below in Table A-45. A description of the methods and data sources for estimating the key parameters for each individual petroleum product appears below.

Table A-45: Carbon Content Coefficients and Underlying Data for Petroleum Products

| Fuel | 2008 Carbon Content | Gross Heat of Combustion | Density | Percent |
|---|---|---|---|---|

| | (Tg C/QBtu) | (MMBtu/Barrel) | (API Gravity) | Carbon |
|---|---|---|---|---|
| Motor Gasoline | 19.46 | a | a | a |
| LPG(total) | 16.97 | b | b | b |
| LPG (energy use) | 16.83 | b | b | b |
| LPG (non-energy use) | 17.06 | b | b | b |
| Jet Fuel | 19.70 | 5.670 | 42.0 | 86.30 |
| Distillate Fuel No. 1 | 19.98 | 5.822 | 35.3 | 86.40 |
| Distillate Fuel No. 2 | 20.17 | 5.809 | 35.8 | 87.30 |
| Distillate Fuel No. 4 | 20.47 | 6.135 | 23.2 | 86.47 |
| Residual Fuel No. 5 | 19.89 | 5.879 | 33.0 | 85.67 |
| Residual Fuel No. 6 | 20.48 | 6.317 | 15.5 | 84.67 |
| Asphalt and Road Oil | 20.55 | 6.636 | 5.6 | 83.47 |
| Lubricants | 20.20 | 6.065 | 25.7 | 85.80 |
| Naphtha (< 400 deg. F) [c] | 18.55 | 5.248 | 62.4 | 84.11 |
| Other Oils (>400 deg. F) [c] | 20.17 | 5.825 | 35.8 | 87.30 |
| Aviation Gas | 18.86 | 5.048 | 69.0 | 85.00 |
| Kerosene | 19.96 | 5.825 | 35.3 | 86.40 |
| Petroleum Coke | 27.85 | 6.024 | - | 92.28 |
| Special Naphtha | 19.74 | 5.248 | 52.0 | 84.75 |
| Petroleum Waxes | 19.80 | 5.537 | 43.3 | 85.30 |
| Still Gas | 18.20 | 6.000 | - | 77.70 |
| Crude Oil | 20.31 | 5.800 | 31.2 | 85.49 |
| Unfinished Oils | 20.31 | 5.825 | 31.2 | 85.49 |
| Miscellaneous Products | 20.31 | 5.796 | 31.2 | 85.49 |
| Pentanes Plus | 19.10 | 4.620 | 81.3 | 83.63 |

[a] Calculation of the carbon content coefficient for motor gasoline in 2008 uses separate higher heating values for conventional and reformulated gasoline of 5.253 and 5.150, respectively (EIA 2008a). Densities and carbon shares (percent carbon) are annually variable and separated by both fuel formulation and grade, see Motor Gasoline and Blending Components, below, for details.
[b] LPG is a blend of multiple paraffinic hydrocarbons: ethane, propane, isobutane, and normal butane, each with their own heat content, density and C content, see Table A-48.
[c] Petrochemical feedstocks have been split into naphthas and other oils for this inventory report. Parameters presented are for naphthas with a boiling temperature less than 400 degrees Fahrenheit. Other oils are petrochemical feedstocks with higher boiling points. They are assumed to have the same characteristics as distillate fuel oil no. 2.
- No sample data available
Sources: EIA (1994), EIA (2009a), EPA (2009b), and EPA (2010).

*Motor Gasoline and Motor Gasoline Blending Components*

Motor gasoline is a complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in spark-ignition engines.[12] "Motor Gasoline" includes conventional gasoline; all types of oxygenated gasoline, including gasohol; and reformulated gasoline; but excludes aviation gasoline.

Gasoline is the most widely used petroleum product in the United States, and its combustion accounts for nearly 20 percent of all U.S. $CO_2$ emissions. EIA collects consumption data (i.e., "petroleum products supplied" to end-users) for several types of finished gasoline over the 1990-2008 time period: regular, mid-grade and premium conventional gasoline (all years) and regular, mid-grade and premium reformulated gasoline (November 1994 to 2008). Leaded and oxygenated gasoline are not separately included in the data used for this report.[13]

The American Society for Testing and Materials (ASTM) standards permit a broad range of densities for gasoline, ranging from 50 to 70 degrees API gravity, or 111.52 to 112.65 kilograms per barrel (EIA 1994), which implies a range of possible C and energy contents per barrel. Table A- 46 reflects changes in the density of gasoline over time and across grades and formulations of gasoline through 2008.

[12] Motor gasoline, as defined in ASTM Specification D 4814 or Federal Specification VV-G-1690C, is characterized as having a boiling range of 122 degrees to 158 degrees Fahrenheit at the 10-percent recovery point to 365 degrees to 374 degrees Fahrenheit at the 90-percent recovery point.

[13] Oxygenated gasoline volumes are included in the conventional gasoline data provided by EIA from 2007 onwards. Leaded gasoline was included in total gasoline by EIA until October 1993.

Table A- 46: Motor Gasoline Density, 1990 – 2011 (Degrees API)

| Fuel Grade | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Conventional - Winter Grade** | | | | | | | | | | | | | | | | | | |
| Low Octane | 62.0 | 59.8 | 60.6 | 61.5 | 61.8 | 61.6 | 61.6 | 61.7 | 61.6 | 61.8 | 62.4 | 62.6 | 62.7 | 63.1 | 63.0 | 63.0 | 63.0 | 63.0 |
| High Octane | 59.0 | 58.0 | 58.5 | 59.3 | 60.0 | 60.3 | 59.7 | 59.1 | 59.0 | 59.9 | 60.7 | 60.9 | 60.0 | 60.3 | 60.9 | 60.9 | 60.9 | 60.9 |
| **Conventional - Summer Grade** | | | | | | | | | | | | | | | | | | |
| Low Octane | 58.2 | 56.1 | 56.9 | 57.1 | 57.6 | 57.7 | 56.8 | 57.2 | 56.5 | 56.8 | 57.4 | 57.9 | 57.8 | 57.5 | 58.6 | 58.6 | 58.6 | 58.6 |
| High Octane | 55.5 | 55.1 | 55.3 | 56.4 | 55.7 | 57.4 | 55.8 | 55.5 | 55.7 | 56.0 | 57.0 | 57.0 | 57.4 | 56.9 | 58.0 | 58.0 | 58.0 | 58.0 |
| **Reformulated - Winter Grade** | | | | | | | | | | | | | | | | | | |
| Low Octane | NA | 61.9 | 62.3 | 62.1 | 62.7 | 62.7 | 62.7 | 62.6 | 61.9 | 62.1 | 62.7 | 62.8 | 62.3 | 62.1 | 62.4 | 62.4 | 62.4 | 62.4 |
| High Octane | NA | 59.9 | 60.8 | 62.1 | 61.4 | 61.0 | 61.1 | 61.0 | 61.8 | 61.9 | 61.8 | 61.8 | 61.7 | 62.1 | 62.5 | 62.5 | 62.5 | 62.5 |
| **Reformulated - Summer Grade** | | | | | | | | | | | | | | | | | | |
| Low Octane | NA | 58.5 | 58.0 | 58.8 | 58.4 | 58.4 | 58.4 | 58.8 | 58.2 | 59.1 | 58.1 | 58.4 | 58.7 | 58.5 | 59.1 | 59.1 | 59.1 | 59.1 |
| High Octane | NA | 56.7 | 57.8 | 58.4 | 58.5 | 57.8 | 58.3 | 58.2 | 58.0 | 58.7 | 58.9 | 58.1 | 59.0 | 59.3 | 59.8 | 59.8 | 59.8 | 59.8 |

Notes: NA – Not Applicable, fuel type was not analyzed.
Source: National Institute of Petroleum and Energy Research (1990 through 2009).

The density of motor gasoline increased across all grades through 1994, partly as a result of the leaded gasoline phase-out. In order to maintain the "anti-knock" quality and octane ratings of gasoline in the absence of lead, the portion of aromatic hydrocarbons blended into gasoline through the refining process was increased. As discussed above, aromatic hydrocarbons have a lower ratio of hydrogen to C than other hydrocarbons typically found in gasoline, and therefore increase fuel density.

The trend in gasoline density was reversed beginning in 1996 with the development of fuel additives that raised oxygen content. In 1995, a requirement for reformulated gasoline in non-attainment areas implemented under the Clean Air Act Amendments further changed the composition of gasoline consumed in the United States. Through 2005, methyl tertiary butyl ether (MTBE), ethanol, ethyl tertiary butyl ether (ETBE) and tertiary amyl methyl ether (TAME) were added to reformulated and sometimes to conventional gasoline to boost its oxygen content, reduce its toxics impacts and increase its octane. The increased oxygen reduced the emissions of carbon monoxide and unburned hydrocarbons. These oxygen-rich blending components are also much lower in C than standard gasoline. The average gallon of reformulated gasoline consumed in 2005 contained over 10 percent MTBE and 0.6 percent TAME (by volume). The characteristics of reformulated fuel additives appear in Table A-47.

Table A-47: Characteristics of Major Reformulated Fuel Additives

| Additive | Density (Degrees API) | Carbon Share (Percent) |
|---|---|---|
| MTBE | 58.6 | 68.13 |
| ETBE | 58.5 | 70.53 |
| TAME | 51.2 | 70.53 |
| DIPE | 62.7 | 70.53 |
| Ethanol (100%) | 45.8 | 52.14 |

Source: EPA, 2009b.

Since 2005, due to concerns about the potential environmental consequences of the use of MTBE in fuels, there has been a shift away from the addition of MTBE, TAME, ETBE and DIPE and towards the use of ethanol as a fuel oxygenate.[14] Ethanol, also called ethyl alcohol, is an anhydrous alcohol with molecular formula $C_2H_5OH$. Ethanol has a lower carbon share than other oxygenates, approximately 52 percent compared to about 70 percent for MTBE and TAME. The density of ethanol was calculated by fitting density data at 10 degree intervals to a polynomial of order two and then using the fit to interpolate the value of the density at 15 degrees Celsius. A common fuel mixture of 10 percent denatured ethanol (denatured by 2 percent hydrocarbons) and 90 percent gasoline, known as E10, is widely used in the United States and does not require any modification to vehicle engines or fuel systems. The average gallon of reformulated alcohol blend gasoline in 2008 contained 8.6 percent ethanol (by volume). As of 2010, ten States require the use of ethanol-

[14] The annual motor gasoline carbon contents that are applied for this inventory do not include the carbon contributed by the ethanol contained in reformulated fuels. Ethanol is a biofuel, and net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change and Forestry.

blended fuel.[15] Ethanol blends up to E85 (85 percent ethanol, 15 percent gasoline) are in use in the United States but can only be used in specially designed vehicles called flexible fuel vehicles (FFVs). Most ethanol fuel in the United States is produced using corn as feedstock,[16] although production pathways utilizing agricultural waste, woody biomass and other resources are in development.

Methodology

*Step 1. Disaggregate U.S. gasoline consumption by grade and type*

Separate monthly data for U.S. sales to end users of finished gasoline by product grade and season for both standard gasoline and reformulated gasoline were obtained from the EIA.

*Step 2. Develop carbon content coefficients for each grade and type*

Annual C content coefficients for each gasoline grade, type and season are derived from four parameters for each constituent of the finished gasoline blend: the volumetric share of each constituent,[17] the density of the constituent, share of the constituent[18] that is C; and the energy content of a gallon of the relevant formulation of gasoline. The percent by mass of each constituent of each gasoline type was calculated using percent by volume data from NIPER and the density of each constituent. The ether additives listed in Table A-47 are accounted for in both reformulated fuels and conventional fuels, to the extent that they were present in the fuel. From 2006 onward, reformulated fuel mass percentages are calculated from their constituents, net of the share provided by ethanol. C content coefficients were then derived from the calculated percent by mass values by weighting the carbon share of each constituent by its contribution to the total mass of the finished motor gasoline product.

*Step 3. Weight overall gasoline carbon content coefficient for consumption of each grade and type*

The C content for each grade, type and season of fuel is multiplied by the share of annual consumption represented by the grade and fuel type during the relevant time period. Individual coefficients are then summed and totaled to yield an overall C content coefficient for each year.

Data Sources

Data for the density of motor gasoline were derived from the National Institute for Petroleum and Energy Research (NIPER) (1990 through 2009). Data on the characteristics of reformulated gasoline, including C share, were also taken from NIPER (1990 through 2009).

Standard heat contents for motor gasoline of 5.253 MMBtu per barrel conventional gasoline and 5.150 MMBtu per barrel reformulated gasoline[19] were adopted from EIA (2009a).

Uncertainty

The uncertainty underlying the C content coefficients for motor gasoline has three underlying sources: the uncertainty in the averages published by NIPER, uncertainty in the C shares assumed in the EPA's analysis to be representative of the constituent hydrocarbon classes within gasoline (aromatics, olefins and saturates) and uncertainty in the heat contents applied.

A variable number of samples are used each year to determine the average percent by volume share of each hydrocarbon within each grade, season and formulation of gasoline that are obtained from NIPER. The total number of samples analyzed for each seasonal NIPER report varies from approximately 730 to over 1,800 samples over the period from 1990 through 2008. The number of samples analyzed that underlie the calculation of the average make-up of each seasonal formulation and grade varies from approximately 50 to over 400, with the greatest number of samples each season being of conventional, regular or premium gasoline. Further, not all sample data submitted to NIPER contains data for each of the properties, such that the number of samples underlying each constituent average value for each season, grade and formulation may be variable within the single gasoline type (e.g., of the 1,073 samples for which some data was

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[15] Ethanol.org. http://www.ethanol.org/index.php?id=79&parentid=26. Retrieved 2-19-2010.

[16] "Ethanol Market Penetration". Alternative Fuels and Advanced Vehicles Data Center, US DOE. http://www.afdc.energy.gov/afdc/ethanol/market.html. Retrieved 2-19-2010.

[17] Calculations account for the properties of the individual constituents of gasoline, including, as applicable to the fuel grade and type: aromatics (excluding benzene), olefins, benzene, saturates, MTBE, TAME, ETBE, DIPE and ethanol.

[18] Saturates are assumed to be octane and aromatics are assumed to be toluene.

[19] The reformulated gasoline heat content is applied to both reformulated blends containing ethers and those containing ethanol.

obtained for gasoline sold in Winter 1995through 1996, benzene content was provided for all samples, while olefin, aromatic and saturate content was provided for just 736 of those samples).

The distribution of sample origin collected for the NIPER report and the calculation of national averages are not reflective of sales volumes. The publication of simple, rather than sales-weighted averages to represent national average values increases the uncertainty in their application to the calculation of carbon content factors for the purposes of this inventory. Further, data for each sample is submitted voluntarily, which may also affect their representativeness.

Additionally, because the simple average constituent shares are calculated based upon data that have been renormalized to account for the share of ethers and alcohols, total average volume shares may not equal 100 percent.

The simple average for each hydrocarbon constituent is contained within a range of values that are as wide as +74.5/-63 percent of the mean across the Winter 2007 through 2008 and +49.6/-51.3 percent across the Summer 2008 samples of conventional, regular grade gasoline. However, these wide ranges exist for benzene, which generally accounts for only 1 percent, by volume, of each gallon. In contrast, saturates, the class of hydrocarbon that contribute the largest share, by volume, ranges only +6.4/-6.5 percent for the same set of Winter samples and +15.7/-8.8 percent for the Summer samples.

Secondly, EPA's calculation of C content factors for each gasoline type includes the following assumptions: for the purposes of assigning a carbon share to each compound in the blend, aromatic content (other than benzene) is assumed to be toluene and saturated hydrocarbons are assumed to be octane. All olefins have the same carbon share because they all have a molecular formula in the form $C_nH_{2n}$, so the C share applied to the olefin portion of the total gasoline blend does not increase the level of uncertainty in the calculation. These assumptions are based upon the use of octane and octane isomers as the primary saturates and toluene as the primary non-benzene aromatic in U.S. motor gasoline blends. The octane rating of a particular blend is based upon the equivalent iso-octane to heptane ratio, which is achieved through significant octane content relative to the other saturates. Aside from benzene, U.S. gasolines will include toluene as a major aromatic component, so toluene may be assumed a reasonable representative of total non-benzene aromatic content (EPA 2009a).

For each hydrocarbon category, the assumed C content lies within a range of possible values for all such hydrocarbons. Among saturated hydrocarbons, the C share of octane (84.12 percent) is at the high end of the range while ethane is represents the low end of the range (79.89 percent C). Total saturates constitute from 40 to 95 percent by volume of a given gasoline blend. For aromatics, toluene (91.25 percent C) lies in the middle of the possible range. This range is bounded by cumene (89.94 percent C) and naphthalene (93.71 percent C). Total aromatics may make up between 3 and 50 percent by volume of any given gasoline blend. The range of these potential values contributes to the uncertainty surrounding the final calculated C factors.

However, as demonstrated above in Figure A-3, the amount of variation in C content of gasoline is restricted by the compounds in the fuel to ±4 percent. Further, despite variation in sampling survey response, sample size and annually variable fuel formulation requirements, the observed variation in the annual weighted motor gasoline coefficients estimated for this inventory is ±0.8 percent over 1990 through 2008.

The third primary contributor to uncertainty is the assumed heat content. The heat contents are industry standards established many years ago. The heat contents are standard conversion factors used by EIA to convert volumetric energy data to energy units. Because the heat contents of fuels change over time, without necessarily and directly altering their volume, the conversion of known volumetric data to energy units may introduce bias. Thus, a more precise approach to estimating emissions factors would be to calculate C content per unit of volume, rather than per unit of energy. Adopting this approach, however, makes it difficult to compare U.S. C content coefficients with those of other nations.

The changes in density of motor gasoline over the last decade suggest that the heat content of the fuels is also changing. However, that change within any season grade has been less than 1 percent over the decade. Of greater concern is the use of a standardized heat content across grades that show a variation in density of ±1.5 percent from the mean for conventional gasoline and ±1.0 percent for reformulated fuels.

*Jet Fuel*

Jet fuel is a refined petroleum product used in jet aircraft engines. There are two classes of jet fuel used in the United States: "naphtha-based" jet fuels and "kerosene-based" jet fuels. In 1989, 13 percent of U.S. consumption was

naphtha-based fuel, with the remainder kerosene-based jet fuel. In 1993, the U.S. Department of Defense began a conversion from naphtha-based JP-4 jet fuel to kerosene-based jet fuel, because of the possibility of increased demand for reformulated motor gasoline limiting refinery production of naphtha-based jet fuel. By 1996, naphtha-based jet fuel represented less than one-half of one percent of all jet fuel consumption. The C content coefficient for jet fuel used in this report prior to 1996 represents a consumption-weighted combination of the naphtha-based and kerosene-based coefficients. From 1996 to 2008, only the kerosene-based portion of total consumption is considered significant.

Methodology

*Step 1. Estimate the carbon content for naphtha-based jet fuels*

Because naphtha-based jet fuels are used on a limited basis in the United States, sample data on its characteristics are limited. The density of naphtha-based jet fuel (49 degrees) was estimated as the central point of the acceptable API gravity range published by ASTM. The heat content of the fuel was assumed to be 5.355 MMBtu per barrel based on EIA industry standards. The C fraction was derived from an estimated hydrogen content of 14.1 percent (Martel and Angello 1977), and an estimated content of sulfur and other non-hydrocarbons of 0.1 percent.

*Step 2. Estimate the carbon content for kerosene-based jet fuels*

The density of kerosene-based jet fuels was estimated at 42 degrees API and the carbon share at 86.3 percent. The density estimate was based on 38 fuel samples examined by NIPER. Carbon share was estimated on the basis of a hydrogen content of 13.6 percent found in fuel samples taken in 1959 and reported by Martel and Angello, and on an assumed sulfur content of 0.1 percent. The EIA's standard heat content of 5.670 MMBtu per barrel was adopted for kerosene-based jet fuel.

*Step 3. Weight the overall jet fuel carbon content coefficient for consumption of each type of fuel (1990-1995 only)*

For years 1990 through1995, the C content for each jet fuel type (naphtha-based, kerosene-based) is multiplied by the share of overall consumption of that fuel type, as reported by EIA (2009a). Individual coefficients are then summed and totaled to yield an overall C content coefficient. Only the kerosene-based C coefficient is reflected in the overall jet fuel coefficient for 1996 through 2008.

Data Sources

Data on the C content of naphtha-based jet fuel was taken from C.R. Martel and L.C. Angello (1977). Data on the density of naphtha-based jet fuel was taken from ASTM (1985). Standard heat contents for kerosene and naphtha-based jet fuels were adopted from EIA (2009a). Data on the C content of kerosene-based jet fuel is based on C.R. Martel and L.C. Angello (1977) and the density is derived from NIPER (1993).

Uncertainty

Variability in jet fuel is relatively small with the average C share of kerosene-based jet fuel varying by less than ±1 percent and the density varying by ±1 percent. This is because the ratio of fuel mass to useful energy must be tightly bounded to maximize safety and range. There is more uncertainty associated with the density and C share of naphtha-based jet fuel because sample data were unavailable and default values were used. This uncertainty has only a small impact on the overall uncertainty of the C content coefficient for jet fuels, however, because naphtha-based jet fuel represents a small and declining share of total jet fuel consumption in the United States and is treated as negligible when calculating carbon content factors for 1996 onwards.

*Distillate Fuel*

Distillate fuel is a general classification for diesel fuels and fuel oils. Products known as No. 1, No. 2, and No. 4 diesel fuel are used in on-highway diesel engines, such as those in trucks and automobiles, as well as off-highway engines, such as those in railroad locomotives and agricultural machinery. No. 1, No. 2, and No. 4 fuel oils are also used for space heating and electric power generation.

Methodology

For this inventory, separate C coefficients have been estimated for each of the three distillates, although the level of aggregation of U.S. energy statistics requires that a single coefficient is used to represent all three grades in inventory calculations. In past inventories, the emission coefficient was only determined for distillate No. 2. Distillate No. 2 remains the representative grade applied to the distillate class for calculation purposes. Coefficients developed for Nos. 1 and 4 distillate are provided for informational purposes. The C share each distillate is drawn from Perry's Chemical Engineers' Handbook, 8$^{th}$ Ed. (Green & Perry 2008). Each C share was combined with individual heat contents of 5.822,

5.809 and 6.135 MMBtu per barrel, respectively for distillates No. 1, No. 2 and No. 4, and densities of 35.3, 35.8 and 23.2 degrees API to calculate C coefficients for each distillate type.

Data Sources

Densities for distillate Nos. 1 and 2 were derived from Alliance of Automobile Manufacturers, Diesel Survey – Winter 2008 (AAM 2009). Densities are based on four, and 144 samples, respectively. The density of distillate fuel oil No. 4 is taken from Perry's Chemical Engineer's Handbook, 8th Ed. (Green & Perry, 2008), Table 24-6.

Heat contents are adopted from EPA (2009b). And carbon shares for each distillate are from Perry's Chemical Engineers' Handbook (Green & Perry 2008), Table 24-6.

Uncertainty

The primary source of uncertainty for the estimated C content of distillate fuel is the selection of No. 2 distillate as the typical distillate fuel oil or diesel fuel. No.2 fuel oil is generally consumed for home heating. No.1 distillate is generally less dense and if it is consumed in large portions for mobile sources, the application of the C content estimated for No. 2 for this report is likely to be too high when applied to both Nos. 1 and 2 distillates. The opposite is true of the application of a coefficient based upon the properties of No. 2 to the consumption of No. 4 distillate, which is of a significantly higher density and thus, has a higher C coefficient despite its lower C share. The overall effect on uncertainty from applying a single factor will depend on the relative annual consumption of each distillate.

The densities applied to the calculation of each carbon factor are an underlying a source of uncertainty. While the density of No. 1 distillate is based upon just four samples, the factor applied to all distillates in the inventory estimates (that for No. 2 oil) is based on a much larger sample size (144). Given the range of densities for these three distillate fuel classes (0.1342 to 0.1452 MT/bbl at 60°F), the uncertainty associated with the assumed density of distillate fuels is predominately a result of the use of No. 2 to represent all distillate consumption. There is also a small amount of uncertainty in the No. 2 distillate density itself. This is due to the possible variation across seasonal diesel formulations and fuel grades and between stationary and transport applications within the No. 2 distillate classification. The range of the density of the samples of No. 2 diesel (regular grade, 15ppm sulfur) is ±2.5 percent from the mean, while the range in density across the small sample set of No. 1 diesel is -2.1 to +1.6 percent of the mean. Samples from AAM (2009) of Premium No. 2 diesel (n=5) and higher sulfur (500 ppm S) regular diesel (n=2), which are also consumed in the U.S., each have nominally higher average densities (+1.3 percent and +0.6 percent, respectively) than do the low-sulfur regular diesel samples that underlie the density applied in this inventory.

The use of the 144 AAM samples to define the density of No. 2 distillate (and those four samples used to define that of No. 1 distillate) may introduce additional uncertainty because the samples were collected from just one season of on-road fuel production (Winter 2008). Despite the limited sample frame, the average No. 2 density calculated from the samples is applied to the calculation of a uniform C coefficient applicable for all years of the inventory and for all types of distillate consumption. The ASTM standards for each grade of diesel fuel oil do not include a required range in which the density must lie, and the density (as well as heat content and carbon share) may vary according to the additives in each seasonal blend and the sulfur content of each sub-grade.

However, previous studies also show relatively low variation in density across samples of No. 2 and across all distillates, supporting the application of a single No. 2 density to all U.S. distillate consumption. The average density calculated from samples analyzed by the EIA in 1994 (n=7) differs only very slightly from the value applied for the purposes of this inventory (-0.12 percent for No. 2 distillate). Further, the difference between the mean density applied to this inventory (No. 2 only) and that calculated from EIA samples of all distillates, regardless of grade, is also near zero (-0.06 percent, based on n=14, of distillates Nos. 1, 2 and 4 combined).

A C share of 87.30 percent is applied to No. 2 distillate, while No. 1 and No. 4 have C shares estimated at 86.40 and 86.47 percent, respectively. Again, the application of parameters specific to No. 2 to the consumption of all three distillates contributes to an increased level of uncertainty in the overall coefficient and emissions estimate and its broad application. For comparison, four No. 1 fuel oil samples obtained by EIA (1994) contained an average of 86.19 percent C, while seven samples No. 2 fuel oil from the same EIA analysis showed an average of 86.60 percent C. Additionally, three samples of No. 4 distillate indicate an average C share of 85.81 percent. The range of C share observed across the seven No. 2 samples is 86.1 to 87.5 percent, and across all samples (all three grades, n=14) the range is 85.3 to 87.5 percent C. There also exists an uncertainty of ±1 percent in the share of C in No. 2 based on the limited sample size.

*Residual Fuel*

Residual fuel is a general classification for the heavier oils, known as No. 5 and No. 6 fuel oils, that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. Residual fuel conforms to ASTM Specifications D 396 and D 975 and Federal Specification VV-F-815C. No. 5, a residual fuel oil of medium viscosity, is also known as Navy Special and is defined in Military Specification MIL-F-859E, including Amendment 2 (NATO Symbol F-770). It is used in steam-powered vessels in government service and inshore power plants. No. 6 fuel oil includes Bunker C fuel oil and is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.

In the United States, electric utilities purchase about one-third of the residual oil consumed. A somewhat larger share is used for vessel bunkering, and the balance is used in the commercial and industrial sectors. The residual oil (defined as No. 6 fuel oil) consumed by electric utilities has an energy content of 6.287 MMBtu per barrel (EIA 2008a) and an average sulfur content of 1 percent (EIA 2001). This implies a density of about 17 degrees API.

Methodology

Because U.S. energy consumption statistics are available only as an aggregate of Nos. 5 and 6 residual oil, a single coefficient must be used to represent the full residual fuel category. As in earlier editions of this report, residual fuel oil has been defined as No. 6 fuel oil, due to the majority of residual consumed in the United States being No. 6. However, for this report, a separate coefficient for fuel oil No. 5 has also been developed for informational purposes. Densities of 33.0 and 15.5 degrees API were adopted when developing the C content coefficients for Nos. 5 and 6, respectively (Wauquier, J.-P., ed. 1995; Green & Perry, ed. 2008).

The estimated C share of fuel oil No. 5 is 85.67 percent, based on an average of 12 ultimate analyses of samples of fuel oil (EIA 1994). An average share of C in No. 6 residual oil of 84.67 percent by mass was used, based on Perry's, 8$^{th}$ Ed. (Green & Perry 2008).

Data Sources

Data on the C share and density of residual fuel oil No. 6 were obtained from Green & Perry, ed. (2008).

Data on the C share of fuel oil No. 5 was adopted from EIA (1994), and the density of No. 5 was obtained from Wauquier, J.-P., ed. (1995).

Heat contents for both Nos. 5 and 6 fuel oil are adopted from EPA (2009b).

Uncertainty

Beyond the application of a C factor based upon No. 6 oil to all residual oil consumption, the largest source of uncertainty in estimating the C content of residual fuel centers on the estimates of density. Fuel oils are likely to differ depending on the application of the fuel (i.e., power generation or as a marine vessel fuel). Slight differences between the density of residual fuel used by utilities and that used in mobile applications are likely attributable to non-sulfur impurities, which reduce the energy content of the fuel, but do not greatly affect the density of the product. Impurities of several percent are commonly observed in residual oil. The extent of the presence of impurities has a greater effect on the uncertainty of C share estimation than it does on density. This is because these impurities do provide some Btu content to the fuel, but they are absent of carbon. Fuel oils with significant sulfur, nitrogen and heavy metals contents would have a different total carbon share than a fuel oil that is closer to pure hydrocarbon. This contributes to the uncertainty of the estimation of an average C share and C coefficient for these varied fuels.

The 12 samples of residual oil (EIA 1994) cover a density range from 4.3 percent below to 8.2 percent above the mean density. The observed range of C share in these samples is -2.5 to +1.8 percent of the mean. Overall, the uncertainty associated with the C content of residual fuel is probably ±1 percent.

*Liquefied Petroleum Gases (LPG)*

EIA identifies four categories of paraffinic hydrocarbons as LPG: ethane, propane, isobutane, and n-butane. Because each of these compounds is a pure paraffinic hydrocarbon, their C shares are easily derived by taking into account the atomic weight of C (12.01) and the atomic weight of hydrogen (1.01). Thus, for example, the C share of propane, $C_3H_8$, is 81.71 percent. The densities and heat contents of the compounds are also well known, allowing C content coefficients to be calculated directly. Table A-48 summarizes the physical characteristic of LPG.

Table A-48: Physical Characteristics of Liquefied Petroleum Gases

| Compound | Chemical Formula | Density (Barrels Per Metric Ton) | Carbon Content (Percent) | Energy Content (MMBtu/Barrel) | Carbon Content Coefficient (Tg C/QBtu) |
|---|---|---|---|---|---|
| Ethane | $C_2H_6$ | 11.55 | 79.89 | 3.082 | 17.16 |
| Propane | $C_3H_8$ | 12.76 | 81.71 | 3.836 | 16.76 |
| Isobutane | $C_4H_{10}$ | 11.42 | 82.66 | 3.974 | 17.77 |
| n-butane | $C_4H_{10}$ | 10.98 | 82.66 | 4.326 | 17.75 |

Source: Densities – CRC Handbook of Chemistry and Physics (2008/09); Carbon Contents – derived from the atomic weights of the elements; Energy Contents – EPA (2009b). All values are for the compound in liquid form. The density and energy content of ethane are for refrigerated ethane (-89 degrees C). Values for n-butane are for pressurized butane (-25 degrees C).

Methodology

*Step 1. Assign carbon content coefficients to each pure paraffinic compound*

Based on their known physical characteristics, a C content coefficient is assigned to each compound contained in the U.S. energy statistics category, Liquefied Petroleum Gases.

*Step 2. Weight individual LPG coefficients for share of fuel use consumption*

A C content coefficient for LPG used as fuel is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics.

*Step 3. Weight individual LPG coefficients for share of non-fuel use consumption*

The mix of LPG consumed for non-fuel use differs significantly from the mix of LPG that is combusted. While the majority of LPG consumed for fuel use is propane, ethane is the largest component of LPG used for non-fuel applications. A C content coefficient for LPG used for non-fuel applications is developed based on the consumption mix of the individual compounds reported in U.S. energy statistics.

*Step 4. Weight the carbon content coefficients for fuel use and non-fuel use by their respective shares of consumption*

The changing shares of LPG fuel use and non-fuel use consumption appear below in Table A- 49.

Data Sources

Data on C share was derived via calculations based on atomic weights of each element of the four individual compounds Densities are from the CRC Handbook of Chemistry and Physics, 89th Ed.. The energy content of each LPG is from the EPA (2009b). LPG consumption was based on data obtained from API (1990 through 2008) and EIA (2009b). Non-fuel use of LPG was obtained from API (1990 through 2008).

Uncertainty

Because LPG consists of pure paraffinic compounds whose density, heat content and C share are physical constants, there is limited uncertainty associated with the C content coefficient for this petroleum product. Any uncertainty is associated with the collection of data tabulating fuel- and non-fuel consumption in U.S. energy statistics. This uncertainty is likely less than ±3 percent.

Table A- 49: Consumption and Carbon Content Coefficients of Liquefied Petroleum Gases, 1990-2011

| | 1990 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Energy Consumption (QBtu)** | | | | | | | | | | | | | |
| **Fuel Use** | **0.88** | **1.31** | **1.16** | **1.25** | **1.22** | **1.26** | **1.21** | **1.19** | **1.20** | **1.13** | **1.13** | **1.16** | **1.16** |
| Ethane | 0.04 | 0.10 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.07 | 0.06 | 0.07 | 0.08 | 0.08 |
| Propane | 0.77 | 1.07 | 1.00 | 1.10 | 1.07 | 1.12 | 1.08 | 1.07 | 1.09 | 1.02 | 1.02 | 1.02 | 1.02 |
| Butane | 0.06 | 0.07 | 0.06 | 0.05 | 0.06 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.03 | 0.05 | 0.05 |
| Isobutane | 0.01 | 0.06 | 0.04 | 0.04 | 0.03 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 |
| **Non-Fuel Use** | **1.35** | **1.90** | **1.77** | **1.85** | **1.75** | **1.80** | **1.70** | **1.74** | **1.78** | **1.67** | **1.80** | **1.96** | **1.96** |
| Ethane | 0.71 | 1.04 | 0.96 | 1.00 | 0.92 | 0.97 | 0.91 | 0.98 | 1.03 | 0.95 | 1.12 | 1.22 | 1.22 |
| Propane | 0.51 | 0.65 | 0.59 | 0.64 | 0.63 | 0.66 | 0.63 | 0.63 | 0.64 | 0.60 | 0.60 | 0.60 | 0.60 |
| Butane | 0.11 | 0.11 | 0.13 | 0.12 | 0.13 | 0.13 | 0.12 | 0.12 | 0.11 | 0.12 | 0.08 | 0.12 | 0.12 |
| Isobutane | 0.02 | 0.09 | 0.09 | 0.08 | 0.07 | 0.03 | 0.03 | 0.02 | 0.01 | 0.00 | 0.01 | 0.03 | 0.03 |

| Carbon Content (Tg C/QBtu) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel Use | 16.86 | | 16.89 | 16.87 | 16.85 | 16.86 | 16.84 | 16.84 | 16.83 | 16.82 | 16.83 | 16.82 | 16.82 | 16.82 |
| Non-Fuel Use | 17.06 | | 17.09 | 17.10 | 17.09 | 17.09 | 17.07 | 17.06 | 17.06 | 17.05 | 17.06 | 17.06 | 17.06 | 17.06 |

Sources: Fuel use of LPG based on data from EIA (2009b) and API (1990 through 2007). Non-fuel use of LPG from API (1990 through 2008). Volumes converted using the energy contents provided in Table A-48. C contents from EPA (2010).

*Aviation Gasoline*

Aviation gasoline is used in piston-powered airplane engines. It is a complex mixture of relatively volatile hydrocarbons with or without small quantities of additives, blended to form a fuel suitable for use in aviation reciprocating engines. Fuel specifications are provided in ASTM Specification D910 and Military Specification MIL-G-5572. Aviation gas is a relatively minor contributor to greenhouse gas emissions compared to other petroleum products, representing approximately 0.1 percent of all consumption.

The ASTM standards for boiling and freezing points in aviation gasoline effectively limit the aromatics content to a maximum of 25 percent (ASTM D910). Because weight is critical in the operation of an airplane, aviation gas must have as many Btu per pound (implying a lower density) as possible, given other requirements of piston engines such as high anti-knock quality.

Methodology

A C content coefficient for aviation gasoline was calculated on the basis of the EIA standard heat content of 5.048 MMBtu per barrel. This implies a density of approximately 69 degrees API gravity or 5.884 pounds per gallon, based on the relationship between heat content and density of petroleum liquids, as described in *Thermal Properties of Petroleum Products* (DOC 1929). To estimate the share of C in the fuel, it was assumed that aviation gasoline is 87.5 percent iso-octane, 9.0 percent toluene, and 3.5 percent xylene. The maximum allowable sulfur content in aviation gasoline is 0.05 percent, and the maximum allowable lead content is 0.1 percent. These amounts were judged negligible and excluded for the purposes of this analysis. This yielded a C share of 85.00 percent and a C content coefficient of 18.86 Tg C/QBtu.

Data Sources

Data sources include ASTM (1985). A standard heat content for aviation gas was adopted from EIA (2009a).

Uncertainty

The relationship used to calculate density from heat content has an accuracy of five percent at 1 atm. The uncertainty associated with the C content coefficient for aviation gasoline is larger than that for other liquid petroleum products examined because no ultimate analyses of samples are available. Given the requirements for safe operation of piston-powered aircraft the composition of aviation gas is well bounded and the uncertainty of the C content coefficient is likely to be ±5 percent.

*Still Gas*

Still gas, or refinery gas, is composed of light hydrocarbon gases that are released as petroleum is processed in a refinery. The composition of still gas is highly variable, depending primarily on the nature of the refining process and secondarily on the composition of the product being processed. Petroleum refineries produce still gas from many different processes. Still gas can be used as a fuel or feedstock within the refinery, sold as a petrochemical feedstock, or purified and sold as pipeline-quality natural gas. For the purposes of this inventory, the coefficient derived here is only applied to still gas that is consumed as a fuel. In general, still gas tends to include large amounts of free hydrogen and methane, as well as smaller amounts of heavier hydrocarbons. Because different refinery operations result in different gaseous byproducts, it is difficult to determine what represents typical still gas.

Methodology

The properties of still gas used to calculate the carbon content are taken from the literature. The carbon share of still gas was calculated from its net calorific value and carbon content from IPCC (2006). This calculation yields a carbon share of 77.7 percent. The density of still gas was estimated to be 0.1405 metric tons per barrel based on its heat content (from EIA 2008a) and the relationship between heat content and density that is described by the U.S. Department of Commerce, Bureau of Standards (DOC 1929).

Data Sources

The carbon share of still gas is calculated from data provided by IPCC (2006). Density is estimated at 0.1405 metric tons per barrel, approximately 28.3 degrees API, based on the heat content of 6.00 MMbtu/barrel of still gas from EIA (2009a).

Uncertainty

The EIA obtained data on four samples of still gas. Table A-50 below shows the composition of those samples.

Table A-50: Composition, Energy Content, and Carbon Content Coefficient for Four Samples of Still Gas

| Sample | Hydrogen (%) | Methane (%) | Ethane (%) | Propane (%) | Btu Per Cubic Foot | Carbon Content (Tg C/QBtu) |
|---|---|---|---|---|---|---|
| One | 12.7 | 28.1 | 17.1 | 11.9 | 1,388 | 17.51 |
| Two | 34.7 | 20.5 | 20.5 | 6.7 | 1,143 | 14.33 |
| Three | 72.0 | 12.8 | 10.3 | 3.8 | 672 | 10.23 |
| Four | 17.0 | 31.0 | 16.2 | 2.4 | 1,100 | 15.99 |

Sources: EIA (2008b).

Because the composition of still gas is highly heterogeneous, the C content coefficient for this product is highly uncertain. Gas streams with a large free hydrogen content are likely to be used as refinery or chemical feedstocks. Therefore, the sample cited above with the very high H content of 72 percent (and the lowest calculated C content) is less likely to be representative of the still gas streams to which the calculated coefficient is applied. The C content coefficient used for this report is probably at the high end of the plausible range given that it is higher than the greatest sample-based C content in Table A-50.

*Asphalt*

Asphalt is used to pave roads. Because most of its C is retained in those roads, it is a small source of carbon dioxide emissions. It is derived from a class of hydrocarbons called "asphaltenes," which are abundant in some crude oils but not in others. Asphaltenes have oxygen and nitrogen atoms bound into their molecular structure, so that they tend to have lower C contents than do other hydrocarbons.

Methodology

Ultimate analyses of twelve samples of asphalts showed an average C content of 83.47 percent. The EIA standard Btu content for asphalt of 6.636 MMBtu per barrel was assumed. The ASTM petroleum measurement tables show a density of 5.6 degrees API or 8.605 pounds per gallon for asphalt. Together, these variables generate C content coefficient of 20.55 Tg C/QBtu.

Data Sources

A standard heat content for asphalt was adopted from EIA (2009a). The density of asphalt was determined by the ASTM (1985). C share is adopted from analyses in EIA (2008b).

Uncertainty

The share of C in asphalt ranges from 79 to 88 percent by weight. Also present in the mixture are hydrogen and sulfur, with shares by weight ranging from seven to 13 percent for hydrogen, and from trace levels to eight percent for sulfur. Because C share and total heat content in asphalts do vary systematically, the overall C content coefficient is likely to be accurate to ±5 percent.

*Lubricants*

Lubricants are substances used to reduce friction between bearing surfaces, or incorporated into processing materials used in the manufacture of other products, or used as carriers of other materials. Petroleum lubricants may be produced either from distillates or residues. Lubricants include all grades of lubricating oils, from spindle oil to cylinder oil to those used in greases. Lubricant consumption is dominated by motor oil for automobiles, but there is a large range of product compositions and end uses within this category.

Methodology

The ASTM Petroleum Measurement tables give the density of lubricants at 25.6 degrees API, or 0.1428 metric tons per barrel. Ultimate analysis of a single sample of motor oil yielded a C content of 85.80 percent. A standard heat

content of 6.065 MMBtu per barrel was adopted from EIA. These factors produce a C content coefficient of 20.20 Tg C/QBtu.

Data Sources

A standard heat content was adopted from the EIA (2009a). The carbon content of lubricants is adopted from ultimate analysis of one sample of motor oil (EPA 2009a). The density of lubricating oils was determined by ASTM (1985).

Uncertainty

Uncertainty in the estimated C content coefficient for lubricants is driven by the large range of product compositions and end uses in this category combined with an inability to establish the shares of the various products captured under this category in U.S. energy statistics. Because lubricants may be produced from either the distillate or residual fractions during refineries, the possible C content coefficients range from 19.89 Tg C/QBtu to 21.48 Tg C/QBtu or an uncertainty band from –1.5 percent to + 1.4 percent of the estimated value.

*Petrochemical Feedstocks*

U.S. energy statistics distinguish between two different kinds of petrochemical feedstocks: those with a boiling temperature below 400 degrees Fahrenheit, generally called "naphtha," and those with a boiling temperature 401 degrees Fahrenheit and above, referred to as "other oils" for the purposes of this inventory.

Methodology

The C content of these petrochemical feedstocks are estimated independently according to the following steps.

*Step 1. Estimate the carbon content coefficient for naphtha*

Because reformed naphtha is used to make motor gasoline (hydrogen is released to raise aromatics content and octane rating), "straight-run" naphtha is assumed to be used as a petrochemical feedstock. Ultimate analyses of five samples of naphtha were examined and showed an average C share of 84.11 percent. A density of 62.4 degrees API gravity was taken from the Handbook of Petroleum Refining Processes, 3rd ed. The standard EIA heat content of 5.248 MMBtu per barrel is used to estimate a C content coefficient of 18.55 Tg C/QBtu.

*Step 2. Estimate the carbon content coefficient for petrochemical feedstocks with a boiling temperature 400 degrees Fahrenheit and above ("other oils")*

The boiling temperature of this product places it into the "middle distillate" fraction in the refining process, and EIA estimates that these petrochemical feedstocks have the same heat content as distillate fuel No. 2. Thus, the C content coefficient of 20.17 Tg C/QBtu used for distillate fuel No. 2 is also adopted for this portion of the petrochemical feedstocks category.

Data Sources

Naphthas: Data on the C content was taken from Unzelman (1992). Density is from Meyers (2004). A standard heat content for naphthas was adopted from EIA (2009a). Other oils: See Distillate Fuel, Distillate No.2.

Uncertainty

Petrochemical feedstocks are not so much distinguished on the basis of chemical composition as on the identity of the purchaser, who are presumed to be a chemical company or a petrochemical unit co-located on the refinery grounds. Naphthas are defined, for the purposes of U.S. energy statistics, as those naphtha products destined for use as a petrochemical feedstock. Because naphthas are also commonly used to produce motor gasoline, there exists a considerable degree of uncertainty about the exact composition of petrochemical feedstocks.

Different naphthas are distinguished by their density and by the share of paraffins, isoparaffins, olefins, naphthenes and aromatics contained in the oil. Naphtha from the same crude oil fraction may have vastly different properties depending on the source of the crude. Two different samples of Egyptian crude, for example, produced two straight run naphthas having naphthene and paraffin contents (percent volume) that differ by 18.1 and 17.5 percent, respectively (Matar and Hatch, 2000).

Naphthas are typically used either as a petrochemical feedstock or a gasoline feedstock, with lighter paraffinic naphthas going to petrochemical production. Naphthas that are rich in aromatics and naphthenes tend to be reformed or blended into gasoline. Thus, the product category encompasses a range of possible fuel compositions, creating a range of possible C shares and densities. The uncertainty associated with the calculated C content of naphthas is primarily a

function of the uncertainty that underlies the average carbon share calculation, which is based on a limited number of samples. Two additional samples cited by the EIA (1994) have a range of 83.80 to 84.42 percent C.

The uncertainty of the carbon content for other oils is based upon the assumption of distillate oil No. 2 as a product representative of the ill-defined classification of "other oils," and from the calculation of the C content of No. 2 itself (see "Distillate Fuels," above). While No. 2 distillate is used as a proxy for "other oils" for the purposes of this inventory's carbon coefficient, important differences exist between these two petroleum products, contributing some uncertainty to the cross-application. Other oils are defined herein as those "oils with a boiling range equal to or greater than 401°F that are generally intended for use as a petrochemical feedstock and are not defined elsewhere." For comparison, various material safety data sheets (MSDSs) published by producers of distillate No. 2 indicate a boiling range for this product of 320-700 degrees Fahrenheit. The relatively open definition of the classification "other oils" leaves room for potentially significant variation in the heating value, density and carbon share properties of each feedstock oil having a boiling point above 400 degrees Fahrenheit, creating a large band of uncertainty beyond that associated with the C factor for distillate No. 2.

*Kerosene*

A light petroleum distillate that is used in space heaters, cook stoves, and water heaters and is suitable for use as a light source when burned in wick-fed lamps, kerosene is drawn from the same petroleum fraction as jet fuel. Kerosene is generally comparable to No.1 distillate oil.

Methodology

The average density and C share of kerosene are assumed to be the same as those for distillate No. 1 since the physical characteristics of the products are very similar. Thus, a density of 35.3 degrees API and average C share of 86.40 percent were applied to a standard heat content for distillate No. 1 of 5.825 MMBtu per barrel to yield a C content coefficient of 19.96 Tg C/QBtu.

Data Sources

A standard heat content for distillate No.1 was adopted from EIA (2009a).

Uncertainty

Uncertainty in the estimated C content for kerosene is driven by the selection of distillate No. 1 as a proxy for kerosene. If kerosene is more like kerosene-based jet fuel, the true C content coefficient is likely to be some 1.3 percent lower. If kerosene is more aptly compared to No. 2 distillate oil, then the true C content coefficient is likely to be about 1.1 percent higher. While kerosene is a light petroleum distillate, like distillate No. 1, the two oil classes are do have some variation in their properties. For example, the boiling range of kerosene is 250-550 degrees Fahrenheit, whereas No. 1 oils typically boil over a range from 350-615 degrees Fahrenheit. The properties of individual kerosenes will vary with their use and particular crude origin, as well. Both kerosene and fuel oil No. 1 are primarily composed of hydrocarbons having 9 to 16 carbon atoms per molecule. However, kerosene is a straight-run No. 1 fuel oil, additional cracking processes and additives contribute to the range of possible fuels that make up the broader distillate No. 1 oil category.

*Petroleum Coke*

Petroleum coke is the solid residue by-product of the extensive processing of crude oil. It is a coal-like solid, usually has a C content greater than 90 percent, and is used as a boiler fuel and industrial raw material.

Methodology

Ultimate analyses of two samples of petroleum coke showed an average C share of 92.28 percent. The ASTM standard density of 9.543 pounds per gallon was adopted and the EIA standard energy content of 6.024 MMBtu per barrel assumed. Together, these factors produced an estimated C content coefficient of 27.85 Tg C/QBtu.

Data Sources

C content was derived from two samples from Martin, S.W. (1960). The density of petroleum coke was taken from the ASTM (1985). A standard heat content for petroleum coke was adopted from EIA (2009a).

Uncertainty

The uncertainty associated with the estimated C content coefficient of petroleum coke can be traced to two factors: the use of only two samples to establish C contents and a standard heat content which may be too low. Together, these uncertainties are likely to bias the C content coefficient upwards by as much as 6 percent.

*Special Naphtha*

Special naphtha is defined as a light petroleum product to be used for solvent applications, including commercial hexane and four classes of solvent: Stoddard solvent, used in dry cleaning; high flash point solvent, used as an industrial paint because of its slow evaporative characteristics; odorless solvent, most often used for residential paints; and high solvency mineral spirits, used for architectural finishes. These products differ in both density and C percentage, requiring the development of multiple coefficients.

Methodology

The method for estimating the C content coefficient of special naphtha includes three steps.

*Step 1. Estimate the carbon content coefficient for hexane*

Hexane is a pure paraffin containing 6 C atoms and 14 hydrogen atoms; thus, it is 83.63 percent C. Its density is 83.7 degrees API or 5.477 pounds per gallon and its derived C content coefficient is 21.40 Tg C/QBtu.

*Step 2. Estimate the carbon contents of non-hexane special naphthas*

The hydrocarbon compounds in special naphthas are assumed to be either paraffinic or aromatic (see discussion above). The portion of aromatics in odorless solvents is estimated at less than 1 percent, Stoddard and high flash point solvents contain 15 percent aromatics and high solvency mineral spirits contain 30 percent aromatics (Boldt and Hall 1977). These assumptions, when combined with the relevant densities, yield the C content factors contained in Table A-51, below.

Table A-51: Characteristics of Non-hexane Special Naphthas

| Special Naphtha | Aromatic Content (Percent) | Density (Degrees API) | Carbon Share (Percent Mass) | Carbon Content (Tg C/QBtu) |
|---|---|---|---|---|
| Odorless Solvent | 1 | 55.0 | 84.51 | 19.41 |
| Stoddard Solvent | 15 | 47.9 | 84.44 | 20.11 |
| High Flash Point | 15 | 47.6 | 84.70 | 20.17 |
| Mineral Spirits | 30 | 43.6 | 85.83 | 20.99 |

Sources: EIA (2008b) and Boldt and Hall (1977).

*Step 3. Develop weighted carbon content coefficient based on consumption of each special naphtha*

EIA reports only a single consumption figure for special naphtha. The C contents of the five special naphthas are weighted according to the following formula: approximately 10 percent of all special naphtha consumed is hexane; the remaining 90 percent is assumed to be distributed evenly among the four other solvents. The resulting emissions coefficient for special naphthas is 19.74 Tg C/QBtu.

Data Sources

A standard heat content for special naphtha was adopted from EIA (2009a). Density and aromatic contents were adopted from Boldt and Hall (1977).

Uncertainty

The principal uncertainty associated with the estimated C content coefficient for special naphtha is the allocation of overall consumption across individual solvents. The overall uncertainty is bounded on the low end by the C content of odorless solvent and on the upper end by the C content of hexane. This implies an uncertainty band of –1.7 percent to +8.4 percent.

*Petroleum Waxes*

The ASTM standards define petroleum wax as a product separated from petroleum that is solid or semi-solid at 77 degrees Fahrenheit (25 degrees Celsius). The two classes of petroleum wax are paraffin waxes and microcrystalline waxes. They differ in the number of C atoms and the type of hydrocarbon compounds. Microcrystalline waxes have longer C chains and more variation in their chemical bonds than paraffin waxes.

Methodology

The method for estimating the C content coefficient for petroleum waxes includes three steps.

*Step 1. Estimate the carbon content of paraffin waxes*

For the purposes of this analysis, paraffin waxes are assumed to be composed of 100 percent paraffinic compounds with a chain of 25 C atoms. The resulting C share for paraffinic wax is 85.23 percent and the density is estimated at 45 degrees API or 6.684 pounds per gallon.

*Step 2. Estimate the carbon content of microcrystalline waxes*

Microcrystalline waxes are assumed to consist of 50 percent paraffinic and 50 percent cycloparaffinic compounds with a chain of 40 C atoms, yielding a C share of 85.56 percent. The density of microcrystalline waxes is estimated at 36.7 degrees API, based on a sample of 10 microcrystalline waxes found in the *Petroleum Products Handbook*.

*Step 3. Develop a carbon content coefficient for petroleum waxes by weighting the density and carbon content of paraffinic and microcrystalline waxes*

A weighted average density and C content was calculated for petroleum waxes, assuming that wax consumption is 80 percent paraffin wax and 20 percent microcrystalline wax. The weighted average C content is 85.30 percent, and the weighted average density is 6.75 pounds per gallon. EIA's standard heat content for waxes is 5.537 MMBtu per barrel. These inputs yield a C content coefficient for petroleum waxes of 19.80 Tg C/QBtu.

Data Sources

Density of paraffin wax was taken from ASTM (1985). Density of microcrystalline waxes was derived from 10 samples found in Guthrie (1960). A standard heat content for petroleum waxes was adopted from EIA (2009a).

Uncertainty

Although there is considerable qualitative uncertainty associated with the allocation of petroleum waxes and microcrystalline waxes, the quantitative variation in the C contents for all waxes is limited to ± 1 percent because of the nearly uniform relationship between C and other elements in petroleum waxes broadly defined.

*Crude Oil, Unfinished Oils, and Miscellaneous Products*

U.S. energy statistics include several categories of petroleum products designed to ensure that reported refinery accounts "balance" and cover any "loopholes" in the taxonomy of petroleum products. These categories include crude oil, unfinished oils, and miscellaneous products. Crude oil is rarely consumed directly, miscellaneous products account for less than one percent of oil consumption, and unfinished oils are a balancing item that may show negative consumption. For C accounting purposes, it was assumed that all these products have the same C content as crude oil.

Methodology

EIA reports on the average density and sulfur content of U.S. crude oil purchased by refineries. To develop a method of estimating C content based on this information, results of ultimate analyses of 182 crude oil samples were collected. Within the sample set, C content ranged from 82 to 88 percent C, but almost all samples fell between 84 percent and 86 percent C. The density and sulfur content of the crude oil data were regressed on the C content, producing the following equation:

$$\text{Percent C} = 76.99 + (10.19 \times \text{Specific Gravity}) + (-0.76 \times \text{Sulfur Content})$$

Absent the term representing sulfur content, the equation had an R-squared of only 0.35.[20] When C content was adjusted to exclude sulfur, the R-squared value rose to 0.65. While sulfur is the most important non-hydrocarbon impurity, nitrogen and oxygen can also be significant, but they do not seem to be correlated with either density or sulfur content. Restating these results, density accounts for about 35 percent of the variation in C content, impurities account for about 30 percent of the variation, and the remaining 35 percent is accounted for by other factors, including (presumably) the degree to which aromatics and polynuclear aromatics are present in the crude oil. Applying this equation to the 2008

[20] R-squared represents the percentage of variation in the dependent variable (in this case carbon content) explained by variation in the independent variables.

crude oil quality data (30.21 degrees API and 1.47 percent sulfur) produces an estimated C content of 84.79 percent. Applying the density and C content to the EIA standard energy content for crude oil of 5.800 MMBtu per barrel produced an emissions coefficient of 20.31 Tg C/QBtu.

Data Sources

C content was derived from 182 crude oil samples, including 150 samples from U.S. National Research Council (1927). A standard heat content for crude oil was adopted from EIA (2009a).

Uncertainty

The uncertainty of the estimated C content for crude oil centers on the 35 percent of variation that cannot be explained by density and sulfur content. This variation is likely to alter the C content coefficient by ±3 percent. Since unfinished oils and miscellaneous products are impossible to define, the uncertainty of applying a crude oil C content is likely to be bounded by the range of petroleum products described in this chapter at ±10 percent.

## Chronology and Explanation of Changes in Individual Carbon Content Coefficients of Fossil Fuels

### Coal

Original 1994 Analysis

A set of 5,426 coal samples from the EIA coal analysis file were used to develop C content estimates. The results from that sample set appear below in Table A-52. The EIA Coal Analysis File was originally developed by the U.S. Bureau of Mines and contained over 60,000 coal samples obtained through numerous coal seams throughout the United States. Many of the samples were collected starting in the 1940s and 1950s through the 1980s and analyzed in U.S. government laboratories.

Table A-52: Carbon Conteannt Coefficients for Coal by Consuming Sector and Coal Rank, 1990 – 2000 (Tg C/QBtu)

| | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Consuming Sector** | | | | | | | | | | | |
| Electric Power | 25.68 | 25.69 | 25.69 | 26.71 | 25.72 | 25.74 | 25.74 | 25.76 | 25.76 | 25.76 | 25.76 |
| Industrial Coking | 25.51 | 25.51 | 25.51 | 25.51 | 25.52 | 25.53 | 25.55 | 25.56 | 25.56 | 25.56 | 25.56 |
| Other Industrial | 25.58 | 25.59 | 25.62 | 25.61 | 25.63 | 25.63 | 25.61 | 25.63 | 25.63 | 25.63 | 25.63 |
| Residential/ Commercial | 25.92 | 26.00 | 26.13 | 25.97 | 25.95 | 26.00 | 25.92 | 26.00 | 26.00 | 26.00 | 26.00 |
| **Coal Rank** | | | | | | | | | | | |
| Anthracite | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 |
| Bituminous | 25.37 | 25.37 | 25.37 | 25.37 | 25.37 | 25.37 | 25.37 | 25.37 | 25.37 | 25.37 | 25.37 |
| Subbituminous | 26.24 | 26.24 | 26.24 | 26.24 | 26.24 | 26.24 | 26.24 | 26.24 | 26.24 | 26.24 | 26.24 |
| Lignite | 26.62 | 26.62 | 26.62 | 26.62 | 26.62 | 26.62 | 26.62 | 26.62 | 26.62 | 26.62 | 26.62 |

Sources: Emission factors be consuming sector from B.D. Hong and E.R. Slatnick, "Carbon Dioxide Emission Factors for Coal, " U.S. Energy Information Administration, *Quarterly Coal Report*, January-March 1994. (Washington, DC, 1994) and Emission factors by rank from Science Applications International Corporation, "Analysis of the Relationship Between Heat and Carbon Content of U.S. Fuels: Final Task Report," Prepared for the U.S. Energy Information Administration, Office of Coal, Nuclear, Electric and Alternative Fuels (Washington, DC 1992).

2002 Update

The methodology employed for these estimates was unchanged from previous years; however, the underlying coal data sample set was updated. A new database, CoalQual 2.0 (1998), compiled by the U.S. Geological Survey was adopted for the updated analysis. The updated sample set included 6,588 coal samples collected by the USGS and its state affiliates between 1973 and 1989. The decision to switch to the sample data contained in the USGS CoalQual database from the EIA database was made because the samples contained in the USGS database were collected and analyzed more recently than those obtained by EIA from the Bureau of Mines. The new coefficients developed in the 2002 revision were in use through the 1990 through 2007 Inventory and are provided in Table A-53, below.

Table A-53: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank, 1990 – 2000 (Tg C/QBtu)

| | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Consuming Sector** | | | | | | | | | | | |
| Electric Power | 25.68 | 25.69 | 25.69 | 25.71 | 25.72 | 25.74 | 25.74 | 25.76 | 25.76 | 25.76 | 25.76 |
| Industrial Coking | 25.51 | 25.51 | 25.51 | 25.51 | 25.52 | 25.53 | 25.55 | 25.56 | 25.56 | 25.56 | 25.56 |
| Other Industrial | 25.58 | 25.60 | 25.62 | 25.61 | 25.63 | 25.63 | 25.61 | 25.63 | 25.63 | 25.63 | 25.63 |
| Residential/ Commercial | 25.92 | 26.00 | 26.13 | 25.97 | 25.95 | 26.00 | 25.92 | 26.00 | 26.00 | 26.00 | 26.00 |
| **Coal Rank** | | | | | | | | | | | |
| Anthracite | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 |
| Bituminous | 25.43 | 25.45 | 25.44 | 25.45 | 25.46 | 25.47 | 25.47 | 25.48 | 25.47 | 25.48 | 25.49 |
| Sub-bituminous | 26.50 | 26.49 | 26.49 | 26.48 | 26.49 | 26.49 | 26.49 | 26.49 | 26.49 | 26.49 | 26.48 |
| Lignite | 26.19 | 26.21 | 26.22 | 26.21 | 26.24 | 26.22 | 26.17 | 26.20 | 26.23 | 26.26 | 26.30 |

Sources: Data from USGS, U.S. Coal Quality Database Version 2.0 (1998) and analysis prepared by SAIC, 2007.

2007 Update

The analysis of the USGS Coal Qual data was updated in 2007 to make a technical correction that affected the value for lignite and those sectors which consume lignite Table A-54 contains the annual coefficients that resulted from the 2007 analysis.

Table A-54: Carbon Content Coefficients for Coal by Consuming Sector and Coal Rank, 1990-2007 [Tg C/QBtu)

| | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Consuming Sector** | | | | | | | | | | | | | | |
| Electric Power | 25.68 | 25.74 | 25.74 | 25.76 | 25.76 | 25.76 | 25.76 | 25.76 | 25.76 | 25.76 | 25.76 | 25.76 | 25.76 | 25.76 |
| Industrial Coking | 25.51 | 25.53 | 25.55 | 25.56 | 25.56 | 25.56 | 25.56 | 25.56 | 25.56 | 25.56 | 25.56 | 25.56 | 25.56 | 25.56 |
| Other Industrial | 25.58 | 25.63 | 25.61 | 25.63 | 25.63 | 25.63 | 25.63 | 25.63 | 25.63 | 25.63 | 25.63 | 25.63 | 25.63 | 25.63 |
| Residential/Commercial | 25.92 | 26.00 | 25.92 | 26.00 | 26.00 | 26.00 | 26.00 | 26.00 | 26.00 | 26.00 | 26.00 | 26.00 | 26.00 | 26.00 |
| **Coal Rank** | | | | | | | | | | | | | | |
| Anthracite | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 | 28.26 |
| Bituminous | 25.43 | 25.47 | 25.47 | 25.48 | 25.47 | 25.48 | 25.49 | 25.49 | 25.49 | 25.49 | 25.49 | 25.49 | 25.49 | 25.49 |
| Sub-bituminous | 26.50 | 26.49 | 26.49 | 26.49 | 26.49 | 26.49 | 26.48 | 26.48 | 26.48 | 26.48 | 26.48 | 26.48 | 26.48 | 26.48 |
| Lignite | 26.19 | 26.22 | 26.17 | 26.20 | 26.23 | 26.26 | 26.30 | 26.30 | 26.30 | 26.30 | 26.30 | 26.30 | 26.30 | 26.57 |

Sources: Data from USGS, U.S. Coal Quality Database Version 2.0 (1998) and analysis prepared by (SAIC 2007).

2010 Update

The estimated annual C content coefficients for coal by rank and sector of consumption were updated again in 2010. Sample data from the Energy Institute at Pennsylvania State University (504 samples) were added to the 6,588 USGS samples to create a new database of 7,092 samples. The same analytical method used in the 2002 update was applied using these additional samples to calculate revised state-level carbon contents for each coal rank and then for national average consumption by end-use sector and by rank.

**Natural Gas**

A revised analytical methodology underlies the natural gas coefficients used in this report. Prior to the current Inventory, descriptive statistics were used to stratify 6,743 samples of pipeline quality natural gas by heat content and then to determine the average C content of natural gas at the national average heat content (EIA 1994). The same coefficient was applied to all pipeline natural gas consumption for all years, because U.S. energy statistics showed a range of national average heat contents of pipeline gas of only 1,025 to 1,031 Btu per cubic foot (1 percent) from 1990 through 1994. A separate factor was developed in the same manner for all flared gas. In the previous Inventory, a weighted national average C content was calculated using the average C contents for each sub-sample of gas that conformed with an individual state's typical cubic foot of natural gas since there is regional variation in energy content. The result was a weighted national average of 14.47 Tg C/QBtu.

The current Inventory is revised to make use of the same set of samples, but utilizes a regression equation, as described above, of sample-based heat content and carbon content data in order to calculate annually-variable national average C content coefficients based on annual national average heat contents for pipeline natural gas and for flare gas. In addition, the revised analysis calculates an average C content from all samples with less than 1.5 percent $CO_2$ and less than 1,050 Btu/cf (samples most closely approximating the makeup of pipeline quality natural gas). The result was identical to the previous weighted national average of 14.47 Tg C/QBtu. The average C contents from the 1994 calculations are presented in Table A-55 below for comparison.

Table A-55: Carbon Content of Pipeline-Quality Natural Gas by Energy Content (Tg C/QBtu)

| Sample | Average Carbon Content |
|---|---|
| GRI Full Sample | 14.51 |
| Greater than 1,000 Btu | 14.47 |
| 1,025 to 1,035 Btu | 14.45 |
| 975 to 1,000 Btu | 14.73 |
| 1,000 to 1,025 Btu | 14.43 |
| 1,025 to 1,050 Btu | 14.47 |
| 1,050 to 1,075 Btu | 14.58 |
| 1,075 to 1,100 Btu | 14.65 |
| Greater than 1,100 Btu | 14.92 |
| Weighted National Average | 14.47 |

Source: EIA (1994).

**Petroleum Products**

All of the petroleum product C coefficients except that for Aviation Gasoline Blending Components have been updated for the current Inventory. EPA is updating these factors to better align the fuel properties data that underlie the Inventory factors with those published in the Mandatory Reporting of Greenhouse Gases Rule (EPA 2009b), Suppliers of Petroleum Products (MM) and Stationary Combustion (C) subparts. The coefficients that were applied in the previous report are provided in Table A-56 below. Specifically, each of the coefficients used in this report have been calculated from updated density and C share data, largely adopted from analyses undertaken for the Rule (EPA 2009b). In some cases, the heat content applied to the conversion to a carbon-per-unit-energy basis has also been updated. Additionally, the category Misc. Products (Territories), which is based upon the coefficients calculated for crude oil, has been allowed to vary annually with the crude oil coefficient. The petrochemical feedstock category has been eliminated for this report because the constituent products—naphthas and other oils—are estimated independently. Further, although the level of aggregation of U.S. energy statistics currently limits the application of coefficients for residual and distillate fuels to these two generic classifications, individual coefficients for the five major types of fuel oil (Nos. 1, 2, 4, 5 and 6) have been estimated for the current report and are presented in Table A-45 above. Each of the C coefficients applied in the previous Inventory is provided below for comparison (Table A-56).

Table A-56: Carbon Content Coefficients and Underlying Data for Petroleum Products

| Fuel | 2007 Carbon Content (Tg C/QBtu) | Gross Heat of Combustion (MMBtu/Barrel) | Density (API Gravity) | Percent Carbon |
|---|---|---|---|---|
| Motor Gasoline | 19.33 | 5.219 | 59.1 | 86.60 |
| LPG(total) | 16.99 | a | a | a |
| LPG (energy use) | 17.18 | a | a | a |
| LPG (non-energy use) | 16.76 | a | a | a |
| Jet Fuel | 19.33 | 5.670 | 42.0 | 86.30 |
| Distillate Fuel | 19.95 | 5.825 | 35.5 | 86.34 |
| Residual Fuel | 21.49 | 6.287 | 11.0 | 85.68 |
| Asphalt and Road Oil | 20.62 | 6.636 | 5.6 | 83.47 |
| Lubricants | 20.24 | 6.065 | 25.6 | 85.80 |
| Petrochemical Feedstocks | 19.37 | 5.248 [b] | 67.1 [b] | 84.11 [b] |
| Aviation Gas | 18.87 | 5.048 | 69.0 | 85.00 |
| Kerosene | 19.72 | 5.670 | 41.4 | 86.01 |
| Petroleum Coke | 27.85 | 6.024 | - | 92.28 |
| Special Naphtha | 19.86 | 5.248 | 51.2 | 84.76 |
| Petroleum Waxes | 19.81 | 5.537 | 43.3 | 85.29 |
| Still Gas | 17.51 | 6.000 | - | - |
| Crude Oil | 20.33 | 5.800 | 30.5 | 85.49 |
| Unfinished Oils | 20.33 | 5.825 | 30.5 | 85.49 |
| Miscellaneous Products | 20.33 | 5.796 | 30.5 | 85.49 |
| Pentanes Plus | 18.24 | 4.620 | 81.7 | 83.70 |
| Natural Gasoline | 18.24 | 4.620 | 81.7 | 83.70 |

[a] LPG is a blend of multiple paraffinic hydrocarbons: ethane, propane, isobutane, and normal butane, each with their own heat content, density and C content, see Table A-48.
[b] Parameters presented are for naphthas with a boiling temperature less than 400 degrees Fahrenheit. Petrochemical feedstocks with higher boiling points are assumed to have the same characteristics as distillate fuel.
- No sample data available
Sources: EIA (1994), EIA (2008a), and SAIC (2007).

Additional revisions to the inventory's C coefficients since 1990 are detailed below.

***Jet Fuel***

1995 Update

Between 1994 and 1995, the C content coefficient for kerosene-based jet fuel was revised downward from 19.71 Tg C/QBtu to 19.33 Tg C/QBtu. This downward revision was the result of a shift in the sample set used from one collected between 1959 and 1972 and reported on by Martel and Angello in 1977 to one collected by Boeing in 1989 and published by Hadaller and Momenthy in 1990. The downward revision was a result of a decrease in density, as well as slightly lower C shares than in the earlier samples. However, the assumed heat content is unchanged because it is based on an EIA standard and probably yields a downward bias in the revised C content coefficient.

1990 through 2008 Inventory Update

The coefficient was revised again for the 1990 through 2008 Inventory, returning to Martel and Angello and NIPER as the source of the carbon share and density data, respectively, for kerosene-based fuels. This change was made in order to align the coefficients used for this report with the values used in the Mandatory Reporting of Greenhouse Gases Rule (EPA 2009b). The return to the use of the Martel and Angello and NIPER coefficients was deemed more appropriate for the Rule as it was considered a more conservative coefficient given the uncertainty and variability in coefficients across the types of jet fuel in use in the United States. The factor will be revisited in future Inventories in light of data received from reporting entities in response to the Rule.

***Liquefied Petroleum Gases (LPG)***

The C content coefficient of LPG is updated annually to reflect changes in the consumption mix of the underlying compounds: ethane; propane; isobutane; and normal butane. In 1994, EIA included pentanes plus—assumed to have the characteristics of hexane—in the mix of compounds broadly described as LPG. In 1995, EIA removed pentanes plus from this fuel category. Because pentanes plus is relatively rich in C per unit of energy, its removal from the consumption mix lowered the C content coefficient for LPG from 17.26 Tg C/QBtu to 16.99 Tg C/QBtu. In 1998, EIA began separating LPG consumption into two categories: energy use and non-fuel use and providing individual coefficients

for each. Because LPG for fuel use typically contains higher proportions of propane than LPG for non-fuel use, the C content coefficient for fuel use was 1.8 to 2.5 percent higher than the coefficient for non-fuel use in previous Inventories (see Table A-56).

However, for the current update of the LPG coefficients, the assumptions that underlie the selection of density and heat content data for each pure LPG compound have been updated, leading to a significant revision of the assumed properties of ethane. For this report, the physical characteristics of ethane, which constitutes over 90 percent of LPG consumption for non-fuel uses, have been updated to reflect ethane that is in (refrigerated) liquid form. Previously, the share of ethane was included using the density and energy content of gaseous ethane. Table A-57, below, compares the values applied for each of the compounds under the two sets of coefficient calculations. The carbon share of each pure compound was also updated by using more precise values for each compound's molecular weight.

Due in large part to the revised assumptions for ethane, the weighted C content for non-fuel use is now higher than that of the weighted coefficient for fuel use, which is dominated by the consumption of more dense propane. Under the revised assumptions, each annual weighted coefficient for non-fuel LPG consumption is 1.2 to 1.7 percent higher each year than is that for LPGs consumed for fuel (energy) uses.

Table A-57: Physical Characteristics of Liquefied Petroleum Gases

| Compound | Chemical Formula | 1990-2007 Density (bbl / MT) | Updated Density (bbl / MT) | 1990-2007 Energy Content (MMBtu/bbl) | Updated Energy Content (MMBtu/bbl) | 1990-2007 C Content Coefficient (Tg C/QBtu) | Updated C Content Coefficient (Tg C/QBtu) |
|---|---|---|---|---|---|---|---|
| Ethane | $C_2H_6$ | 16.88 | 11.55 | 2.916 | 3.082 | 16.25 | 17.16 |
| Propane | $C_3H_8$ | 12.44 | 12.76 | 3.824 | 3.836 | 17.20 | 16.76 |
| Isobutane | $C_4H_{10}$ | 11.20 | 11.42 | 4.162 | 3.974 | 17.75 | 17.77 |
| n-butane | $C_4H_{10}$ | 10.79 | 10.98 | 4.328 | 4.326 | 17.72 | 17.75 |

Sources: Updated: Densities – CRC Handbook of Chemistry and Physics, 89th Ed. (2008/09); Energy Contents – EPA (2009b). All values are for the compound in liquid form. The density and energy content of ethane are for refrigerated ethane (-89 degrees C). Values for n-butane are for pressurized butane (-25 degrees C). Values in previous editions of this inventory: Gurthrie (1960).

***Motor Gasoline***

The C content coefficient for motor gasoline varies annually based on the density of and proportion of additives in a representative sample of motor gasoline examined each year. However, in 1997 EIA began incorporating the effects of the introduction of reformulated gasoline into its estimate of C content coefficients for motor gasoline. This change resulted in a downward step function in C content coefficients for gasoline of approximately 0.3 percent beginning in 1995. In 2005-2006 reformulated fuels containing ethers began to be phased out nationally. Ethanol was added to gasoline blends as a replacement oxygenate, leading to another shift in gasoline density (see Table A- 46), in the list and proportion of constituents that form the blend and in the blended C share based on those constituents.

Table A-58: Carbon Content Coefficients for Petroleum Products, 1990-2007 [Tg C/QBtu)

| Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Petroleum** | | | | | | | | | | | | | | |
| Asphalt and Road Oil | 20.62 | 20.62 | 20.62 | 20.62 | 20.62 | 20.62 | 20.62 | 20.62 | 20.62 | 20.62 | 20.62 | 20.62 | 20.62 | 20.62 |
| Aviation Gasoline | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 |
| Distillate Fuel Oil | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 |
| Jet Fuel[a] | 19.40 | 19.34 | 19.33 | 19.33 | 19.33 | 19.33 | 19.33 | 19.33 | 19.33 | 19.33 | 19.33 | 19.33 | 19.33 | 19.33 |
| Kerosene | 19.72 | 19.72 | 19.72 | 19.72 | 19.72 | 19.72 | 19.72 | 19.72 | 19.72 | 19.72 | 19.72 | 19.72 | 19.72 | 19.72 |
| LPG (energy use)[a] | 17.21 | 17.20 | 17.20 | 17.18 | 17.23 | 17.25 | 17.20 | 17.21 | 17.20 | 17.21 | 17.20 | 17.19 | 17.19 | 17.18 |
| LPG (non-energy use)[a] | 16.83 | 16.87 | 16.86 | 16.88 | 16.88 | 16.84 | 16.81 | 16.83 | 16.82 | 16.84 | 16.81 | 16.81 | 16.78 | 16.76 |
| Lubricants | 20.24 | 20.24 | 20.24 | 20.24 | 20.24 | 20.24 | 20.24 | 20.24 | 20.24 | 20.24 | 20.24 | 20.24 | 20.24 | 20.24 |
| Motor Gasoline[a] | 19.41 | 19.38 | 19.36 | 19.35 | 19.33 | 19.33 | 19.34 | 19.34 | 19.35 | 19.33 | 19.33 | 19.33 | 19.33 | 19.33 |
| Residual Fuel | 21.49 | 21.49 | 21.49 | 21.49 | 21.49 | 21.49 | 21.49 | 21.49 | 21.49 | 21.49 | 21.49 | 21.49 | 21.49 | 21.49 |
| **Other Petroleum** | | | | | | | | | | | | | | |
| Av Gas Blend Comp. | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 | 18.87 |
| Mo Gas Blend Comp[a] | 19.41 | 19.38 | 19.36 | 19.35 | 19.33 | 19.33 | 19.34 | 19.34 | 19.35 | 19.33 | 19.33 | 19.33 | 19.33 | 19.33 |
| Crude Oil[a] | 20.16 | 20.23 | 20.25 | 20.24 | 20.24 | 20.19 | 20.23 | 20.29 | 20.30 | 20.28 | 20.33 | 20.33 | 20.33 | 20.33 |
| Misc. Products[a] | 20.16 | 20.23 | 20.25 | 20.24 | 20.24 | 20.19 | 20.23 | 20.29 | 20.30 | 20.28 | 20.33 | 20.33 | 20.33 | 20.33 |
| Misc. Products (Terr.) | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 |
| Naphtha (<401 deg. F) | 18.14 | 18.14 | 18.14 | 18.14 | 18.14 | 18.14 | 18.14 | 18.14 | 18.14 | 18.14 | 18.14 | 18.14 | 18.14 | 18.14 |
| Other oil (>401 deg. F) | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 | 19.95 |
| Pentanes Plus | 18.24 | 18.24 | 18.24 | 18.24 | 18.24 | 18.24 | 18.24 | 18.24 | 18.24 | 18.24 | 18.24 | 18.24 | 18.24 | 18.24 |
| Petrochemical Feed. | 19.37 | 19.37 | 19.37 | 19.37 | 19.37 | 19.37 | 19.37 | 19.37 | 19.37 | 19.37 | 19.37 | 19.37 | 19.37 | 19.37 |
| Petroleum Coke | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 | 27.85 |
| Still Gas | 17.51 | 17.51 | 17.51 | 17.51 | 17.51 | 17.51 | 17.51 | 17.51 | 17.51 | 17.51 | 17.51 | 17.51 | 17.51 | 17.51 |
| Special Naphtha | 19.86 | 19.86 | 19.86 | 19.86 | 19.86 | 19.86 | 19.86 | 19.86 | 19.86 | 19.86 | 19.86 | 19.86 | 19.86 | 19.86 |
| Unfinished Oils[a] | 20.16 | 20.23 | 20.25 | 20.24 | 20.24 | 20.19 | 20.23 | 20.29 | 20.30 | 20.28 | 20.33 | 20.33 | 20.33 | 20.33 |
| Waxes | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 |
| Other Wax and Misc. | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 | 19.81 |

[a]C contents vary annually based on changes in fuel composition.

[b]C content for utility coal used in the electric power calculations. All coefficients based on higher heating value. Higher heating value (gross heating value) is the total amount of heat released when a fuel is burned. Coal, crude oil, and natural gas all include chemical compounds of carbon and hydrogen. When those fuels are burned, the carbon and hydrogen combine with oxygen in the air to produce $CO_2$ and water. Some of the energy released in burning goes into transforming the water into steam and is usually lost. The amount of heat spent in transforming the water into steam is counted as part of gross heat content. Lower heating value (net heating value), in contrast, does not include the heat spent in transforming the water into steam. Using a simplified methodology based on International Energy Agency defaults, higher heating value can be converted to lower heating value for coal and petroleum products by multiplying by 0.95 and for natural gas by multiplying by 0.90. Carbon content coefficients are presented in higher heating value because U.S. energy statistics are reported by higher heating value.

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## 2.3. Methodology for Estimating Carbon Emitted from Non-Energy Uses of Fossil Fuels

Carbon (C) storage associated with the non-energy use of fossil fuels was calculated by multiplying each fuel's potential emissions (i.e., each fuel's total C content) by a fuel-specific storage factor, as listed in Table A-59. The remaining C—i.e., that which is not stored—is emitted. This sub-annex explains the methods and data sources employed in developing the storage factors for petrochemical feedstocks (industrial other coal, natural gas for non-fertilizer uses, LPG, pentanes plus, naphthas, other oils, still gas, special naphtha), asphalt and road oil, lubricants, waxes, and miscellaneous products. The storage factors[21] for the remaining non-energy fuel uses are either based on values recommended for use by IPCC (2006), or when these were not available, assumptions based on the potential fate of C in the respective NEU products.

Table A-59: Fuel Types and Percent of C Stored for Non-Energy Uses

| Sector/Fuel Type | Storage Factor (%) |
|---|---|
| **Industry** | - |
| Industrial Coking Coal[a] | 10 |
| Industrial Other Coal [b] | 59 |
| Natural Gas to Chemical Plants [b] | 59 |
| Asphalt & Road Oil | 100 |
| LPG [b] | 59 |
| Lubricants | 9 |
| Pentanes Plus [b] | 59 |
| Naphtha (<401 deg. F) [b] | 59 |
| Other Oil (>401 deg. F) [b] | 59 |
| Still Gas [b] | 59 |
| Petroleum Coke[c] | 30 |
| Special Naphtha [b] | 59 |
| Distillate Fuel Oil | 50 |
| Waxes | 58 |
| Miscellaneous Products | 0 |
| **Transportation** | - |
| Lubricants | 9 |
| **U.S. Territories** | - |
| Lubricants | 9 |
| Other Petroleum (Misc. Prod.) | 10 |

- Not applicable

[a] Includes processes for which specific coking coal consumption and emission factor data are not available. Consumption of coking coal for production of iron and steel is covered in the Industrial Processes chapter.

[b] The storage factor listed is the value for 2011. As described in this annex, the factor varies over time.

[c] Assumes petroleum coke consumption is for pigments. Consumption of petroleum coke for production of primary aluminum anodes, electric arc furnace anodes, titanium dioxide, ammonia, urea, and ferroalloys is covered in the Industrial Processes chapter.

The following sections describe the non-energy uses in greater detail, outlining the methods employed and data used in estimating each storage factor. Several of the fuel types tracked by EIA are used in organic chemical synthesis and in other manufacturing processes, and are referred to collectively as "petrochemical feedstocks." Because the methods and data used to analyze them overlap, they are handled as a group and are discussed first. Discussions of the storage factors for asphalt and road oil, lubricants, waxes, and miscellaneous products follow.

[21] Throughout this section, references to "storage factors" represent the proportion of carbon stored.

## Petrochemical Feedstocks

Petrochemical feedstocks—industrial other coal, natural gas for non-fertilizer uses, LPG, pentanes plus, naphthas, other oils, still gas, special naphtha—are used in the manufacture of a wide variety of man-made chemicals and products. Plastics, rubber, synthetic fibers, solvents, paints, fertilizers, pharmaceuticals, and food additives are just a few of the derivatives of these fuel types. Chemically speaking, these fuels are diverse, ranging from simple natural gas (i.e., predominantly $CH_4$) to heavier, more complex naphthas and other oils.[22]

After adjustments for (1) use in industrial processes and (2) net exports, these eight fuel categories constituted approximately 207.6 Tg $CO_2$ Eq., or 64% percent, of the 323.3 Tg $CO_2$ Eq. of non-energy fuel consumption in 2011. For 2011 the storage factor for the eight fuel categories was 59 percent. In other words, of the net consumption, 59 percent was destined for long-term storage in products—including products subsequently combusted for waste disposal—while the remaining 41 percent was emitted to the atmosphere directly as $CO_2$ (e.g., through combustion of industrial byproducts) or indirectly as $CO_2$ precursors (e.g., through evaporative product use). The indirect emissions include a variety of organic gases such as volatile organic compounds (VOCs) and carbon monoxide (CO), which eventually oxidize into $CO_2$ in the atmosphere. The derivation of the storage factor is described in the following sections.

### Methodology and Data Sources

The petrochemical feedstocks storage factor is equal to the ratio of C stored in the final products to total C content for the non-energy fossil fuel feedstocks used in industrial processes, after adjusting for net exports of feedstocks. One aggregate storage factor was calculated to represent all eight fuel feedstock types. The feedstocks were grouped because of the overlap of their derivative products. Due to the many reaction pathways involved in producing petrochemical products (or wastes), it becomes extraordinarily complex to link individual products (or wastes) to their parent fuel feedstocks.

Import and export data for feedstocks were obtained from the Energy Information Administration (EIA) for the major categories of petrochemical feedstocks. EIA's *Petroleum Supply Annual* publication tracks imports and exports of petrochemical feedstocks, including butanes, butylenes, ethane, ethylene, propane, propylene, LPG, and naphthas (i.e., most of the large volume primary chemicals produced by petroleum refineries). These imports and exports are already factored into the U.S. fuel consumption statistics. However, EIA does not track imports and exports of chemical intermediates and products produced by the chemical industry (e.g., xylenes, vinyl chloride), which are derived from the primary chemicals produced by the refineries. These products represent very large flows of C derived from fossil fuels (i.e., fossil C), so estimates of net flows not already considered in EIA's dataset were developed for the entire time series from 1990 to 2011.

The approach to estimate imports and exports involves three steps, listed here and then described in more detail below:

*Step 1.* Identify commodities derived from petrochemical feedstocks, and calculate net import/export for each.

*Step 2.* Estimate the C content for each commodity.

*Step 3.* Sum the net C imports/exports across all commodities.

Step 1 relies heavily on information provided by the National Petrochemical and Refiners Association (NPRA) and U.S. Bureau of the Census (BoC) trade statistics published by the U.S. International Trade Commission (USITC). NPRA provided a spreadsheet of the ten-digit BoC Harmonized Tariff Schedule (HTS) Commodity Codes used to compile import-export data for periodic reports issued to NPRA's membership on trade issues. Additional feedstock commodities were identified by HTS code in the BoC data system and included in the net import/export analysis.

One of the difficulties in analyzing trade data is that a large portion of the outputs from the refining industry are fuels and fuel components, and it was difficult to segregate these from the outputs used for non-energy uses. The NPRA-supplied codes identify fuels and fuel components, thus providing a sound basis for isolating net imports/exports of petrochemical feedstocks. Although MTBE and related ether imports are included in the published NPRA data, these commodities are not included in the total net imports/exports calculated here, because it is assumed that they are fuel additives and do not contribute to domestic petrochemical feedstocks. Net exports of MTBE and related ethers are also not included in the totals, as these commodities are considered to be refinery products that are already accounted for in the

[22] Naphthas are compounds distilled from petroleum containing 4 to 12 carbon atoms per molecule and having a boiling point less than 401° F. "Other oils" are distillates containing 12 to 25 carbon atoms per molecule and having a boiling point greater than 401° F.

EIA data. Imports and exports of commodities for which production and consumption data are provided by EIA (e.g., butane, ethylene, and liquefied petroleum gases) are also not included in the totals, to avoid double-counting.

Another difficulty is that one must be careful to assure that there is not double-counting of imports and exports in the data set. Other parts of the mass balance (described later) provide information on C flows, in some cases based on production data and in other cases based on consumption data. Production data relates only to production within the country; consumption data incorporates information on imports and exports as well as production. Because many commodities are emissive in their use, but not necessarily their production, consumption data is appropriately used in calculations for emissive fates. For purposes of developing an overall mass balance on U.S. non-energy uses of C, for those materials that are non-emissive (e.g., plastics), production data is most applicable. And for purposes of adjusting the mass balance to incorporate C flows associated with imports and exports, it was necessary to carefully review whether or not the mass balance already incorporated cross-boundary flows (through the use of consumption data), and to adjust the import/export balance accordingly.

The BoC trade statistics are publicly available[23] and cover a complete time series from 1990 to 2011. These statistics include information on imports and exports of thousands of commodities. After collecting information on annual flows of the more than 100 commodities identified by NPRA, Step 2 involves calculating the C content for each commodity from its chemical formula. In cases where the imports and exports were expressed in units of volume, rather than mass, they were converted to mass based on the commodities' densities.

Step 3 involves summing the net C imports/exports across all commodities. The results of this step are shown in Table A-60. As shown in the table, the United States has been a net exporter of chemical intermediates and products throughout the 1990 to 2011 period.

Table A-60: Net Exports of Petrochemical Feedstocks, 1990 – 2011 (Tg $CO_2$ Eq.)

| | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Net Exports | 12.0 | 11.1 | 8.3 | 1.8 | 7.3 | 14.8 | 20.2 | 6.5 | 4.1 | 8.4 | 4.5 | 9.0 | 7.7 | 8.3 |

After adjusting for imports and exports, the C budget is adjusted for the quantity of C that is used in the Industrial Processes sector of the Inventory. Fossil fuels used for non-energy purposes in industrial processes—and for which C emissions and storage have been characterized through mass balance calculations and/or emission factors that directly link the non-energy use fossil fuel raw material and the industrial process product—are not included in the non-energy use sector. These industrial processes (and their non-energy use fossil fuel raw materials) include iron and steel (coal coke), primary aluminum (petroleum coke), titanium oxide (petroleum coke), ferroalloys (petroleum coke), and ammonia and urea (petroleum coke and natural gas).

For each year of the Inventory, the total C content of non-energy uses was calculated by starting with the EIA estimate of non-energy use, and reducing it by the adjustment factor for net exports (see Table A-60) to yield net domestic fuel consumption for non-energy. The balance was apportioned to either stored C or emissive C, based on a storage factor.

The overall storage factor for the feedstocks was determined by developing a mass balance on the C in feedstocks, and characterizing products, uses, and environmental releases as resulting in either storage or emissions. The total C in the system was estimated by multiplying net domestic consumption for non-energy by the C content of each of the feedstocks (i.e., industrial other coal, natural gas for non-fertilizer uses, LPG, pentanes plus, naphthas, other oils, still gas, special naphtha). C content values for the fuel feedstocks are discussed in the Estimating Emissions from Fossil Fuel Combustion and Estimating the Carbon Content from Fossil Fuel Combustion Annexes.

Next, C pools and releases in a variety of industrial releases, energy recovery processes, and products were characterized. The C fate categories are plastics, energy recovery, synthetic rubber, synthetic fibers, organic solvents, C black, detergents and personal cleansers, industrial non-methane volatile organic compound (NMVOC) emissions, hazardous waste incineration, industrial toxic chemical (i.e., TRI) releases, pesticides, food additives, antifreeze and deicers (glycols), and silicones.[24]

[23] See the U.S International Trade Commission (USITC) Trade Dataweb at <http://dataweb.usitc.gov/>.

[24] For the most part, the releases covered by the U.S. Toxic Release Inventory (TRI) represent air emissions or water discharges associated with production facilities. Similarly, VOC emissions are generally associated with production facilities. These emissions

The C in each product or waste produced was categorized as either stored or emitted. The aggregate storage factor is the C-weighted average of storage across fuel types. As discussed later in the section on uncertainty, the sum of stored C and emitted C (i.e., the outputs of the system) exceeded total C consumption (i.e., the inputs to the system) for some years in the time series.[25] To address this mass imbalance, the storage factor was calculated as C storage divided by total C outputs (rather than C storage divided by C inputs).

Note that the system boundaries for the storage factor do not encompass the entire life-cycle of fossil-based C consumed in the United States insofar as emissions of $CO_2$ from waste combustion are accounted for separately in the Inventory and are discussed in the Incineration of Waste section of the Energy chapter.

The following sections provide details on the calculation steps, assumptions, and data sources employed in estimating and classifying the C in each product and waste shown in Table A-61. Summing the C stored and dividing it by total C outputs yields the overall storage factor, as shown in the following equation for 2011:

$$\text{Overall Storage Factor} = \text{C Stored} / (\text{C Stored} + \text{C Emitted}) =$$

$$136.7 \text{ Tg } CO_2 \text{ Eq.} / (136.7 + 93.0) \text{ Tg } CO_2 \text{ Eq.} = 59\%$$

Table A-61: C Stored and Emitted by Products from Feedstocks in 2011 (Tg $CO_2$ Eq.)

| Product/Waste Type | C Stored (Tg $CO_2$ Eq.) | C Emitted (Tg $CO_2$ Eq.) |
|---|---|---|
| **Industrial Releases** | **0.1** | **4.3** |
| TRI Releases | 0.1 | 1.0 |
| Industrial VOCs | - | 2.3 |
| Non-combustion CO | - | 0.7 |
| Hazardous Waste Incin. | - | 0.4 |
| **Energy Recovery** | **-** | **74.8** |
| **Products** | **136.6** | **13.9** |
| Plastics | 118.4 | - |
| Synthetic Rubber | 10.5 | - |
| Antifreeze and deicers | - | 0.7 |
| Abraded tire rubber | - | 0.3 |
| Food additives | - | 0.8 |
| Silicones | 0.5 | - |
| Synthetic Fiber | 7.0 | - |
| Pesticides | 0.2 | 0.2 |
| Soaps, shampoos, detergents | - | 6.5 |
| Solvent VOCs | - | 5.3 |
| **Total** | **136.7** | **93.0** |

- Not applicable
Note: Totals may not sum due to independent rounding.

The three categories of C accounted for in the table are industrial releases, energy recovery, and products. Each is discussed below.

### *Industrial Releases*

Industrial releases include toxic chemicals reported through the Toxics Release Inventory, industrial emissions of volatile organic compounds (VOCs), CO emissions (other than those related to fuel combustion), and emissions from hazardous waste incineration.

could have been accounted for as part of the Waste chapter, but because they are not necessarily associated with waste management, they were included here. Toxic releases are not a "product" category, but they are referred to as such for ease of discussion.

[25] Overall, there was fairly close agreement between inputs and outputs: for the entire 1990 through2010 time series, inputs exceeded outputs by a time-weighted average of 0.2 percent. During the period 1990 through 2000, carbon inputs exceeded carbon outputs (i.e., the sum of carbon stored and carbon emitted) by a time-weighted average of 10 percent. For those years, the assumption was made that the "missing" carbon was lost through fates leading to emissions. This discrepancy shifted during the period from 2001 through 2010, in which carbon outputs exceeded carbon inputs by a time-weighted average of 12 percent.

*TRI Releases*

Fossil-derived C is found in many toxic substances released by industrial facilities. The Toxics Release Inventory (TRI), maintained by EPA, tracks these releases by chemical and environmental release medium (i.e., land, air, or water) on a biennial basis (EPA 2000b). By examining the C contents and receiving media for the top 35 toxic chemicals released, which account for 90 percent of the total mass of chemicals, the quantity of C stored and emitted in the form of toxic releases can be estimated.

The TRI specifies releases by chemical, so C contents were assigned to each chemical based on molecular formula. The TRI also classifies releases by disposal location as either off-site or on-site. The on-site releases are further subdivided into air emissions, surface water discharges, underground injection, and releases to land; the latter is further broken down to disposal in a RCRA Subtitle C (i.e., hazardous waste) landfill or to "Other On-Site Land Disposal."[26] The C released in each disposal location is provided in Table A-62.

Each on-site classification was assigned a storage factor. A 100 percent storage factor was applied to disposition of C to underground injection and to disposal to RCRA-permitted landfills, while the other disposition categories were assumed to result in an ultimate fate of emission as $CO_2$ (i.e., a storage factor of zero was applied to these categories.) The release allocation is not reported for off-site releases; therefore, the approach was to develop a C-weighted average storage factor for the on-site C and apply it to the off-site releases.

For the remaining 10 percent of the TRI releases, the weights of all chemicals were added and an average C content value, based upon the top 35 chemicals' C contents, was applied. The storage and emission allocation for the remaining 10 percent of the TRI releases was carried out in the same fashion as for the 35 major chemicals.

Data on TRI releases for the full 1990 through 2011 time series were not readily available. Since this category is small (less than 1 Tg C emitted and stored), the 1998 value was applied for the entire time series.

Table A-62: 1998 TRI Releases by Disposal Location (Gg $CO_2$ Eq.)

| Disposal Location | Carbon Stored (Gg $CO_2$ Eq.) | Carbon Emitted (Gg $CO_2$ Eq.) |
|---|---|---|
| Air Emissions | - | 924.0 |
| Surface Water Discharges | - | 6.7 |
| Underground Injection | 89.4 | - |
| RCRA Subtitle C Landfill Disposal | 1.4 | - |
| Other On-Site Land Releases | - | 15.9 |
| Off-site Releases | 6.4 | 36.0 |
| **Total** | **97.2** | **982.6** |

- Not applicable
Note: Totals may not sum due to independent rounding.

*Volatile Organic Compound Emissions from Industrial Processes and Solvent Evaporation Emissions*

Data on annual non-methane volatile organic compound (NMVOC) emissions were obtained from preliminary data (EPA 2010, EPA 2009b), 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. The 1990-2011 Trends data include information on NMVOC emissions by end-use category; some of these fall into the heading of "industrial releases" in Table A-62 above, and others are related to "product use"; for ease of discussion, both are covered here. The end-use categories that represent "Industrial NMVOC Emissions" include some chemical and allied products, certain petroleum related industries, and other industrial processes. NMVOC emissions from solvent utilization (product use) were considered to be a result of non-energy use of petrochemical feedstocks. These categories were used to distinguish non-energy uses from energy uses; other categories where VOCs could be emitted due to combustion of fossil fuels were excluded to avoid double counting. As data for 2010 and 2011 are not yet available, they have been set equal to 2009 values.

[26] Only the top 9 chemicals had their land releases separated into RCRA Landfills and Other Land Disposal. For the remaining chemicals, it was assumed that the ratio of disposal in these two categories was equal to the carbon-weighted average of the land disposal fate of the top 9 chemicals (i.e., 8 percent attributed to RCRA Landfills and 92 percent in the "Other" category).

Because solvent evaporation and industrial NMVOC emission data are provided in tons of total NMVOCs, assumptions were made concerning the average C content of the NMVOCs for each category of emissions. The assumptions for calculating the C fraction of industrial and solvent utilization emissions were made separately and differ significantly. For industrial NMVOC emissions, a C content of 85 percent was assumed. This value was chosen to reflect the C content of an average volatile organic compound based on the list of the most abundant NMVOCs provided in the Trends Report. The list contains only pure hydrocarbons, including saturated alkanes (C contents ranging from 80 to 85 percent based upon C number), alkenes (C contents approximately 85 percent), and some aromatics (C contents approximately 90 percent, depending upon substitution).

An EPA solvent evaporation emissions dataset (Tooly 2001) was used to estimate the C content of solvent emissions. The dataset identifies solvent emissions by compound or compound category for six different solvent end-use categories: degreasing, graphic arts, dry cleaning, surface coating, other industrial processes, and non-industrial processes. The percent C of each compound identified in the dataset was calculated based on the molecular formula of the individual compound (e.g., the C content of methylene chloride is 14 percent; the C content of toluene is 91 percent). For solvent emissions that are identified in the EPA dataset only by chemical category (e.g., butanediol derivatives) a single individual compound was selected to represent each category, and the C content of the category was estimated based on the C content of the representative compound. The overall C content of the solvent evaporation emissions for 1998, estimated to be 56 percent, is assumed to be constant across the entire time series.

The results of the industrial and solvent NMVOC emissions analysis are provided in Table A-63 for 1990 through 2011. Solvent evaporation emissions in 2011 were 5.3 Tg $CO_2$ Eq., and industrial NMVOC emissions in 2011 were 2.3 Tg $CO_2$ Eq.

Table A-63: Industrial and Solvent NMVOC Emissions

| | 1990 | 1995 | 2000 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|
| **Industrial NMVOCs[a]** | | | | | | | | | | |
| NMVOCs ('000 Short Tons) | 1,279 | 1,358 | 803 | 824 | 806 | 788 | 769 | 829 | 829 | 829 |
| Carbon Content (%) | 85% | 85% | 85% | 85% | 85% | 85% | 85% | 85% | 85% | 85% |
| Carbon Emitted (Tg $CO_2$ Eq.) | 3.6 | 3.8 | 2.3 | 2.3 | 2.3 | 2.2 | 2.2 | 2.3 | 2.3 | 2.3 |
| **Solvent Evaporation[b]** | | | | | | | | | | |
| Solvents ('000 Short Tons) | 5,750 | 6,183 | 4,832 | 4,245 | 4,239 | 4,232 | 4,226 | 2,847 | 2847 | 2,847 |
| Carbon Content (%) | 56% | 56% | 56% | 56% | 56% | 56% | 56% | 56% | 56% | 56% |
| Carbon Emitted (Tg $CO_2$ Eq.) | 10.8 | 11.6 | 9.0 | 7.9 | 7.9 | 7.9 | 7.9 | 5.3 | 5.3 | 5.3 |

[a] Includes emissions from chemical and allied products, petroleum and related industries, and other industrial processes categories.
[b] Includes solvent usage and solvent evaporation emissions from degreasing, graphic arts, dry cleaning, surface coating, other industrial processes, and non-industrial processes.

*Non-Combustion Carbon Monoxide Emissions*

Carbon monoxide (CO) emissions data were also obtained from the NEI preliminary data (EPA 2010, EPA 2009b), and disaggregated based on EPA (2003). There are three categories of CO emissions in the report that are classified as process-related emissions not related to fuel combustion. These include chemical and allied products manufacturing, metals processing, and other industrial processes. Some of these CO emissions are accounted for in the Industrial Processes section of this report, and are therefore not accounted for in this section. These include total C emissions from the primary aluminum, titanium dioxide, iron and steel, and ferroalloys production processes. The total C (CO and CO2) emissions from oil and gas production, petroleum refining, and asphalt manufacturing are also accounted for elsewhere in this Inventory. Biogenic emissions (e.g., pulp and paper process emissions) are accounted for in the Land Use, Land-Use Change and Forestry chapter and excluded from calculation of CO emissions in this section. Those CO emissions that are not accounted for elsewhere are considered to be byproducts of non-fuel use of feedstocks, and are thus included in the calculation of the petrochemical feedstocks storage factor. Table A-64 lists the CO emissions that remain after taking into account the exclusions listed above. As data for 2010 and 2011 are not yet available, they have been set equal to 2009 values.

Table A-64: Non-Combustion Carbon Monoxide Emissions[a]

| | 1990 | 1995 | 2000 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|
| Thousand short tons CO | 489 | 481 | 623 | 461 | 469 | 477 | 484 | 461 | 461 | 461 |
| Carbon Emitted (Tg $CO_2$ Eq.) | 0.7 | 0.7 | 0.9 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |

Includes emissions from chemical and allied products, petroleum and related industries, metals processing, and other industrial processes categories.

*Hazardous Waste Incineration*

Hazardous wastes are defined by the EPA under the Resource Conservation and Recovery Act (RCRA).[27] Industrial wastes, such as rejected products, spent reagents, reaction by-products, and sludges from wastewater or air pollution control, are federally regulated as hazardous wastes if they are found to be ignitable, corrosive, reactive, or toxic according to standardized tests or studies conducted by the EPA.

Hazardous wastes must be treated prior to disposal according to the federal regulations established under the authority of RCRA. Combustion is one of the most common techniques for hazardous waste treatment, particularly for those wastes that are primarily organic in composition or contain primarily organic contaminants. Generally speaking, combustion devices fall into two categories: incinerators that burn waste solely for the purpose of waste management, and boilers and industrial furnaces (BIFs) that burn waste in part to recover energy from the waste. More than half of the hazardous waste combusted in the United States is burned in BIFs; because these processes are included in the energy recovery calculations described below, they are not included as part of hazardous waste incineration.

EPA's Office of Solid Waste requires biennial reporting of hazardous waste management activities, and these reports provide estimates of the amount of hazardous waste burned for incineration or energy recovery. EPA stores this information in its Resource Conservation and Recovery Act (RCRA) Information system (EPA 2013), formerly reported in its Biennial Reporting System (BRS) database (EPA 2000a, 2009a). Combusted hazardous wastes are identified based on EPA-defined management system types M041 through M049 (incineration). Combusted quantities are grouped into four representative waste form categories based on the form codes reported in the BRS: aqueous liquids, organic liquids and sludges, organic solids, and inorganic solids. To relate hazardous waste quantities to C emissions, "fuel equivalent" factors were derived for hazardous waste by assuming that the hazardous wastes are simple mixtures of a common fuel, water, and noncombustible ash. For liquids and sludges, crude oil is used as the fuel equivalent and coal is used to represent solids.

Fuel equivalent factors were multiplied by the tons of waste incinerated to obtain the tons of fuel equivalent. Multiplying the tons of fuel equivalent by the C content factors (discussed in the Estimating the Carbon Content from Fossil Fuel Combustion Annex) yields tons of C emitted. Implied C content is calculated by dividing the tons of C emitted by the associated tons of waste incinerated.

Waste quantity data for hazardous wastes were obtained from EPA's RCRA Information/BRS database for reporting years 1989, 1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007, 2009, and 2011 (EPA 2000a, 2009a, 2013). Combusted waste quantities were obtained from Form GM (Generation and Management) for wastes burned on site and Form WR (Wastes Received) for waste received from off-site for combustion. For each of the waste types, assumptions were developed on average waste composition (see Table A-65). Regulations require incinerators to achieve at least 99.99 percent destruction of organics; this formed the basis for assuming the fraction of C oxidized. Emissions from hazardous waste incineration in 2011 were 0.4 Tg $CO_2$ Eq. Table A-66 lists the $CO_2$ emissions from hazardous waste incineration.

Table A-65: Assumed Composition of Combusted Hazardous Waste by Weight (Percent)

| Waste Type | Water (%) | Noncombustibles (%) | Fuel Equivalent (%) |
|---|---|---|---|
| Aqueous Waste | 90 | 5 | 5 |
| Organic Liquids and Sludges | 40 | 20 | 40 |
| Organic Solids | 20 | 40 | 40 |
| Inorganic Solids | 20 | 70 | 10 |

Table A-66: $CO_2$ Emitted from Hazardous Waste Incineration (Tg $CO_2$ Eq.)

| | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C Emissions | 1.1 | 1.7 | 1.0 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.5 | 0.4 | 0.4 | 0.3 | 0.3 | 0.4 |

***Energy Recovery***

The amount of feedstocks combusted for energy recovery was estimated from data included in EIA's Manufacturers Energy Consumption Survey (MECS) for 1991, 1994, 1998, 2002, and 2006 (EIA 1994, 1997, 2001, 2005,

[27] [42 U.S.C. §6924, SDWA §3004]

2010). Some fraction of the fossil C exiting refineries and designated for use for feedstock purposes actually ends up being combusted for energy recovery (despite the designation of feedstocks as a "non-energy" use) because the chemical reactions in which fuel feedstocks are used are not 100 percent efficient. These chemical reactions may generate unreacted raw material feedstocks or generate byproducts that have a high energy content. The chemical industry and many downstream industries are energy-intensive and often have boilers or other energy recovery units on-site, and thus these unreacted feedstocks or byproducts are often combusted for energy recovery. Also, as noted above in the section on hazardous waste incineration, regulations provide a strong incentive—and in some cases require—burning of organic wastes generated from chemical production processes.

Information available from the MECS include data on the consumption for energy recovery of "other" fuels in the petroleum and coal products, chemicals, primary metals, nonmetallic minerals, and other manufacturing sectors. These "other" fuels include refinery still gas; waste gas; waste oils, tars, and related materials; petroleum coke, coke oven and blast furnace gases; scrap tires; and other uncharacterized fuels. Fuel use of petroleum coke is included separately in the fuel use data provided annually by EIA, and energy recovery of coke oven gas and blast furnace gas (i.e., byproducts of the iron and steel production process) is addressed in the Iron and Steel production section in the Industrial Processes chapter. Consumption of refinery still gas in the refinery sector is also included separately in the fuel use data from EIA. The combustion of scrap tires in cement kilns, lime kilns, and electric arc furnaces is accounted for in the Waste Incineration chapter; data from the Rubber Manufacturers Association (RMA 2009a) were used to difference out energy recovery from scrap tires in these industries. Consumption of net steam, assumed to be generated from fossil fuel combustion, is also included separately in the fuel use data from EIA. Therefore, these categories of "other" fuels are addressed elsewhere in the Inventory and not considered as part of the petrochemical feedstocks energy recovery analysis. The remaining categories of fuels, including waste gas; waste oils, tars, and related materials; and other uncharacterized fuels are assumed to be petrochemical feedstocks burned for energy recovery (see Table A-67). The conversion factors listed in the Estimating Emissions from Fossil Fuel Combustion Annex were used to convert the Btu values for each fuel feedstock to Tg $CO_2$. Petrochemical feedstocks combusted for energy recovery corresponded to 42.5 Tg $CO_2$ Eq. in 1991, 35.1 Tg $CO_2$ Eq. in 1994, 58.0 Tg $CO_2$ Eq. in 1998, 70.6 Tg $CO_2$ Eq. in 2002, and 74.8 Tg $CO_2$ Eq. in 2006. Values for petrochemical feedstocks burned for energy recovery for years between 1991 and 1994, between 1994 and 1998, between 1998 and 2002, and between 2002 and 2006 have been estimated by linear interpolation. The value for 1990 is assumed to be the same as the value for 1991, and values for years subsequent to 2006 are assumed to be the same as the value for 2006 (Table A-68).

Table A-67: Summary of 2006 MECS Data for Other Fuels Used in Manufacturing/Energy Recovery (Trillion Btu)

| Subsector and Industry | NAICS CODE | Waste Gas[a] | Waste Oils/Tars[b] | Refinery Still Gas[c] | Net Steam[d] | Other Fuels[e] |
|---|---|---|---|---|---|---|
| Printing and Related Support | 323 | 0 | 0 | 0 | 0 | 0 |
| Petroleum and Coal Products | 324 | 0 | 7 | 1,482 | 110 | 90 |
| Chemicals | 325 | 459 | 15 | 0 | 168 | 435 |
| Plastics and Rubber Products | 326 | 0 | 0 | 0 | 0 | 0 |
| Nonmetallic Mineral Products | 327 | 1 | 20 | 0 | 1 | 14 |
| Primary Metals | 331 | 1 | 0 | 0 | 17 | 20 |
| Fabricated Metal Products | 332 | 0 | 0 | 0 | 0 | 0 |
| Machinery | 333 | 0 | 0 | 0 | 1 | 1 |
| Computer and Electronic Products | 334 | 0 | 0 | 0 | 0 | 1 |
| Electrical Equip., Appliances, Components | 335 | 0 | 0 | 0 | 0 | 0 |
| Transportation Equipment | 336 | 5 | 0 | 0 | 0 | 11 |
| Furniture and Related Products | 337 | 0 | 0 | 0 | 0 | 0 |
| Miscellaneous | 339 | 0 | 0 | 0 | 0 | 0 |
| **Total (Trillion Btu)** | | 466 | 42 | 1,482 | 297 | 572 |
| Average C Content (Tg/QBtu) | | 18.1 | 20.6 | 17.5 | 0 | 19.4 |
| Fraction Oxidized | | 1 | 1 | 1 | 0 | 1 |
| **Total C (Tg)** | | 8.5 | 0.9 | 25.9 | 0.0 | 11.1 |
| **Total C (Tg) (ex. still gas from refining)** | | 8.5 | 0.9 | - | - | 11.1 |

- Not applicable
[a] C content: Waste Gas is assumed to be same as naphtha <401 deg. F
[b] C content: Waste Oils/Tars is assumed to be same as asphalt/road oil
[c] Refinery "still gas" fuel consumption is reported elsewhere in the Inventory and is excluded from the total C content estimate
[d] Net steam fuel consumption is reported elsewhere in the Inventory and is excluded from the total C content estimate
[e] C content: "Other" is assumed to be the same as petrochemical feedstocks

Table A-68: Carbon Emitted from Fuels Burned for Energy Recovery (Tg $CO_2$ Eq.)

| | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C Emissions | 42.5 | 40.8 | 64.3 | 67.4 | 70.6 | 71.6 | 72.7 | 73.7 | 74.8 | 74.8 | 74.8 | 74.8 | 74.8 | 74.8 |

*Products*

More C is found in products than in industrial releases or energy recovery. The principal types of products are plastics; synthetic rubber; synthetic fiber; C black; pesticides; soaps, detergents, and cleansers; food additives; antifreeze and deicers (glycols); silicones; and solvents. Solvent evaporation was discussed previously along with industrial releases of NMVOCs; the other product types are discussed below.

*Plastics*

Data on annual production of plastics through 2005 were taken from the American Plastics Council (APC), as published in *Chemical & Engineering News* and on the APC and Society of Plastics Industry (SPI) websites, and through direct communication with the APC (APC 2000, 2001, 2003 through 2006; SPI 2000; Eldredge-Roebuck 2000). Data for 2006 through 2011 were taken directly or derived from the American Chemistry Council (ACC 2007 through 2010 supplemented by Vallianos 2011, 2012). In 2009, the American Chemistry Council consolidated the resin categories for which it reports plastics production. Production numbers in the original categories were provided via personal correspondence for 2009 and 2011 (Vallianos 2011, 2012) but were unavailable for 2010. Instead, production figures for the consolidated resin categories in 2010 were extrapolated based on the relative contribution of each category in 2008, the last year in which the full set of categories was reported. Production was organized by resin type (see Table A-69) and by year.

Several of the resin categories included production from Canada and/or Mexico, in addition to the U.S. values for part of the time series. The production data for the affected resins and years were corrected using an economic adjustment factor, based on the percent of North American production value in this industry sector accounted for by the United States. A C content was then assigned for each resin. These C contents were based on molecular formulae and are listed in Table A-70 and Table A-71. In cases where the resin type is generic, referring to a group of chemicals and not a single polymer (e.g., phenolic resins, other styrenic resins), a representative compound was chosen. For other resins, a weighted C content of 68 percent was assumed (i.e., it was assumed that these resins had the same content as those for which a representative compound could be assigned).

There were no emissive uses of plastics identified, so 100 percent of the C was considered stored in products. As noted in the chapter, an estimate of emissions related to the combustion of these plastics in the municipal solid waste stream can be found in the Incineration of Waste section of the Energy chapter; those emissions are not incorporated in the mass balance for feedstocks (described in this annex) to avoid double-counting.

Table A-69: 2011 Plastic Resin Production (Tg dry weight) and C Stored (Tg $CO_2$ Eq.)

| Resin Type | 2011 Production[a] (Tg dry weight) | Carbon Stored (Tg $CO_2$ Eq.) |
|---|---|---|
| Epoxy | 0.3 | 0.8 |
| Urea | 0.5 | 0.6 |
| Melamine | 0.5 | 0.5 |
| Phenolic | 1.4 | 3.9 |
| Low-Density Polyethylene (LDPE) | 2.8 | 8.9 |
| Linear Low-Density Polyethylene (LLDPE) | 5.7 | 17.8 |
| High Density Polyethylene (HDPE) | 7.2 | 22.7 |
| Polypropylene (PP) | 6.7 | 21.2 |
| Acrylonitrile-butadiene-styrene (ABS) | 0.4 | 1.3 |
| Other Styrenics[c] | 0.5 | 1.7 |
| Polystyrene (PS) | 2.3 | 7.8 |
| Nylon | 0.5 | 1.1 |
| Polyvinyl chloride (PVC)[b] | 6.1 | 8.6 |
| Thermoplastic Polyester | 3.2 | 7.4 |
| All Other (including Polyester (unsaturated)) | 5.6 | 14.1 |
| **Total** | **43.7** | **118.4** |

[a] Production estimates provided by the American Chemistry Council include Canadian production for Urea, Melamine, Phenolic, LDPE, LLDPE, HDPE, PP, ABS, SAN, Other Styrenics, PS, Nylon, PVC, and Thermoplastic Polyester, and Mexican production for PP, ABS, SAN, Other Styrenics, Nylon, and Thermoplastic Polyester. Values have been adjusted to account just for U.S. production.
[b] Includes copolymers
[c] Includes Styrene-acrylonitrile (SAN)
Note: Totals may not sum due to independent rounding.

Table A-70: Assigned C Contents of Plastic Resins (% by weight)

| Resin Type | C Content | Source of C Content Assumption |
|---|---|---|
| Epoxy | 76% | Typical epoxy resin made from epichlorhydrin and bisphenol A |
| Polyester (Unsaturated) | 63% | Poly (ethylene terephthalate) (PET) |
| Urea | 34% | 50% carbamal, 50% N-(hydroxymethyl) urea * |
| Melamine | 29% | Trimethylol melamine * |
| Phenolic | 77% | Phenol |
| Low-Density Polyethylene (LDPE) | 86% | Polyethylene |
| Linear Low-Density Polyethylene (LLDPE) | 86% | Polyethylene |
| High Density Polyethylene (HDPE) | 86% | Polyethylene |
| Polypropylene (PP) | 86% | Polypropylene |
| Acrylonitrile-Butadiene-Styrene (ABS) | 85% | 50% styrene, 25% acrylonitrile, 25% butadiene |
| Styrene-Acrylonitrile (SAN) | 80% | 50% styrene, 50% acrylonitrile |
| Other Styrenics | 92% | Polystyrene |
| Polystyrene (PS) | 92% | Polystyrene |
| Nylon | 65% | Average of nylon resins (see Table A-71) |
| Polyvinyl Chloride (PVC) | 38% | Polyvinyl chloride |
| Thermoplastic Polyester | 63% | Polyethylene terephthalate |
| All Other | 69% | Weighted average of other resin production |

*Does not include alcoholic hydrogens.

Table A-71: Major Nylon Resins and their C Contents (% by weight)

| Resin | C Content |
|---|---|
| Nylon 6 | 64% |
| Nylon 6,6 | 64% |
| Nylon 4 | 52% |
| Nylon 6,10 | 68% |
| Nylon 6,11 | 69% |
| Nylon 6,12 | 70% |
| Nylon 11 | 72% |

*Synthetic Rubber*

Data on synthetic rubber in tires were derived from data on the scrap tire market and the composition of scrap tires from the Rubber Manufacturers' Association (RMA). The market information is presented in the report *Scrap Tire Markets in the United States 2007 Edition* (RMA 2009a), while the tire composition information is from the "Scrap Tires, Facts and Figures" section of the organization's website (RMA 2009b). Data on synthetic rubber in other products (durable goods, nondurable goods, and containers and packaging) were obtained from EPA's *Municipal Solid Waste in the United States* reports (1996 through 2003a, 2005, 2007b, 2008, 2009a, 2011a) and detailed unpublished backup data for some years not shown in the *Characterization of Municipal Solid Waste in the United States* reports (Schneider 2007). The abraded rubber from scrap passenger tires was assumed to be 2.5 lbs per scrap tire, while the abraded rubber from scrap commercial tires was assumed to be 10 lbs per scrap tire. Data on abraded rubber weight were obtained by calculating the average weight difference between new and scrap tires (RMA 2009b). RMA data were not yet available for 2010 and 2011, so they were set equal to 2009 values.

A C content for synthetic rubber (90 percent for tire synthetic rubber and 85 percent for non-tire synthetic rubber) was assigned based on the weighted average of C contents (based on molecular formula) by elastomer type consumed in 1998, 2001, and 2002 (see Table A-72). The 1998 consumption data were obtained from the International Institute of Synthetic Rubber Producers (IISRP) press release "Synthetic Rubber Use Growth to Continue Through 2004, Says IISRP and RMA" (IISRP 2000). The 2001 and 2002 consumption data were obtained from the IISRP press release, "IISRP Forecasts Moderate Growth in North America to 2007" (IISRP 2003).

The rubber in tires that is abraded during use (the difference between new tire and scrap tire rubber weight) was considered to be 100 percent emitted. Other than abraded rubber, there were no emissive uses of scrap tire and non-tire rubber identified, so 100 percent of the non-abraded amount was assumed stored. Emissions related to the combustion of rubber in scrap tires and consumer goods can be found in the Incineration of Waste section of the Energy chapter.

Table A-72: 2002 Rubber Consumption (Gg) and C Content (%)

| Elastomer Type | 2002 Consumption (Gg)* | C Content |
|---|---|---|
| SBR Solid | 768 | 91% |
| Polybutadiene | 583 | 89% |
| Ethylene Propylene | 301 | 86% |
| Polychloroprene | 54 | 59% |
| NBR Solid | 84 | 77% |
| Polyisoprene | 58 | 88% |
| Others | 367 | 88% |
| **Weighted Average** | **-** | **90%** |
| **Total** | **2,215** | **-** |

* Includes consumption in Canada.
- Not applicable
Note: Totals may not sum due to independent rounding.

*Synthetic Fibers*

Annual synthetic fiber production data were obtained from the Fiber Economics Bureau, as published in *Chemical & Engineering News* (FEB 2001, 2003, 2005, 2007, 2009, 2010, 2011, 2012). These data are organized by year and fiber type. For each fiber, a C content was assigned based on molecular formula (see Table A-73). For polyester, the C content for poly (ethylene terephthalate) (PET) was used as a representative compound. For nylon, the average C

content of nylon 6 and nylon 6.6 was used, since these are the most widely produced nylon fibers. Cellulosic fibers, such as acetate and rayon, have been omitted from the synthetic fibers' C accounting displayed here because much of their C is of biogenic origin and carbon fluxes from biogenic compounds are accounted for in the Land Use, Land-Use Change and Forestry chapter. These fibers account for only 4 percent of overall fiber production by weight.

There were no emissive uses of fibers identified, so 100 percent of the C was considered stored. Note that emissions related to the combustion of textiles in municipal solid waste are accounted for under the Incineration of Waste section of the Energy chapter.

Table A-73: 2011 Fiber Production (Tg), C Content (%), and C Stored (Tg $CO_2$ Eq.)

| Fiber Type | Production (Tg) | C Content | C Stored (Tg $CO_2$ Eq.) |
|---|---|---|---|
| Polyester | 1.1 | 63% | 2.5 |
| Nylon | 0.6 | 64% | 1.4 |
| Olefin | 1.0 | 86% | 3.0 |
| Acrylic | + | 68% | 0.1 |
| **Total** | **2.7** | **-** | **7.0** |

+ Less than 0.05 Tg
- Not applicable
Note: Totals may not sum due to independent rounding

*Pesticides*

Pesticide consumption data were obtained from the *1994/1995, 1996/1997, 1998/1999, 2000/2001, 2006/2007 Pesticides Industry Sales and Usage Market Estimates* (EPA 1998, 1999, 2002, 2004, 2011b) reports. The most recent data available were for 2007, so it was assumed that the 2008 through 2010 consumption was equal to that of 2007. Active ingredient compound names and consumption weights were available for the top 25 agriculturally-used pesticides and top 10 pesticides used in the home and garden and the industry/commercial/government categories. The report provides a range of consumption for each active ingredient; the midpoint was used to represent actual consumption. Each of these compounds was assigned a C content value based on molecular formula. If the compound contained aromatic rings substituted with chlorine or other halogens, then the compound was considered persistent and the C in the compound was assumed to be stored. All other pesticides were assumed to release their C to the atmosphere. Over one-third of 2007 total pesticide active ingredient consumption was not specified by chemical type in the *Sales and Usage* report (EPA 2011b). This unspecified portion of the active ingredient consumption was treated as a single chemical and assigned a C content and a storage factor based on the weighted average of the known chemicals' values.

Table A-74: Active Ingredient Consumption in Pesticides (Million lbs.) and C Emitted and Stored (Tg $CO_2$ Eq.) in 2001

| Pesticide Use* | Active Ingredient (Million lbs.) | C Emitted (Tg $CO_2$ Eq.) | C Stored (Tg $CO_2$ Eq.) |
|---|---|---|---|
| Agricultural Uses | 458.5 | 0.1 | 0.2 |
| Non-Agricultural Uses | 84.5 | + | + |
| Home & Garden | 38.5 | + | + |
| Industry/Gov't/Commercial | 46.0 | + | + |
| Other | 345.0 | 0.1 | 0.1 |
| **Total** | **888.0** | **0.2** | **0.3** |

+ Less than 0.05 Tg $CO_2$ Eq.
*2001 estimates (EPA 2004b).
Note: Totals may not sum due to independent rounding.

*Soaps, Shampoos, and Detergents*

Cleansers—soaps, shampoos, and detergents—are among the major consumer products that may contain fossil C. All of the C in cleansers was assumed to be fossil-derived, and, as cleansers eventually biodegrade, all of the C was assumed to be emitted. The first step in estimating C flows was to characterize the "ingredients" in a sample of cleansers. For this analysis, cleansers were limited to the following personal household cleaning products: bar soap, shampoo, laundry detergent (liquid and granular), dishwasher detergent, and dishwashing liquid. Data on the annual consumption of household personal cleansers were obtained from the U.S. Census Bureau 1992, 1997, 2002, and 2007 Economic Census (U.S. Bureau of the Census 1994, 1999, 2004, 2009). Consumption values for 1990 and 1991 were assumed to be the same as the 1992 value; consumption was interpolated between 1992 and 1997, 1997 and 2002, and 2002 and 2007; consumption for 2008, 2009, and 2010 was assumed to equal the 2007 value. Cleanser consumption values were adjusted by import and export data to develop US consumption estimates.

Chemical formulae were used to determine C contents (as percentages) of the ingredients in the cleansers. Each product's overall C content was then derived from the composition and contents of its ingredients. From these values the mean C content for cleansers was calculated to be 21.9 percent.

The Census Bureau presents consumption data in terms of quantity (in units of million gallons or million pounds) and/or terms of value (thousands of dollars) for eight specific categories, such as "household liquid laundry detergents, heavy duty" and "household dry alkaline automatic dishwashing detergents." Additionally, the report provides dollar values for the total consumption of "soaps, detergents, etc.—dry" and "soaps, detergents, etc.—liquid." The categories for which both quantity and value data are available is a subset of total production. Those categories that presented both quantity and value data were used to derive pounds per dollar and gallons per dollar conversion rates, and they were extrapolated (based on the Census Bureau estimate of total value) to estimate the total quantity of dry and liquid[28] cleanser categories, respectively.

Next, the total tonnage of cleansers was calculated (wet and dry combined) for 1997. Multiplying the mean C content (21.9 percent) by this value yielded an estimate of 4.6 Tg $CO_2$ Eq. in cleansers for 1997. For all subsequent years, it was assumed that the ratio of value of shipments to total carbon content remained constant. For 1998 through 2009, value of shipments was adjusted to 1997 dollars using the producer price index for soap and other detergent manufacturing (Bureau of Labor Statistics 2009). The ratio of value of shipments to carbon content was then applied to arrive at total carbon content of cleansers. For 1992, 2002, and 2007 the estimates are 3.6 Tg $CO_2$ Eq., 5.1 Tg $CO_2$ Eq., 7.6 Tg $CO_2$ Eq., respectively. Estimates for other years are based on these values as described above, and are shown in Table A-75.

Table A-75: C Emitted from Utilization of Soaps, Shampoos, and Detergents (Tg $CO_2$ Eq.)

| | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C Emissions | 3.6 | 4.2 | 4.5 | 4.8 | 5.1 | 5.7 | 6.2 | 6.7 | 7.0 | 7.6 | 7.1 | 6.7 | 6.7 | 6.5 |

*Antifreeze and Deicers*

Glycol compounds, including ethylene glycol, propylene glycol, diethylene glycol, and triethylene glycol, are used as antifreeze in motor vehicles, deicing fluids for commercial aircraft, and other similar uses. These glycol compounds are assumed to ultimately enter wastewater treatment plants where they are degraded by the wastewater treatment process to $CO_2$ or to otherwise biodegrade to $CO_2$. Glycols are water soluble and degrade rapidly in the environment (Howard 1993).

Annual production data for each glycol compound used as antifreeze and deicers were obtained from the Guide to the Business of Chemistry (ACC 2012). Import and export data were used to adjust annual production data to annual consumption data. The percentage of the annual consumption of each glycol compound used for antifreeze and deicing applications was estimated from Chemical Profiles data published on The Innovation Group website[29] and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005[30]. Production data for propylene glycol, diethylene glycol, and triethylene glycol are no longer reported in the Guide to the Business of Chemistry, so data from ICIS Chemical Business on total demand was used with import and export data to estimate production of these chemicals.

The glycol compounds consumed in antifreeze and deicing applications is assumed to be 100 percent emitted as $CO_2$. Emissions of $CO_2$ from utilization of antifreeze and deicers are summarized in Table A-76.

[28] A density of 1.05 g/mL—slightly denser than water—was assumed for liquid cleansers.

[29] See <http://www.the-innovation-group.com/ChemProfiles>

[30] See < http://www.icis.com/home/default.aspx>

Table A-76: C Emitted from Utilization of Antifreeze and Deicers (Tg $CO_2$ Eq.)

| | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C Emissions | 1.2 | 1.4 | 1.5 | 1.3 | 1.3 | 1.3 | 1.4 | 1.2 | 1.3 | 1.2 | 1.0 | 0.9 | 0.8 | 0.7 |

*Food Additives*

Petrochemical feedstocks are used to manufacture synthetic food additives, including preservatives, flavoring agents, and processing agents. These compounds include glycerin, propylene glycol, benzoic acid, and other compounds. These compounds are incorporated into food products, and are assumed to ultimately enter wastewater treatment plants where they are degraded by the wastewater treatment processes to $CO_2$ or to otherwise biodegrade to $CO_2$. Certain food additives, e.g., glycerin, are manufactured both from petrochemical feedstocks and from biogenic feedstocks. Food additives that are derived from biogenic feedstocks are accounted for in the Land Use, Land-Use Change and Forestry chapter.

Annual production data for food additive compounds were obtained from the Guide to the Business of Chemistry (ACC 2012). Import and export data were used to adjust annual production data to annual consumption data. The percentage of the annual consumption of food additive compounds was estimated from Chemical Profiles data published on The Innovation Group website[31] and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005.[32] Production data for several food additive compounds are no longer reported in the Guide to the Business of Chemistry, so data from ICIS Chemical Business on total demand was used with import and export data to estimate production of these chemicals. The consumption of synthetic food additives is assumed to be 100 percent emitted as $CO_2$. Emissions of $CO_2$ from utilization of synthetic food additives are summarized in Table A-77.

Table A-77: C Emitted from Utilization of Food Additives (Tg $CO_2$ Eq.)

| | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C Emissions | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |

*Silicones*

Silicone compounds (e.g., polymethyl siloxane) are used as sealants and in manufactured products. Silicone compounds are manufactured from petrochemical feedstocks including methyl chloride. It is assumed that petrochemical feedstocks used to manufacture silicones are incorporated into the silicone products and not emitted as $CO_2$ in the manufacturing process. It is also assumed that the C contained in the silicone products is stored, and not emitted as $CO_2$.

Annual production data for each silicone manufacturing compound were obtained from the Guide to the Business of Chemistry (ACC 2012). Import and export data were used to adjust annual production data to annual consumption data. The percentage of the annual consumption of each silicone manufacturing compound was estimated from Chemical Profiles data published on The Innovation Group website and from similar data published in the Chemical Market Reporter, which became ICIS Chemical Business in 2005[33]. The consumption of silicone manufacturing compounds is assumed to be 100 percent stored, and not emitted as $CO_2$. Storage of silicone manufacturing compounds is summarized in Table A-78.

Table A-78: C Stored in Silicone Products (Tg $CO_2$ Eq.)

| | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C Storage | 0.3 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

**Uncertainty – TO BE UPDATED**

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the feedstocks C storage factor and the quantity of C emitted from feedstocks in 2010. The Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the Inventory estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for production data (the majority of the variables) were assumed to exhibit a normal distribution with a relative error of ±20 percent in the

[31] See <http://www.the-innovation-group.com/ChemProfiles>

[32] See <http://www.icis.com/home/default.aspx>

[33] Ibid.

underlying EIA estimates, plus an additional ±15 percent to account for uncertainty in the assignment of imports and exports. An additional 10 percent (for a total of ±45 percent) was applied to the production of other oils (>401 deg. F) to reflect the additional uncertainty in the assignment of part of the production quantity to industrial processes. A relatively narrow uniform distribution ±1 percent to ±15 percent, depending on the fuel type) was applied to each C coefficient.

The Monte Carlo analysis produced a storage factor distribution that approximates a normal curve, with a mean of 59 percent, a standard deviation of 1.8 percent, and the 95 percent confidence interval of 54 percent and 61 percent. This compares to the calculated Inventory estimate of 59 percent. The analysis produced a C emission distribution approximating a normal curve with a mean of 84.2 Tg $CO_2$ Eq., standard deviation of 11.5 Tg $CO_2$ Eq., and 95 percent confidence limits of 65.2 and 114.0 Tg $CO_2$ Eq. This compares with a calculated Inventory estimate of 83.7 Tg $CO_2$ Eq.

The apparently tight confidence limits for the storage factor and C storage probably understate uncertainty, as a result of the way this initial analysis was structured. As discussed above, the storage factor for feedstocks is based on an analysis of six fates that result in long-term storage (e.g., plastics production), and eleven that result in emissions (e.g., volatile organic compound emissions). Rather than modeling the total uncertainty around all 17 of these fate processes, the current analysis addresses only the storage fates, and assumes that all C that is not stored is emitted. As the production statistics that drive the storage factors are relatively well-characterized, this approach yields a result that is probably biased toward understating uncertainty.

As far as specific sources of uncertainty, there are several cross-cutting factors that pervade the characterization of C flows for feedstocks. The aggregate storage factor for petrochemical feedstocks (industrial other coal, natural gas for non-fertilizer uses, LPG, pentanes plus, naphthas, other oils, still gas, special naphtha) is based on assuming that the ultimate fates of all of these fuel types—in terms of storage and emissions—are similar. In addition, there are uncertainties associated with the simplifying assumptions made for each end use category C estimate. Generally, the estimate for a product is subject to one or more of the following uncertainties:

- The value used for estimating the C content has been assumed or assigned based upon a representative compound.
- The split between C storage and emission has been assumed based on an examination of the environmental fate of the products in each end use category.
- Environmental fates leading to emissions are assumed to operate rapidly, i.e., emissions are assumed to occur within one year of when the fossil C enters the non-energy mass balance. Some of the pathways that lead to emissions as $CO_2$ may actually take place on a time-scale of several years or decades. By attributing the emissions to the year in which the C enters the mass balance (i.e., the year in which it leaves refineries as a non-energy fuel use and thus starts being tracked by EIA), this approach has the effect of "front-end loading" the emission profile.

Another cross-cutting source of uncertainty is that for several sources the amount of C stored or emitted was calculated based on data for only a single year. This specific year may not be representative of storage for the entire Inventory period. Sources of uncertainty associated with specific elements of the analysis are discussed below.

Import and export data for petrochemical feedstocks were obtained from EIA, the National Petroleum Refiners Association, and the U.S. BoC for the major categories of petrochemical feedstocks (EIA 2001, NPRA 2001, and U.S. BoC 2006). The complexity of the organic chemical industry, with multiple feedstocks, intermediates, and subtle differences in nomenclature, makes it difficult to ensure that the adjustments to the EIA data for imports and exports is accurate and the approach used here may underestimate or overestimate net exports of C.

Oxidation factors have been applied to non-energy uses of petrochemical feedstocks in the same manner as for energy uses. However, for those fuels where IPCC storage factors are used, this "oxidation factor" may be inherent in the storage factor applied when calculating emissions from non-energy consumption, which would result in a double-counting of the unoxidized C. Oxidation factors are small corrections, on the order of 1 percent, and therefore application of oxidation factors to non-energy uses may result in a slight underestimation of C emissions from non-energy uses.

The major uncertainty in using the TRI data is the possibility of double counting emissions that are already accounted for in the NMVOC data (see above) and in the storage and emission assumptions used. The approach for predicting environmental fate simplifies some complex processes, and the balance between storage and emissions is very sensitive to the assumptions on fate. Extrapolating from known to unknown characteristics also introduces uncertainty. The two extrapolations with the greatest uncertainty are: 1) that the release media and fate of the off-site releases were

assumed to be the same as for on-site releases, and 2) that the C content of the least frequent 10 percent of TRI releases was assumed to be the same as for the chemicals comprising 90 percent of the releases. However, the contribution of these chemicals to the overall estimate is small. The off-site releases only account for 3 percent of the total releases, by weight, and, by definition, the less frequent compounds only account for 10 percent of the total releases.

The principal sources of uncertainty in estimating $CO_2$ emissions from solvent evaporation and industrial NMVOC emissions are in the estimates of (a) total emissions and (b) their C content. Solvent evaporation and industrial NMVOC emissions reported by EPA are based on a number of data sources and emission factors, and may underestimate or overestimate emissions. The C content for solvent evaporation emissions is calculated directly from the specific solvent compounds identified by EPA as being emitted, and is thought to have relatively low uncertainty. The C content for industrial emissions has more uncertainty, however, as it is calculated from the average C content of an average volatile organic compound based on the list of the most abundant measured NMVOCs provided in EPA (2002a).

Uncertainty in the hazardous waste combustion analysis is introduced by the assumptions about the composition of combusted hazardous wastes, including the characterization that hazardous wastes are similar to mixtures of water, noncombustibles, and fuel equivalent materials. Another limitation is the assumption that all of the C that enters hazardous waste combustion is emitted—some small fraction is likely to be sequestered in combustion ash—but given that the destruction and removal efficiency for hazardous organics is required to meet or exceed 99.99 percent, this is a very minor source of uncertainty. C emission estimates from hazardous waste should be considered central value estimates that are likely to be accurate to within ±50 percent.

The amount of feedstocks combusted for energy recovery was estimated from data included in the Manufacturers Energy Consumption Surveys (MECS) for 1991, 1994, 1998, 2002, and 2006 (EIA 1994, 1997, 2001, 2005, 2010). MECS is a comprehensive survey that is conducted every four years and intended to represent U.S. industry as a whole, but because EIA does not receive data from all manufacturers (i.e., it is a sample rather than a census), EIA must extrapolate from the sample. Also, the "other" fuels are identified in the MECS data in broad categories, including refinery still gas; waste gas; waste oils, tars, and related materials; petroleum coke, coke oven and blast furnace gases; and other uncharacterized fuels. Moreover, the industries using these "other" fuels are also identified only in broad categories, including the petroleum and coal products, chemicals, primary metals, nonmetallic minerals, and other manufacturing sectors. The "other" fuel consumption data are reported in BTUs (energy units) and there is uncertainty concerning the selection of a specific conversion factor for each broad "other" fuel category to convert energy units to mass units. Taken as a whole, the estimate of energy recovery emissions probably introduces more uncertainty than any other element of the non-energy analysis.

Uncertainty in the C storage estimate for plastics arises primarily from four factors. First, production of some plastic resins is not tracked directly and must be estimated based on other market data. Second, the raw data on production for several resins include Canadian and/or Mexican production and may overestimate the amount of plastic produced from U.S. fuel feedstocks; this analysis includes adjustments to "back out" the Canadian and Mexican values, but these adjustments are approximate. Third, the assumed C content values are estimates for representative compounds, and thus do not account for the many formulations of resins available. This uncertainty is greater for resin categories that are generic (e.g., phenolics, other styrenics, nylon) than for resins with more specific formulations (e.g., polypropylene, polyethylene). Fourth, the assumption that all of the C contained in plastics is stored ignores certain end uses (e.g., adhesives and coatings) where the resin may be released to the atmosphere; however, these end-uses are likely to be small relative to use in plastics.

The quantity of C stored in synthetic rubber only accounts for the C stored in scrap tire synthetic rubber. The value does not take into account the rubber stored in other durable goods, clothing, footwear, and other non-durable goods, or containers and packaging. This adds uncertainty to the total mass balance of C stored. There are also uncertainties as to the assignment of C content values; however, they are much smaller than in the case of plastics. There are probably fewer variations in rubber formulations than in plastics, and the range of potential C content values is much narrower. Lastly, assuming that all of the C contained in rubber is stored ignores the possibility of volatilization or degradation during product lifetimes. However, the proportion of the total C that is released to the atmosphere during use is probably negligible.

A small degree of uncertainty arises from the assignment of C content values in textiles; however, the magnitude of this uncertainty is less than that for plastics or rubber. Although there is considerable variation in final textile products, the stock fiber formulations are standardized and proscribed explicitly by the Federal Trade Commission.

For pesticides, the largest source of uncertainty involves the assumption that an active ingredient's C is either 0 percent stored or 100 percent stored. This split is a generalization of chemical behavior, based upon active-ingredient molecular structure, and not on compound-specific environmental data. The mechanism by which a compound is bound or released from soils is very complicated and can be affected by many variables, including the type of crop, temperature,

application method, and harvesting practice. Another smaller source of uncertainty arises from the C content values applied to the unaccounted for portion of active ingredient. C contents vary widely among pesticides, from 7 to 72 percent, and the remaining pesticides may have a chemical make-up that is very different from the 32 pesticides that have been examined. Additionally, pesticide consumption data were only available for 1987, 1993, 1995, 1997, 1999, and 2001; the majority of the time series data were interpolated or held constant at the latest (2001) value. Another source of uncertainty is that only the "active" ingredients of pesticides are considered in the calculations; the "inactive" ingredients may also be derived from petrochemical feedstocks.

It is important to note that development of this uncertainty analysis is a multi-year process. The current feedstocks analysis examines NEU fuels that end in storage fates Thus only C stored in pesticides, plastics, synthetic fibers, synthetic rubbers, silicones, and TRI releases to underground injection and Subtitle C landfills is accounted for in the uncertainty estimate above. In the future this analysis will be expanded to include the uncertainty surrounding emitted fates in addition to the storage fates. Estimates of variable uncertainty will also be refined where possible to include fewer assumptions. With these major changes in future Inventories, the uncertainty estimate is expected to change, and likely increase. An increase in the uncertainty estimate in the coming years will not indicate that the Inventory calculations have become less certain, but rather that the methods for estimating uncertainty have become more comprehensive; thus, potential future changes in the results of this analysis will reflect a change in the uncertainty analysis, not a change in the Inventory quality.

## Asphalt and Road Oil

Asphalt is one of the principal non-energy uses of fossil fuels. The term "asphalt" generally refers to a mixture of asphalt cement and a rock material aggregate, a volatile petroleum distillate, or water. For the purposes of this analysis, "asphalt" is used interchangeably with asphalt cement, a residue of crude oil. Though minor amounts of C are emitted during production, asphalt has an overall C storage factor of almost 100 percent, as discussed below.

Paving is the primary application of asphalt cement, comprising 86 percent of production. The three types of asphalt paving produced in the United States are hot mix asphalt (HMA), cut-backs, and emulsified asphalt. HMA, which makes up 90 percent of total asphalt paving (EPA 2001), contains asphalt cement mixed with an aggregate of rock materials. Cut-back asphalt is composed of asphalt cement thinned with a volatile petroleum distillate (e.g., naphtha). Emulsified asphalt contains only asphalt cement and water. Roofing products are the other significant end use of asphalt cement, accounting for approximately 14 percent of U.S. production (Kelly 2000). No data were available on the fate of C in asphalt roofing; it was assumed that it has the same fate as C in asphalt paving applications.

### Methodology and Data Sources

A C storage factor was calculated for each type of asphalt paving. The fraction of C emitted by each asphalt type was multiplied by consumption data for asphalt paving (EPA 2001) to estimate a weighted average C storage factor for asphalt as a whole.

The fraction of C emitted by HMA was determined by first calculating the organic emissions (volatile organic compounds [VOCs], carbon monoxide [CO], polycyclic aromatic hydrocarbons [PAHs], hazardous air pollutants [HAPs], and phenol) from HMA paving, using emission factors reported in EPA (2001) and total HMA production.[34] The next step was to estimate the C content of the organic emissions. This calculation was based on the C content of CO and phenol, and an assumption of 85 percent C content for PAHs and HAPs. The C content of asphalt paving is a function of (1) the proportion of asphalt cement in asphalt paving, assumed to be 8 percent asphalt cement content based on EPA (2001), and (2) the proportion of C in asphalt cement. For the latter factor, all paving types were characterized as having a mass fraction of 85 percent C in asphalt cement, based on the assumption that asphalt is primarily composed of saturated paraffinic hydrocarbons. By combining these estimates, the result is that over 99.99 percent of the C in asphalt cement was retained (i.e., stored), and less than 0.01 percent was emitted.

Cut-back asphalt is produced in three forms: rapid, medium, and slow cure. The production processes for all three forms emit C primarily from the volatile petroleum distillate used in the process as a diluent to thin the asphalt cement so that it can be applied more readily (EPA 2001).

[34] The emission factors are expressed as a function of asphalt paving tonnage (i.e., including the rock aggregate as well as the asphalt cement).

A mass balance on C losses from asphalt was constructed by first estimating the amount of carbon emitted as VOCs. Values for medium cure asphalt are used to represent all cut-back asphalt. The average weight of distillates used in medium cure cut-back asphalt (35 percent) is multiplied by the loss rate (as emissions of VOCs) of 70 percent from the *Emissions Inventory Guidebook* to arrive at an estimate that 25 percent of the diluent is emitted (Environment Canada 2006). Next, the fraction of C in the asphalt/ diluent mix that is emitted was estimated, assuming 85 percent C content; this yields an overall storage factor of 93.5 percent for cut-back asphalt.

One caveat associated with this calculation is that it is possible that the carbon flows for asphalt and diluent (volatile petroleum distillate) are accounted for separately in the EIA statistics on fossil fuel flows, and thus the mass balance calculation may need to re-map the system boundaries to correctly account for carbon flows. EPA plans to re-evaluate this calculation in the future.

It was assumed that there was no loss of C from emulsified asphalt (i.e., the storage factor is 100 percent) based on personal communication with an expert from Akzo Nobel Coatings, Inc. (James 2000).

Data on asphalt and road oil consumption and C content factors were supplied by EIA. Hot mix asphalt production and emissions factors, and the asphalt cement content of HMA were obtained from "Hot Mix Asphalt Plants Emissions Assessment Report" from EPA's *AP-42* (EPA 2001) publication. The consumption data for cut-back and emulsified asphalts were taken from a Moulthrop, et al. study used as guidance for estimating air pollutant emissions from paving processes (EIIP 2001). "Asphalt Paving Operation" *AP-42* (EPA 2001) provided the emissions source information used in the calculation of the C storage factor for cut-back asphalt. The storage factor for emulsified asphalt was provided by Alan James of Akzo Nobel Coatings, Inc. (James 2000).

**Uncertainty – TO BE UPDATED**

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the asphalt C storage factor and the quantity of C stored in asphalt in 2009. The Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the Inventory estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for asphalt production were assumed to be ±20 percent, while the asphalt property variables were assumed to have narrower distributions. A narrow uniform distribution, with maximum 5 percent uncertainty (± 5 percent) around the mean, was applied to the C content coefficient.

The Monte Carlo analysis produced a tight distribution of storage factor values, with the 95 percent confidence interval of 99.1 percent and 99.8 percent, with the mean value of 99.5 percent. This compares to the storage factor value used in the Inventory of 99.6 percent. The analysis produced a C emission distribution with a mean of 0.31 Tg $CO_2$ Eq., standard deviation of 0.13 and 95 percent confidence limits of 0.12 Tg $CO_2$ Eq. and 0.63 Tg $CO_2$ Eq. This compares with an Inventory calculated estimate of 0.29 Tg $CO_2$ Eq.

The principal source of uncertainty is that the available data are from short-term studies of emissions associated with the production and application of asphalt. As a practical matter, the cement in asphalt deteriorates over time, contributing to the need for periodic re-paving. Whether this deterioration is due to physical erosion of the cement and continued storage of C in a refractory form or physicochemical degradation and eventual release of $CO_2$ is uncertain. Long-term studies may reveal higher lifetime emissions rates associated with degradation.

Many of the values used in the analysis are also uncertain and are based on estimates and professional judgment. For example, the asphalt cement input for hot mix asphalt was based on expert advice indicating that the range is variable—from about 3 to 5 percent—with actual content based on climate and geographical factors (Connolly 2000). Over this range, the effect on the calculated C storage factor is minimal (on the order of 0.1 percent). Similarly, changes in the assumed C content of asphalt cement would have only a minor effect.

The consumption figures for cut-back and emulsified asphalts are based on information reported for 1994. More recent trends indicate a decrease in cut-back use due to high VOC emission levels and a related increase in emulsified asphalt use as a substitute. This change in trend would indicate an overestimate of emissions from asphalt.

Future improvements to this uncertainty analysis, and to the overall estimation of a storage factor for asphalt, include characterizing the long-term fate of asphalt.

## Lubricants

Lubricants are used in industrial and transportation applications. They can be subdivided into oils and greases, which differ in terms of physical characteristics (e.g., viscosity), commercial applications, and environmental fate.

According to EIA (2012), the C content from U.S. production of lubricants in 2011 was approximately 5.6 Tg C. Based on apportioning oils and greases to various environmental fates, and characterizing those fates as resulting in either long-term storage or emissions, the overall C storage factor was estimated to be 9.2 percent; thus, emissions in 2011 were about 5.1 Tg C, or 18.6 Tg $CO_2$ Eq.

### Methodology and Data Sources

For each lubricant category, a storage factor was derived by identifying disposal fates and applying assumptions as to the disposition of the C for each practice. An overall lubricant C storage factor was calculated by taking a production-weighted average of the oil and grease storage factors.

#### *Oils*

Regulation of used oil in the United States has changed dramatically over the past 20 years.[35] The effect of these regulations and policies has been to restrict landfilling and dumping, and to encourage collection of used oil. The economics of the petroleum industry have generally not favored re-refining—instead, most of the used oil that has been collected has been combusted.

Table A-79 provides an estimated allocation of the fates of lubricant oils (Rinehart 2000), along with an estimate of the proportion of C stored in each fate. The ultimate fate of the majority of oils (about 84 percent) is combustion, either during initial use or after collection as used oil. Combustion results in 99 percent oxidation to $CO_2$ (EIIP 1999), with correspondingly little long-term storage of C in the form of ash. Dumping onto the ground or into storm sewers, primarily by "do-it-yourselfers" who change their own oil, is another fate that results in conversion to $CO_2$ given that the releases are generally small and most of the oil is biodegraded (based on the observation that land farming—application to soil—is one of the most frequently used methods for degrading refinery wastes). In the landfill environment, which tends to be anaerobic within municipal landfills, it is assumed that 90 percent of the oil persists in an undegraded form, based on analogy with the persistence of petroleum in native petroleum-bearing strata, which is also anaerobic. Re-refining adds a recycling loop to the fate of oil. Re-refined oil was assumed to have a storage factor equal to the weighted average for the other fates (i.e., after re-refining, the oil would have the same probability of combustion, landfilling, or dumping as virgin oil), that is, it was assumed that about 97 percent of the C in re-refined oil is ultimately oxidized. Because of the dominance of fates that result in eventual release as $CO_2$, only about 3 percent of the C in oil lubricants goes into long-term storage.

Table A-79: Commercial and Environmental Fate of Oil Lubricants (Percent)

| Fate of Oil | Portion of Total Oil | C Stored |
|---|---|---|
| **Combusted During Use** | **20%** | **0.2%** |
| **Not Combusted During Use** | **80%** | **2.7%** |
| Combusted as Used Oil * | 64% | 0.6% |
| Dumped on the ground or in storm sewers | 6% | - |
| Landfilled | 2% | 1.8% |
| Re-refined into lube oil base stock and other products | 8% | 0.2% |
| **Weighted Average** | | **2.9%** |

* (e.g., in boilers or space heaters)
- Not applicable

#### *Greases*

Table A-80 provides analogous estimates for lubricant greases. Unlike oils, grease is generally not combusted during use, and combustion for energy recovery and re-refining is thought to be negligible. Although little is known about the fate of waste grease, it was assumed that 90 percent of the non-combusted portion is landfilled, and the remainder is dumped onto the ground or storm sewers. Because much of the waste grease will be in containers that render it relatively inaccessible to biodegradation, and because greases contain longer chain paraffins, which are more persistent than oils, it

[35] For example, the U.S. EPA "RCRA (Resource Conservation and Recovery Act) On-line" web site (<http://www.epa.gov/rcraonline/>) has over 50 entries on used oil regulation and policy for 1994 through 2000.

was assumed that 90 percent and 50 percent of the C in landfilled and dumped grease, respectively, would be stored. The overall storage factor is 82 percent for grease.

Table A-80: Commercial and Environmental Fate of Grease Lubricants (Percent)

| Fate of Grease | Portion of Total Grease | C Stored |
|---|---|---|
| **Combusted During Use** | **5%** | **0.1%** |
| **Not Combusted During Use** | **95%** | **81.7%** |
| Landfilled | 86% | 77.0% |
| Dumped on the ground or in storm sewers | 10% | 4.8% |
| **Weighted Average** | - | **81.8%** |

- Not applicable

Having derived separate storage factors for oil and grease, the last step was to estimate the weighted average for lubricants as a whole. No data were found apportioning the mass of lubricants into these two categories, but the U.S. Census Bureau does maintain records of the value of production of lubricating oils and lubricating greases. These were retrieved from the relevant industry series summaries from the 1997 Economic Census (Census Bureau 1999). Assuming that the mass of lubricants can be allocated according to the proportion of value of production (92 percent oil, 8 percent grease), applying these weights to the storage factors for oils and greases (3 percent and 82 percent) yields an overall storage factor of 9.2 percent.

#### Uncertainty – TO BE UPDATED

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the lubricants weighted average C storage factor and the quantity of C emitted from lubricants in 2009. The Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the Inventory estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for oil and grease variables were assumed to have a moderate variance, in triangular or uniform distribution. Uncertainty estimates for lubricants production were assumed to be rather high (±20 percent). A narrow uniform distribution, with 6 percent uncertainty (± 6 percent) around the mean, was applied to the lubricant C content coefficient.

The Monte Carlo analysis produced a storage factor distribution with the 95 percent confidence interval of 4 percent and 17 percent around a mean value of 10 percent. This compares to the calculated Inventory estimate of 9 percent. The analysis produced a C emission distribution approximating a normal curve with a mean of 19.4 Tg $CO_2$ Eq., standard deviation of 1.7 and 95 percent confidence limits of 16.2 Tg $CO_2$ Eq. and 22.8 Tg $CO_2$ Eq.. This compares with an Inventory calculated estimate of 19.6 Tg $CO_2$ Eq.

The principal sources of uncertainty for the disposition of lubricants are the estimates of the commercial use, post-use, and environmental fate of lubricants, which, as noted above, are largely based on assumptions and judgment. There is no comprehensive system to track used oil and greases, which makes it difficult to develop a verifiable estimate of the commercial fates of oil and grease. The environmental fate estimates for percent of C stored are less uncertain, but also introduce uncertainty in the estimate.

The assumption that the mass of oil and grease can be divided according to their value also introduces uncertainty. Given the large difference between the storage factors for oil and grease, changes in their share of total lubricant production have a large effect on the weighted storage factor.

Future improvements to the analysis of uncertainty surrounding the lubricants C storage factor and C stored include further refinement of the uncertainty estimates for the individual activity variables.

## Waxes

Waxes are organic substances that are solid at ambient temperature, but whose viscosity decreases as temperature increases. Most commercial waxes are produced from petroleum refining, though "mineral" waxes derived from animals, plants, and lignite [coal] are also used. An analysis of wax end uses in the United States, and the fate of C in these uses, suggests that about 42 percent of C in waxes is emitted, and 58 percent is stored.

#### Methodology and Data Sources

The National Petroleum Refiners Association (NPRA) considers the exact amount of wax consumed each year by end use to be proprietary (Maguire 2004). In general, about thirty percent of the wax consumed each year is used in packaging materials, though this percentage has declined in recent years. The next highest wax end use, and fastest

growing end use, is candles, followed by construction materials and firelogs. Table A-81 categorizes some of the wax end uses, which the NPRA generally classifies into cosmetics, plastics, tires and rubber, hot melt (adhesives), chemically modified wax substances, and other miscellaneous wax uses (NPRA 2002)

Table A-81: Emissive and Non-emissive (Storage) Fates of Waxes: Uses by Fate and Percent of Total Mass

| Use | Emissive | Non-emissive |
|---|---|---|
| **Packaging** | **6%** | **24%** |
| **Non-packaging** | **36%** | **34%** |
| Candles | 18% | 2% |
| Construction Materials | 4% | 14% |
| Firelogs | 7% | + |
| Cosmetics | 1% | 2% |
| Plastics | 1% | 2% |
| Tires/Rubber | 1% | 1% |
| Hot Melts | 1% | 1% |
| Chemically Modified | 0% | 1% |
| Other | 2% | 9% |
| **Total** | **42%** | **58%** |

+ Does not exceed 0.5 percent

A C storage factor for each wax end use was estimated and then summed across all end uses to provide an overall C storage factor for wax. Because no specific data on C contents of wax used in each end use were available, all wax products are assumed to have the same C content. Table A-82 categorizes wax end uses identified by the NPRA, and lists each end use's estimated C storage factor.

Table A-82: Wax End-Uses by Fate, Percent of Total Mass, Percent C Stored, and Percent of Total C Mass Stored

| Use | Percent of Total Wax Mass | Percent of C Stored | Percent of Total C Mass Stored |
|---|---|---|---|
| **Packaging** | **30%** | **79%** | **24%** |
| **Non-Packaging** | | | |
| Candles | 20% | 10% | 2% |
| Construction Materials | 18% | 79% | 14% |
| Firelogs | 7% | 1% | + |
| Cosmetics | 3% | 79% | 2% |
| Plastics | 3% | 79% | 2% |
| Tires/Rubber | 3% | 47% | 1% |
| Hot Melts | 3% | 50% | 1% |
| Chemically Modified | 1% | 79% | 1% |
| Other | 12% | 79% | 9% |
| **Total** | **100%** | **NA** | **58%** |

+ Does not exceed 0.5 percent
Source, mass percentages: NPRA 2002. Estimates of percent stored are based on professional judgment, ICF International.
Note: Totals may not sum due to independent rounding.

Emissive wax end-uses include candles, firelogs (synthetic fireplace logs), hotmelts (adhesives), matches, and explosives. At about 20 percent, candles consume the greatest portion of wax among emissive end uses. As candles combust during use, they release emissions to the atmosphere. For the purposes of the Inventory, it is assumed that 90 percent of C contained in candles is emitted as $CO_2$. In firelogs, petroleum wax is used as a binder and as a fuel, and is combusted during product use, likely resulting in the emission of nearly all C contained in the product. Similarly, C contained in hotmelts is assumed to be emitted as $CO_2$ as heat is applied to these products during use. It is estimated that 50 percent of the C contained in hot melts is stored. Together, candles, firelogs, and hotmelts constitute approximately 30 percent of annual wax production (NPRA 2002).

All of the wax utilized in the production of packaging, cosmetics, plastics, tires and rubber, and other products is assumed to remain in the product (i.e., it is assumed that there are no emissions of $CO_2$ from wax during the production of the product). Wax is used in many different packaging materials including wrappers, cartons, papers, paperboard, and

corrugated products (NPRA 2002). Davie (1993) and Davie et al. (1995) suggest that wax coatings in packaging products degrade rapidly in an aerobic environment, producing $CO_2$; however, because packaging products ultimately enter landfills typically having an anaerobic environment, most of the C from this end use is assumed to be stored in the landfill.

In construction materials, petroleum wax is used as a water repellent on wood-based composite boards, such as particle board (IGI 2002). Wax used for this end-use should follow the life-cycle of the harvested wood used in product, which is classified into one of 21 categories, evaluated by life-cycle, and ultimately assumed to either be disposed of in landfills or be combusted (EPA 2003).

The fate of wax used for packaging, in construction materials, and for most remaining end uses is ultimately to enter the municipal solid waste (MSW) stream, where it is either combusted or sent to landfill for disposal. Most of the C contained in these wax products will be stored. It is assumed that approximately 21 percent of the C contained in these products will be emitted through combustion or at landfill. With the exception of tires and rubber, these end-uses are assigned a C storage factor of 79 percent.

Waxes used in tires and rubber follow the life cycle of the tire and rubber products. Used tires are ultimately recycled, landfilled, or combusted. The life-cycle of tires is addressed elsewhere in this annex as part of the discussion of rubber products derived from petrochemical feedstocks. For the purposes of the estimation of the C storage factor for waxes, wax contained in tires and rubber products is assigned a C storage factor of 47 percent.

#### Uncertainty – TO BE UPDATED

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the estimates of the wax C storage factor and the quantity of C emitted from wax in 2009. A Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the Inventory estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. Uncertainty estimates for wax variables were assumed to have a moderate variance, in normal, uniform, or triangular distribution; uniform distributions were applied to total consumption of waxes and the C content coefficients.

The Monte Carlo analysis produced a storage factor distribution, whose 95 percent confidence interval values fell within the range of 49 percent and 71 percent, around the mean value of about 60 percent. This compares to the calculated Inventory estimate of 58 percent. The analysis produced an emission distribution, with the 95 percent confidence interval values of 0.3 Tg $CO_2$ Eq. and 0.8 Tg $CO_2$ Eq., with a mean value of 0.5 Tg $CO_2$ Eq. This compares with a calculated Inventory estimate of 0.5 Tg $CO_2$ Eq., which falls within the range of 95 percent confidence limits established by this quantitative uncertainty analysis. Uncertainty associated with the wax storage factor is considerable due to several assumptions pertaining to wax imports/exports, consumption, and fates.

### Miscellaneous Products

Miscellaneous products are defined by the U.S. Energy Information Administration as: “all finished [petroleum] products not classified elsewhere, e.g., petrolatum; lube refining byproducts (e.g., aromatic extracts and tars); absorption oils; ram-jet fuel; petroleum rocket fuel; synthetic natural gas feedstocks; and specialty oils."

#### Methodology and Data Sources

Data are not available concerning the distribution of each of the above-listed subcategories within the "miscellaneous products" category. However, based on the anticipated disposition of the products in each subcategory, it is assumed that all of the C content of miscellaneous products is emitted rather than stored. Petrolatum and specialty oils (which include greases) are likely to end up in solid waste or wastewater streams rather than in durable products, and would be emitted through waste treatment. Absorption oil is used in natural gas processing and is not a feedstock for manufacture of durable products Jet fuel and rocket fuel are assumed to be combusted in use, and synthetic natural gas feedstocks are assumed to be converted to synthetic natural gas that is also combusted in use. Lube refining byproducts could potentially be used as feedstocks for manufacture of durable goods, but such byproducts are more likely to be used in emissive uses. Lube refining byproducts and absorption oils are liquids and are precluded from disposal in landfills. Because no sequestering end uses of any of the miscellaneous products subcategories have been identified, a zero percent storage factor is assigned to miscellaneous products. According to EIA (2012), the C content of miscellaneous petroleum products in 2011 was approximately 20.3 Tg C/QBtu. One hundred percent of the C content is assumed to be emitted to the atmosphere, where it is oxidized to $CO_2$.

#### Uncertainty

A separate uncertainty analysis was not conducted for miscellaneous products, though this category was included in the uncertainty analysis of other non-energy uses discussed in the following section.

## Other Non-Energy Uses

The remaining fuel types use storage factors that are not based on U.S.-specific analysis. For industrial coking coal and distillate fuel oil, storage factors were taken from IPCC (2006), which in turn draws from Marland and Rotty (1984). These factors are 0.1 and 0.5, respectively.

IPCC does not provide guidance on storage factors for the remaining fuel types (petroleum coke, miscellaneous products, and other petroleum), and assumptions were made based on the potential fate of C in the respective NEUs. Specifically, the storage factor for petroleum coke is 0.3, based on information from Huurman (2006) indicating that petroleum coke is used in the Netherlands for production of pigments, with 30% being stored long-term. EIA (2012) defines "miscellaneous products" as "all finished products not classified elsewhere (e.g., petrolatum, lube refining byproducts (aromatic extracts and tars), absorption oils, ram-jet fuel, petroleum rocket fuels, synthetic natural gas feedstocks, and specialty oils)." All of these uses are emissive, and therefore the storage factor for miscellaneous products is set at zero. The "other petroleum" category is reported by U.S. territories and accounts mostly for the same products as miscellaneous products, but probably also includes some asphalt, known to be non-emissive. The exact amount of asphalt or any of the other miscellaneous products is confidential business information, but based on judgment the storage factor for this category was estimated at 0.1.

For all these fuel types, the overall methodology simply involves multiplying C content by a storage factor, yielding an estimate of the mass of C stored. To provide a complete analysis of uncertainty for the entire NEU subcategory, the uncertainty around the estimate of "other" NEUs was characterized, as discussed below.

#### Uncertainty – TO BE UPDATED

A Tier 2 Monte Carlo analysis was performed using @RISK software to determine the level of uncertainty surrounding the weighted average of the remaining fuels' C storage factors and the total quantity of C emitted from these other fuels in 2009. A Tier 2 analysis was performed to allow the specification of probability density functions for key variables, within a computational structure that mirrors the calculation of the Inventory estimate. Statistical analyses or expert judgments of uncertainty were not available directly from the information sources for some of the activity variables; thus, uncertainty estimates were determined using assumptions based on source category knowledge. A uniform distribution was applied to coking coal consumption, while the remaining consumption inputs were assumed to be normally distributed. The C content coefficients were assumed to have a uniform distribution; the greatest uncertainty range of 10 percent (±10%) around the inventory value, was applied to coking coal and miscellaneous products. C coefficients for distillate fuel oil ranged from 18.5 to 21.1 Tg C/QBtu. The fuel-specific storage factors were assigned wide triangular distributions indicating greater uncertainty.

The Monte Carlo analysis produced a storage factor distribution with 95 percent confidence limits of 10 percent and 44 percent, with a mean of 25 percent. This compares to the Inventory calculation of weighted average (across the various fuels) storage factor of about 16 percent. The analysis produced an emission distribution, with the 95 percent confidence limit of 12.6 Tg $CO_2$ Eq. and 22.2 Tg $CO_2$ Eq., and a mean of 17.4 Tg $CO_2$ Eq.. This compares with the Inventory estimate of 19.7Tg $CO_2$ Eq., which falls closer to the upper boundary of the 95 percent confidence limit. The uncertainty analysis results are driven primarily by the very broad uncertainty inputs for the storage factors.

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# ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories

## 3.1. Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Indirect Greenhouse Gases from Stationary Combustion

### Estimates of $CH_4$ and $N_2O$ Emissions

Methane ($CH_4$) and nitrous oxide ($N_2O$) emissions from stationary combustion were estimated using IPCC emission factors and methods. Estimates were obtained by multiplying emission factors—by sector and fuel type—by fossil fuel and wood consumption data. This "top-down" methodology is characterized by two basic steps, described below. Beginning in this inventory, the electric power sector utilizes a Tier 2 methodology, whereas all other sectors utilize a Tier 1 methodology. The differences in the methodology applied are described within each of the steps below. Data are presented in Table A-83 through Table A-88.

#### Step 1: Determine Energy Consumption by Sector and Fuel Type

Energy consumption from stationary combustion activities was grouped by sector: industrial, commercial, residential, electric power, and U.S. territories. For $CH_4$ and $N_2O$ from industrial, commercial, residential, and U.S. territories, estimates were based upon consumption of coal, gas, oil, and wood. Energy consumption data for the United States were obtained from EIA's *Monthly Energy Review, December 2012* and Published Supplemental Tables on Petroleum Product detail (EIA 2012a). Wood consumption data for the United States was obtained from EIA's *Annual Energy Review* (EIA 2012b). Because the United States does not include territories in its national energy statistics, fuel consumption data for territories were collected separately from the EIA from Jacobs (2010).[36] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[37] Construction and agricultural fuel use was obtained from EPA (2011). The energy consumption data by sector were then adjusted from higher to lower heating values by multiplying by 0.9 for natural gas and wood and by 0.95 for coal and petroleum fuel. This is a simplified convention used by the International Energy Agency. Table A-83 provides annual energy consumption data for the years 1990 through 2011.

In this inventory, the emission estimation methodology for the electric power sector was revised from Tier 1 to Tier 2 as fuel consumption by technology-type for the electricity generation sector was obtained from the Acid Rain Program Dataset (EPA 2012). This combustion technology-and fuel-use data was available by facility from 1996 to 2011. Since there was a difference between the EPA (2012) and EIA (2012a) total energy consumption estimates, the remainder between total energy consumption using EPA (2012) and EIA (2012a) was apportioned to each combustion technology type and fuel combination using a ratio of energy consumption by technology type from 1996 to 2011.

Energy consumption estimates were not available from 1990 to 1995 in the EPA (2012) dataset, and as a result, consumption was calculated using total electric power consumption from EIA (2012a) and the ratio of combustion technology and fuel types from EPA 2012. The consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type to the total EIA consumption for each year from 1990 to 1995.

Lastly, there were significant differences between wood biomass consumption in the electric power sector between the EPA (2012) and EIA (2012a) datasets. The difference in wood biomass consumption in the electric power sector was distributed to the residential, commercial, and industrial sectors according to their percent share of wood biomass energy consumption calculated from EIA (2012a).

#### Step 2: Determine the Amount of $CH_4$ and $N_2O$ Emitted

Activity data for industrial, commercial, residential, and U.S. territories and fuel type for each of these sectors were then multiplied by default Tier 1 emission factors to obtain emission estimates. Emission factors for the residential,

[36] U.S. territories data also include combustion from mobile activities because data to allocate territories' energy use were unavailable. For this reason, $CH_4$ and $N_2O$ emissions from combustion by U.S. Territories are only included in the stationary combustion totals.

[37] Though emissions from construction and farm use occur due to both stationary and mobile sources, detailed data was not available to determine the magnitude from each. Currently, these emissions are assumed to be predominantly from mobile sources.

commercial, and industrial sectors were taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). These $N_2O$ emission factors by fuel type (consistent across sectors) were also assumed for U.S. territories. The $CH_4$ emission factors by fuel type for U.S. territories were estimated based on the emission factor for the primary sector in which each fuel was combusted. Table A-84 provides emission factors used for each sector and fuel type. For the electric power sector, emissions were estimated by multiplying fossil fuel and wood consumption by technology- and fuel-specific Tier 2 IPCC emission factors shown in Table A-85.

## Estimates of NOx, CO, and NMVOC Emissions

Emissions estimates for $NO_x$, CO, and NMVOCs were obtained from preliminary data (EPA 2010b, EPA 2009) 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.

For indirect greenhouse gases, the major source categories included coal, fuel oil, natural gas, wood, other fuels (i.e., bagasse, liquefied petroleum gases, coke, coke oven gas, and others), and stationary internal combustion, which includes emissions from internal combustion engines not used in transportation. EPA periodically estimates emissions of $NO_x$, CO, and NMVOCs by sector and fuel type using a "bottom-up" estimating procedure. In other words, the emissions were calculated either for individual sources (e.g., industrial boilers) or for many sources combined, using basic activity data (e.g., fuel consumption or deliveries, etc.) as indicators of emissions. The national activity data used to calculate the individual categories were obtained from various sources. Depending upon the category, these activity data may include fuel consumption or deliveries of fuel, tons of refuse burned, raw material processed, etc. Activity data were used in conjunction with emission factors that relate the quantity of emissions to the activity.

The basic calculation procedure for most source categories presented in EPA (2003) and EPA (2009) is represented by the following equation:

$$E_{p,s} = A_s \times EF_{p,s} \times (1 - C_{p,s}/100)$$

Where,

| | | |
|---|---|---|
| E | = | Emissions |
| p | = | Pollutant |
| s | = | Source category |
| A | = | Activity level |
| EF | = | Emission factor |
| C | = | Percent control efficiency |

The EPA currently derives the overall emission control efficiency of a category from a variety of sources, including published reports, the 1985 National Acid Precipitation and Assessment Program (NAPAP) emissions inventory, and other EPA databases. The U.S. approach for estimating emissions of $NO_x$, CO, and NMVOCs from stationary combustion as described above is similar to the methodology recommended by the IPCC (IPCC/UNEP/OECD/IEA 1997).

Table A-83: Fuel Consumption by Stationary Combustion for Calculating $CH_4$ and $N_2O$ Emissions (TBtu)

| Fuel/End-Use Sector | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Coal** | **19,610** | **20,888** | **21,328** | **21,879** | **22,224** | **22,159** | **23,080** | **22,391** | **22,343** | **22,576** | **22,636** | **22,949** | **22,458** | **22,710** | **22,223** | **19,670** | **20,759** | **19,072** |
| Residential | 31 | 17 | 17 | 16 | 12 | 14 | 11 | 12 | 12 | 12 | 11 | 8 | 6 | 8 | 8 | 8 | 7 | 7 |
| Commercial | 124 | 117 | 122 | 129 | 93 | 103 | 92 | 97 | 90 | 82 | 103 | 97 | 65 | 70 | 69 | 63 | 60 | 53 |
| Industrial | 1,640 | 1,527 | 1,455 | 1,458 | 1,471 | 1,373 | 1,349 | 1,358 | 1,244 | 1,249 | 1,262 | 1,219 | 1,189 | 1,131 | 1,084 | 880 | 1,016 | 950 |
| Electric Power | 17,807 | 19,217 | 19,724 | 20,266 | 20,637 | 20,659 | 21,618 | 20,920 | 20,987 | 21,199 | 21,228 | 21,591 | 21,161 | 21,465 | 21,026 | 18,682 | 19,639 | 18,024 |
| U.S. Territories | 7 | 10 | 10 | 10 | 11 | 10 | 10 | 4 | 11 | 34 | 32 | 33 | 37 | 37 | 37 | 37 | 37 | 38 |
| **Petroleum** | **6,277** | **5,655** | **6,142** | **6,201** | **5,885** | **6,189** | **6,011** | **6,554** | **5,935** | **6,303** | **6,502** | **6,438** | **6,153** | **6,029** | **5,345** | **4,714** | **4,871** | **4,490** |
| Residential | 1,375 | 1,261 | 1,397 | 1,334 | 1,207 | 1,342 | 1,427 | 1,463 | 1,359 | 1,466 | 1,475 | 1,369 | 1,205 | 1,225 | 1,215 | 1,165 | 1,132 | 1,086 |
| Commercial | 891 | 694 | 718 | 655 | 609 | 614 | 694 | 719 | 645 | 762 | 767 | 716 | 678 | 681 | 669 | 697 | 679 | 654 |
| Industrial | 2,838 | 2,378 | 2,710 | 2,667 | 2,220 | 2,313 | 2,149 | 2,461 | 2,299 | 2,409 | 2,600 | 2,725 | 3,060 | 2,954 | 2,481 | 1,933 | 2,033 | 1,869 |
| Electric Power | 797 | 860 | 883 | 1,100 | 1,403 | 1,459 | 1,269 | 1,279 | 1,074 | 1,043 | 1,007 | 1,004 | 590 | 618 | 488 | 383 | 412 | 266 |
| U.S. Territories | 375 | 462 | 435 | 445 | 445 | 461 | 472 | 632 | 557 | 622 | 654 | 623 | 621 | 552 | 492 | 536 | 614 | 614 |
| **Natural Gas** | **17,266** | **19,337** | **20,233** | **20,131** | **19,840** | **19,778** | **20,919** | **20,224** | **20,908** | **20,894** | **21,152** | **20,938** | **20,626** | **22,019** | **22,281** | **21,946** | **22,671** | **23,009** |
| Residential | 4,491 | 4,954 | 5,354 | 5,093 | 4,646 | 4,835 | 5,105 | 4,889 | 4,995 | 5,209 | 4,981 | 4,946 | 4,476 | 4,835 | 5,010 | 4,883 | 4,883 | 4,824 |
| Commercial | 2,682 | 3,096 | 3,226 | 3,285 | 3,083 | 3,115 | 3,252 | 3,097 | 3,212 | 3,261 | 3,201 | 3,073 | 2,902 | 3,085 | 3,228 | 3,187 | 3,164 | 3,228 |
| Industrial | 7,716 | 8,723 | 9,020 | 9,033 | 8,826 | 8,425 | 8,656 | 7,949 | 8,086 | 7,845 | 7,914 | 7,330 | 7,323 | 7,521 | 7,566 | 7,119 | 7,438 | 7,735 |
| Electric Power | 2,376 | 2,564 | 2,632 | 2,720 | 3,285 | 3,403 | 3,894 | 4,266 | 4,591 | 4,551 | 5,032 | 5,565 | 5,899 | 6,550 | 6,447 | 6,730 | 7,159 | 7,194 |
| U.S. Territories | NE | NE | NE | NE | NE | NE | 13 | 23 | 23 | 27 | 25 | 24 | 26 | 27 | 29 | 27 | 28 | 28 |
| **Wood** | **2,216** | **2,370** | **2,437** | **2,371** | **2,184** | **2,214** | **2,262** | **2,006** | **1,995** | **2,002** | **2,121** | **2,137** | **2,099** | **2,070** | **2,040** | **1,891** | **1,988** | **1,987** |
| Residential | 614 | 547 | 571 | 455 | 404 | 414 | 444 | 393 | 409 | 434 | 442 | 468 | 413 | 445 | 486 | 470 | 460 | 466 |
| Commercial | 70 | 76 | 80 | 78 | 68 | 71 | 76 | 71 | 74 | 78 | 76 | 76 | 71 | 76 | 79 | 79 | 78 | 76 |
| Industrial | 1,526 | 1,739 | 1,779 | 1,831 | 1,704 | 1,720 | 1,731 | 1,533 | 1,503 | 1,480 | 1,592 | 1,581 | 1,599 | 1,526 | 1,448 | 1,319 | 1,425 | 1,421 |
| Electric Power | 7 | 8 | 8 | 8 | 8 | 9 | 11 | 9 | 9 | 10 | 11 | 11 | 17 | 23 | 27 | 23 | 25 | 24 |
| U.S. Territories | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE |

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table A-84: $CH_4$ and $N_2O$ Emission Factors by Fuel Type and Sector (g/GJ)[38]

| Fuel/End-Use Sector | $CH_4$ | $N_2O$ |
|---|---|---|
| **Coal** | | |
| Residential | 300 | 1.5 |
| Commercial | 10 | 1.5 |
| Industrial | 10 | 1.5 |
| Electric Power | 1 | 1.5 |
| U.S. Territories | 1 | 1.5 |
| **Petroleum** | | |
| Residential | 10 | 0.6 |
| Commercial | 10 | 0.6 |
| Industrial | 3 | 0.6 |
| Electric Power | 3 | 0.6 |
| U.S. Territories | 5 | 0.6 |
| **Natural Gas** | | |
| Residential | 5 | 0.1 |
| Commercial | 5 | 0.1 |
| Industrial | 1 | 0.1 |
| Electric Power | 1 | 0.1 |
| U.S. Territories | 1 | 0.1 |
| **Wood** | | |
| Residential | 300 | 4.0 |
| Commercial | 300 | 4.0 |
| Industrial | 30 | 4.0 |
| Electric Power | 30 | 4.0 |
| U.S. Territories | NA | NA |

NA (Not Applicable)

Table A-85: $CH_4$ and $N_2O$ Emission Factors by Technology Type and Fuel Type for the Electric Power Sector(g/GJ)[39]

| Technology | Configuration | $CH_4$ | $N_2O$ |
|---|---|---|---|
| **Liquid Fuels** | | | |
| Residual Fuel Oil/Shale Oil Boilers | Normal Firing | 0.8 | 0.3 |
| | Tangential Firing | 0.8 | 0.3 |
| Gas/Diesel Oil Boilers | Normal Firing | 0.9 | 0.4 |
| | Tangential Firing | 0.9 | 0.4 |
| Large Diesel Oil Engines >600 hp (447kW) | | 4 | NA |
| **Solid Fuels** | | | |
| Pulverized Bituminous Combination Boilers | Dry Bottom, wall fired | 0.7 | 0.5 |
| | Dry Bottom, tangentially fired | 0.7 | 1.4 |
| | Wet bottom | 0.9 | 1.4 |
| Bituminous Spreader Stoker Boilers | With and without re-injection | 1 | 0.7 |
| Bituminous Fluidized Bed Combustor | Circulating Bed | 1 | 61 |
| | Bubbling Bed | 1 | 61 |
| Bituminous Cyclone Furnace | | 0.2 | 0.6 |
| Lignite Atmospheric Fluidized Bed | | NA | 71 |
| **Natural Gas** | | | |
| Boilers | | 1 | 1 |
| Gas-Fired Gas Turbines >3MW | | 4 | 1 |
| Large Duel-Fuel Engines | | 258 | NA |
| Combined Cycle | | 1 | 3 |
| **Peat** | | | |
| Peat Fluidized Bed Combustion | Circulating Bed | 3 | 7 |
| | Bubbling Bed | 3 | 3 |
| **Biomass** | | | |
| Wood/Wood Waste Boilers | | 11 | 7 |
| Wood Recovery Boilers | | 1 | 1 |

[38] GJ (Gigajoule) = $10^9$ joules. One joule = $9.486\times10^{-4}$ Btu

[39] GJ (Gigajoule) = $10^9$ joules. One joule = $9.486\times10^{-4}$ Btu

1 Source: IPCC (2006)

Table A-86: NOx Emissions from Stationary Combustion (Gg)

| Sector/Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Electric Power** | **6,045** | **5,792** | **5,581** | **5,683** | **5,637** | **5,183** | **4,829** | **4,453** | **4,265** | **3,988** | **3,711** | **3,434** | **3,121** | **3,007** | **2,722** | **1,766** | **1,766** | **1,766** |
| Coal | 5,119 | 5,061 | 5,079 | 5,118 | 4,932 | 4,437 | 4,130 | 3,802 | 3,634 | 3,398 | 3,162 | 2,926 | 2,659 | 2,562 | 2,319 | 1,505 | 1,505 | 1,505 |
| Fuel Oil | 200 | 87 | 107 | 131 | 202 | 179 | 147 | 149 | 142 | 133 | 124 | 114 | 104 | 100 | 91 | 59 | 59 | 59 |
| Natural gas | 513 | 510 | 248 | 277 | 329 | 393 | 376 | 325 | 310 | 290 | 270 | 250 | 227 | 219 | 198 | 128 | 128 | 128 |
| Wood | NA | NA | 5 | 6 | 24 | 33 | 36 | 37 | 36 | 33 | 31 | 29 | 26 | 25 | 23 | 15 | 15 | 15 |
| Other Fuels[a] | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Internal Combustion | 213 | 134 | 142 | 150 | 149 | 141 | 140 | 140 | 143 | 134 | 124 | 115 | 105 | 101 | 91 | 59 | 59 | 59 |
| **Industrial** | **2,559** | **2,650** | **2,666** | **2,614** | **2,570** | **2,283** | **2,278** | **2,296** | **1,699** | **1,638** | **1,577** | **1,515** | **1,520** | **1,525** | **1,530** | **1,478** | **1,478** | **1,478** |
| Coal | 530 | 541 | 490 | 487 | 475 | 475 | 484 | 518 | 384 | 370 | 356 | 342 | 343 | 344 | 345 | 334 | 334 | 334 |
| Fuel Oil | 240 | 224 | 203 | 196 | 190 | 190 | 166 | 153 | 114 | 110 | 105 | 101 | 102 | 102 | 102 | 99 | 99 | 99 |
| Natural gas | 877 | 999 | 900 | 880 | 869 | 706 | 710 | 711 | 526 | 507 | 488 | 469 | 471 | 472 | 474 | 458 | 458 | 458 |
| Wood | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Other Fuels[a] | 119 | 111 | 109 | 103 | 104 | 100 | 109 | 116 | 86 | 82 | 79 | 76 | 77 | 77 | 77 | 74 | 74 | 74 |
| Internal Combustion | 792 | 774 | 965 | 948 | 932 | 813 | 809 | 798 | 591 | 569 | 548 | 527 | 528 | 530 | 532 | 514 | 514 | 514 |
| **Commercial** | **671** | **607** | **734** | **539** | **510** | **483** | **507** | **428** | **438** | **456** | **473** | **490** | **486** | **483** | **479** | **501** | **501** | **501** |
| Coal | 36 | 35 | 30 | 32 | 34 | 23 | 21 | 21 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 |
| Fuel Oil | 88 | 94 | 86 | 88 | 73 | 54 | 52 | 52 | 50 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| Natural gas | 181 | 210 | 224 | 229 | 220 | 156 | 161 | 165 | 157 | 156 | 156 | 155 | 155 | 155 | 154 | 154 | 154 | 154 |
| Wood | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Other Fuels[a] | 366 | 269 | 394 | 191 | 183 | 249 | 273 | 189 | 213 | 231 | 249 | 267 | 263 | 261 | 257 | 280 | 280 | 280 |
| **Residential** | **749** | **813** | **726** | **699** | **651** | **441** | **439** | **446** | **423** | **421** | **420** | **418** | **417** | **417** | **416** | **414** | **414** | **414** |
| Coal[b] | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Fuel Oil[b] | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Natural Gas[b] | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Wood | 42 | 44 | 27 | 27 | 27 | 25 | 21 | 22 | 21 | 21 | 21 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Other Fuels[a] | 707 | 769 | 699 | 671 | 624 | 416 | 417 | 424 | 402 | 400 | 399 | 397 | 397 | 396 | 396 | 394 | 394 | 394 |
| **Total** | **10,023** | **9,862** | **9,707** | **9,534** | **9,369** | **8,390** | **8,053** | **7,623** | **6,825** | **6,503** | **6,181** | **5,858** | **5,545** | **5,432** | **5,148** | **4,159** | **4,159** | **4,159** |

NA (Not Applicable)

[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2003, 2009, 2010b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2003, 2009, 2010b).

Note: Totals may not sum due to independent rounding.

Table A-87: CO Emissions from Stationary Combustion (Gg)

| Sector/Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Electric Power** | **329** | **337** | **369** | **385** | **410** | **450** | **439** | **439** | **595** | **590** | **586** | **582** | **598** | **616** | **633** | **631** | **631** | **631** |
| Coal | 213 | 227 | 228 | 233 | 220 | 187 | 221 | 220 | 298 | 296 | 293 | 292 | 300 | 308 | 317 | 316 | 316 | 316 |
| Fuel Oil | 18 | 9 | 11 | 13 | 17 | 36 | 27 | 28 | 38 | 37 | 37 | 37 | 38 | 39 | 40 | 40 | 40 | 40 |
| Natural gas | 46 | 49 | 72 | 76 | 88 | 150 | 96 | 92 | 125 | 124 | 123 | 122 | 126 | 129 | 133 | 132 | 132 | 132 |
| Wood | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Other Fuels[a] | NA | NA | 7 | 8 | 30 | 24 | 31 | 32 | 44 | 43 | 43 | 43 | 44 | 45 | 46 | 46 | 46 | 46 |
| Internal Combustion | 52 | 52 | 52 | 54 | 55 | 52 | 63 | 67 | 91 | 90 | 89 | 89 | 91 | 94 | 97 | 96 | 96 | 96 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Industrial** | **797** | | **958** | **1,078** | **1,054** | **1,044** | **1,100** | **1,106** | **1,137** | **1,149** | **1,115** | **1,080** | **1,045** | **1,064** | **1,084** | **1,103** | **1,030** | **1,030** | **1,030** |
| Coal | 95 | | 88 | 100 | 99 | 96 | 114 | 118 | 125 | 127 | 123 | 119 | 115 | 117 | 119 | 121 | 113 | 113 | 113 |
| Fuel Oil | 67 | | 64 | 49 | 47 | 46 | 54 | 48 | 45 | 46 | 44 | 43 | 42 | 42 | 43 | 44 | 41 | 41 | 41 |
| Natural gas | 205 | | 313 | 307 | 307 | 305 | 350 | 355 | 366 | 370 | 359 | 347 | 336 | 342 | 349 | 355 | 331 | 331 | 331 |
| Wood | NA | | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Other Fuels[a] | 253 | | 270 | 316 | 302 | 303 | 286 | 300 | 321 | 325 | 315 | 305 | 296 | 301 | 307 | 312 | 291 | 291 | 291 |
| Internal Combustion | 177 | | 222 | 305 | 299 | 294 | 296 | 285 | 279 | 282 | 274 | 265 | 257 | 261 | 266 | 271 | 253 | 253 | 253 |
| **Commercial** | **205** | | **211** | **122** | **126** | **122** | **151** | **151** | **154** | **177** | **173** | **169** | **166** | **166** | **167** | **168** | **158** | **158** | **158** |
| Coal | 13 | | 14 | 13 | 13 | 14 | 16 | 14 | 13 | 15 | 15 | 15 | 14 | 15 | 15 | 15 | 14 | 14 | 14 |
| Fuel Oil | 16 | | 17 | 17 | 18 | 15 | 17 | 17 | 17 | 20 | 19 | 19 | 19 | 19 | 19 | 19 | 18 | 18 | 18 |
| Natural gas | 40 | | 49 | 58 | 59 | 57 | 81 | 83 | 84 | 97 | 95 | 93 | 91 | 91 | 92 | 92 | 87 | 87 | 87 |
| Wood | NA | | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Other Fuels[a] | 136 | | 132 | 34 | 36 | 36 | 36 | 36 | 38 | 44 | 43 | 42 | 41 | 42 | 42 | 42 | 40 | 40 | 40 |
| **Residential** | **3,668** | | **3,877** | **2,364** | **2,361** | **2,352** | **3,323** | **2,644** | **2,648** | **3,044** | **2,981** | **2,919** | **2,856** | **2,867** | **2,878** | **2,889** | **2,725** | **2,725** | **2,725** |
| Coal[b] | NA | | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Fuel Oil[b] | NA | | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Natural Gas[b] | NA | | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Wood | 3,430 | | 3,629 | 2,133 | 2,133 | 2,133 | 3,094 | 2,416 | 2,424 | 2,787 | 2,730 | 2,672 | 2,615 | 2,624 | 2,635 | 2,645 | 2,495 | 2,495 | 2,495 |
| Other Fuels[a] | 238 | | 248 | 231 | 229 | 220 | 229 | 228 | 224 | 257 | 252 | 246 | 241 | 242 | 243 | 244 | 230 | 230 | 230 |
| **Total** | **5,000** | | **5,383** | **3,934** | **3,926** | **3,928** | **5,024** | **4,340** | **4,377** | **4,965** | **4,860** | **4,753** | **4,649** | **4,695** | **4,744** | **4,792** | **4,543** | **4,543** | **4,543** |

NA (Not Applicable)
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2003, 2009, 2010b).
[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2003, 2009, 2010b).
Note: Totals may not sum due to independent rounding.

Table A-88: NMVOC Emissions from Stationary Combustion (Gg)

| Sector/Fuel Type | 1990 | | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Electric Power** | **43** | | **40** | **44** | **47** | **51** | **49** | **56** | **55** | **44** | **44** | **44** | **44** | **44** | **45** | **45** | **46** | **46** | **46** |
| Coal | 24 | | 26 | 25 | 26 | 26 | 25 | 27 | 26 | 21 | 21 | 21 | 21 | 21 | 22 | 22 | 22 | 22 | 22 |
| Fuel Oil | 5 | | 2 | 3 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 4 | 4 |
| Natural gas | 2 | | 2 | 7 | 7 | 9 | 9 | 12 | 12 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Wood | NA | | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Other Fuels[a] | NA | | NA | + | + | 1 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Internal Combustion | 11 | | 9 | 9 | 10 | 10 | 10 | 11 | 11 | 8 | 8 | 8 | 8 | 8 | 9 | 9 | 9 | 9 | 9 |
| **Industrial** | **165** | | **187** | **163** | **160** | **159** | **156** | **157** | **160** | **138** | **132** | **126** | **121** | **120** | **119** | **118** | **110** | **110** | **110** |
| Coal | 7 | | 5 | 6 | 6 | 6 | 9 | 9 | 10 | 9 | 9 | 8 | 8 | 8 | 8 | 8 | 7 | 7 | 7 |
| Fuel Oil | 11 | | 11 | 8 | 7 | 7 | 10 | 9 | 9 | 7 | 7 | 7 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| Natural gas | 52 | | 66 | 54 | 54 | 54 | 52 | 53 | 54 | 47 | 45 | 43 | 41 | 41 | 40 | 40 | 37 | 37 | 37 |
| Wood | NA | | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Other Fuels[a] | 46 | | 45 | 33 | 31 | 31 | 26 | 27 | 29 | 25 | 24 | 23 | 22 | 22 | 22 | 22 | 20 | 20 | 20 |
| Internal Combustion | 49 | | 60 | 63 | 62 | 61 | 60 | 58 | 57 | 49 | 47 | 45 | 43 | 43 | 42 | 42 | 39 | 39 | 39 |
| **Commercial** | **18** | | **21** | **22** | **22** | **21** | **25** | **28** | **29** | **61** | **53** | **45** | **33** | **36** | **38** | **40** | **23** | **23** | **23** |
| Coal | 1 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | + | + | + |
| Fuel Oil | 3 | | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 6 | 5 | 3 | 2 | 3 | 4 | 5 | 1 | 1 | 1 |
| Natural gas | 7 | | 10 | 13 | 13 | 12 | 11 | 14 | 14 | 23 | 18 | 14 | 9 | 12 | 16 | 19 | 4 | 4 | 4 |
| Wood | NA | | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Other Fuels[a] | 8 | | 8 | 5 | 5 | 5 | 10 | 9 | 10 | 31 | 29 | 27 | 22 | 19 | 17 | 15 | 18 | 18 | 18 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Residential** | **686** | | **725** | **788** | **788** | **786** | **815** | **837** | **837** | **1,341** | **1,066** | **792** | **519** | **719** | **918** | **1,117** | **244** | **244** | **244** |
| Coal[b] | NA | | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Fuel Oil[b] | NA | | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Natural Gas[b] | NA | | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| Wood | 651 | | 688 | 756 | 757 | 756 | 794 | 809 | 809 | 1,298 | 1,032 | 767 | 502 | 695 | 888 | 1,081 | 236 | 236 | 236 |
| Other Fuels[a] | 35 | | 37 | 33 | 32 | 30 | 21 | 27 | 27 | 43 | 35 | 26 | 17 | 23 | 30 | 36 | 8 | 8 | 8 |
| **Total** | **912** | | **973** | **1,018** | **1,017** | **1,016** | **1,045** | **1,077** | **1,081** | **1,585** | **1,296** | **1,008** | **716** | **918** | **1,120** | **1,321** | **424** | **424** | **424** |

NA (Not Applicable)
+ Does not exceed 1 Gg.
[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2003, 2009, 2010b).
[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2003, 2009, 2010b).
Note: Totals may not sum due to independent rounding.

## 3.2. Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related GHG Emissions

### Estimating $CO_2$ Emissions by Transportation Mode

Transportation-related $CO_2$ emissions, as presented in the Carbon Dioxide Emissions from Fossil Fuel Combustion section of the Energy chapter, were calculated using the methodology described in Annex 2.1. This section provides additional information on the data sources and approach used for each transportation fuel type. As noted in Annex 2.1, $CO_2$ emissions estimates for the transportation sector were calculated directly for on-road diesel fuel and motor gasoline based on data sources for individual modes of transportation (considered a "bottom up" approach). For most other fuel and energy types (i.e., jet fuel, aviation gasoline, residual fuel oil, natural gas, LPG, and electricity), $CO_2$ emissions were calculated based on transportation sector-wide fuel consumption estimates from the Energy Information Administration (EIA 2013 and EIA 2012a) and apportioned to individual modes (considered a "top down" approach).

Based on interagency discussions between EPA, EIA, and FHWA beginning in 2005, it was agreed that use of "bottom up" data would be more accurate for diesel fuel and motor gasoline, based on the availability of reliable transportation-specific data sources. A "bottom up" diesel calculation was implemented in the 1990-2005 Inventory, and a bottom-up gasoline calculation was introduced in the 1990-2006 Inventory for the calculation of emissions from on-road vehicles. Motor gasoline and diesel consumption data for on-road vehicles come from FHWA's *Highway Statistics*, Table VM-1 (FHWA 1996 through 2013)[40], and are based on federal and state fuel tax records. These fuel consumption estimates were then combined with estimates of fuel shares by vehicle type from DOE's Transportation Energy Data Book (DOE 1993 through 2012) to develop an estimate of fuel consumption for each vehicle type (i.e., passenger cars, light-duty trucks, buses, medium- and heavy-duty trucks, motorcycles). The on-road gas and diesel fuel consumption estimates by vehicle type were then adjusted for each year so that the sum of gasoline and diesel fuel consumption across all vehicle categories matched the fuel consumption estimates in *Highway Statistics'* Tables MF-21 and MF-27 (FHWA 1996 through 2013). Table MF-21 provided fuel consumption estimates for the most current Inventory year; Table MF-27 provided fuel consumption estimates for years 1990-2009. This resulted in a final estimate of motor gasoline and diesel fuel use by vehicle type, consistent with the FHWA total for on-road motor gasoline and diesel fuel use.

Estimates of diesel fuel consumption from rail were taken from the Association of American Railroads (AAR 2008 through 2012) for Class I railroads, the American Public Transportation Association (APTA 2007 through 2012 and APTA 2006) and Gaffney (2007) for commuter rail, the Upper Great Plains Transportation Institute (Benson 2002 through 2004) and Whorton (2006 through 2012) for Class II and III railroads, and DOE's *Transportation Energy Data Book* (DOE 1993 through 2012) for passenger rail. Estimates of diesel from ships and boats were taken from EIA's *Fuel Oil and Kerosene Sales* (1991 through 2013).

Since EIA's total fuel consumption estimate for each fuel type is considered to be accurate at the national level, adjustments needed to be made in the estimates for other sectors to equal the EIA total. In the case of motor gasoline, estimates of fuel use by recreational boats come from EPA's NONROAD Model (EPA 2012b), and these estimates along with those from other sectors (e.g., commercial sector, industrial sector) were adjusted. Similarly, to ensure consistency with EIA's total diesel estimate for all sectors, the diesel consumption totals for the residential, commercial, and industrial sectors were adjusted downward proportionately.

As noted above, for fuels other than motor gasoline and diesel, EIA's transportation sector total was apportioned to specific transportation sources. For jet fuel, estimates come from: FAA (2013,) for commercial aircraft, FAA (2012)) for general aviation aircraft, and DESC (2012) for military aircraft. Estimates for biofuels, including ethanol and biodiesel were discussed separately and were not apportioned to specific transportation sources. Consumption estimates for biofuels were calculated based on data from the Energy Information Administration (EIA 2012a).

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[40] In 2011 FHWA changed how they defined vehicle types for the purposes of reporting VMT for the years 2007-2010. The old approach to vehicle classification was based on body type and split passenger vehicles into "Passenger Cars" and "Other 2 Axle 4-Tire Vehicles". The new approach is a vehicle classification system based on wheelbase. Vehicles with a wheelbase less than or equal to 121 inches are counted as "Light-duty Vehicles –Short Wheelbase". Passenger vehicles with a Wheelbase greater than 121 inches are counted as "Light-duty Vehicles - Long Wheelbase". This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this emission inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

Table A-89 displays estimated fuel consumption by fuel and vehicle type. Table A-90 displays estimated energy consumption by fuel and vehicle type. The values in both of these tables correspond to the figures used to calculate $CO_2$ emissions from transportation. Except as noted above, they are estimated based on EIA transportation sector energy estimates by fuel type, with activity data used to apportion consumption to the various modes of transport. For motor gasoline, the figures do not include ethanol blended with gasoline; although ethanol is included in FHWA's totals for reported motor gasoline use. Ethanol is a biofuel and in order to be in line with IPCC methodological guidance and UNFCCC reporting obligations, net carbon fluxes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change and Forestry chapter, not in Energy chapter totals. Ethanol and biodiesel consumption estimates are shown separately in Table A-91.

Table A-89. Fuel Consumption by Fuel and Vehicle Type (million gallons unless otherwise specified)

| Fuel/Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007[a] | 2008[a] | 2009[a] | 2010[a] | 2011[f] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Motor Gasoline[b]** | **110,441** | **118,217** | **120,617** | **122,040** | **125,576** | **128,258** | **129,102** | **130,582** | **133,257** | **133,900** | **135,708** | **134,659** | **132,947** | **132,546** | **127,528** | **127,323** | **126,930** | **124,152** |
| Passenger Cars | 69,763 | 67,948 | 68,996 | 69,034 | 71,303 | 73,144 | 72,860 | 73,466 | 74,911 | 72,623 | 72,223 | 74,600 | 71,647 | 89,795 | 86,376 | 86,019 | 85,661 | 83,668 |
| Light-Duty Trucks | 34,698 | 44,369 | 45,954 | 47,528 | 48,668 | 50,901 | 50,774 | 51,251 | 52,442 | 55,951 | 58,118 | 54,274 | 55,460 | 35,401 | 33,723 | 34,312 | 34,339 | 33,540 |
| Motorcycles | 194 | 200 | 197 | 201 | 206 | 213 | 210 | 194 | 191 | 185 | 195 | 184 | 212 | 478 | 496 | 479 | 425 | 415 |
| Buses | 39 | 42 | 42 | 42 | 42 | 45 | 44 | 40 | 38 | 36 | 50 | 41 | 42 | 81 | 86 | 89 | 88 | 88 |
| Medium- and Heavy-Duty Trucks | 4,350 | 4,072 | 3,976 | 3,901 | 3,957 | 4,018 | 4,096 | 3,990 | 4,038 | 3,479 | 3,510 | 3,962 | 4,008 | 5,233 | 5,322 | 4,918 | 4,937 | 4,973 |
| Recreational Boats[c] | 1,397 | 1,585 | 1,452 | 1,334 | 1,400 | -62 | 1,119 | 1,641 | 1,637 | 1,626 | 1,612 | 1,599 | 1,577 | 1,557 | 1,524 | 1,506 | 1,481 | 1,468 |
| **Distillate Fuel Oil (Diesel Fuel)** | **25,631** | **31,605** | **33,160** | **34,625** | **35,728** | **37,863** | **39,241** | **39,058** | **40,348** | **41,177** | **42,668** | **44,659** | **45,848** | **46,432** | **43,236** | **39,294** | **40,911** | **42,478** |
| Passenger Cars | 771 | 765 | 657 | 593 | 546 | 427 | 356 | 357 | 364 | 412 | 419 | 414 | 403 | 402 | 362 | 354 | 366 | 359 |
| Light-Duty Trucks | 1,119 | 1,452 | 1,529 | 1,586 | 1,682 | 1,847 | 1,961 | 2,029 | 2,133 | 2,652 | 2,822 | 2,518 | 2,610 | 1,326 | 1,182 | 1,181 | 1,226 | 1,203 |
| Buses | 781 | 851 | 884 | 901 | 922 | 1,034 | 997 | 906 | 860 | 930 | 1,316 | 1,030 | 1,049 | 1,547 | 1,477 | 1,374 | 1,374 | 1,390 |
| Medium- and Heavy-Duty Trucks | 18,574 | 23,241 | 24,489 | 25,929 | 27,153 | 28,833 | 30,180 | 30,125 | 31,418 | 31,540 | 32,599 | 35,160 | 36,079 | 37,496 | 35,692 | 32,384 | 33,719 | 34,106 |
| Recreational Boats | 190 | 228 | 236 | 243 | 251 | 258 | 266 | 274 | 282 | 289 | 297 | 305 | 313 | 321 | 88 | 337 | 345 | 353 |
| Ships and Other Boats | 735 | 1,204 | 1,432 | 1,426 | 1,199 | 1,342 | 1,377 | 1,248 | 1,202 | 1,178 | 807 | 785 | 729 | 800 | 218 | 128 | 74 | 1,068 |
| Rail | 3,461 | 3,864 | 3,934 | 3,947 | 3,975 | 4,122 | 4,106 | 4,119 | 4,089 | 4,176 | 4,407 | 4,446 | 4,665 | 4,539 | 4,216 | 3,535 | 3,807 | 3,998 |
| **Jet Fuel[d]** | **16,171** | **15,565** | **15,869** | **16,152** | **16,026** | **17,248** | **17,848** | **16,431** | **15,855** | **16,031** | **16,596** | **17,398** | **17,784** | **17,886** | **16,806** | **15,501** | **14,679** | **14,697** |
| Commercial Aircraft | 11,925 | 12,510 | 12,877 | 13,336 | 12,990 | 14,149 | 14,709 | 13,154 | 12,806 | 12,975 | 13,180 | 14,011 | 14,463 | 14,745 | 13,434 | 12,620 | 11,961 | 12,097 |
| General Aviation Aircraft | 663 | 560 | 608 | 642 | 815 | 967 | 972 | 918 | 938 | 932 | 1,231 | 1,527 | 1,643 | 1,486 | 1,706 | 1,447 | 1,435 | 1,433 |
| Military Aircraft | 3,583 | 2,495 | 2,384 | 2,174 | 2,221 | 2,132 | 2,167 | 2,359 | 2,110 | 2,123 | 2,185 | 1,860 | 1,679 | 1,656 | 1,667 | 1,434 | 1,283 | 1,166 |
| **Aviation Gasoline[d]** | **374** | **329** | **311** | **330** | **295** | **326** | **302** | **291** | **281** | **251** | **260** | **294** | **278** | **263** | **235** | **221** | **225** | **225** |
| General Aviation Aircraft | 374 | 329 | 311 | 330 | 295 | 326 | 302 | 291 | 281 | 251 | 260 | 294 | 278 | 263 | 235 | 221 | 225 | 225 |
| **Residual Fuel Oil[d, e]** | **2,006** | **2,587** | **2,104** | **912** | **527** | **1,174** | **2,963** | **1,066** | **1,522** | **662** | **1,245** | **1,713** | **2,046** | **2,579** | **1,770** | **1,372** | **1,715** | **1,791** |
| Ships and Other Boats | 2,006 | 2,587 | 2,104 | 912 | 527 | 1,174 | 2,963 | 1,066 | 1,522 | 662 | 1,245 | 1,713 | 2,046 | 2,579 | 1,770 | 1,372 | 1,715 | 1,791 |
| **Natural Gas[d]** (million cubic feet) | **0.7** | **0.7** | **0.7** | **0.8** | **0.6** | **0.7** | **0.7** | **0.6** | **0.7** | **0.6** | **0.6** | **0.6** | **0.6** | **0.6** | **0.7** | **0.7** | **0.7** | **0.7** |
| Passenger Cars | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Light-Duty Trucks | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Buses | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Pipelines | 0.7 | 0.7 | 0.7 | 0.8 | 0.6 | 0.7 | 0.6 | 0.6 | 0.7 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 |
| **LPG[d]** | **265** | **206** | **182** | **165** | **205** | **166** | **138** | **159** | **166** | **191** | **222** | **327** | **320** | **257** | **468** | **331** | **347** | **366** |
| Buses | 0.0 | 1.6 | 3.4 | 3.0 | 3.6 | 2.4 | 1.5 | 0.3 | 0.6 | 0.7 | 0.7 | 1.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Light-Duty Trucks | 106 | 98 | 87 | 80 | 100 | 91 | 88 | 108 | 117 | 134 | 167 | 247 | 229 | 185 | 340 | 228 | 242 | 255 |
| Medium- and Heavy-Duty Trucks | 159 | 106 | 91 | 82 | 102 | 72 | 49 | 51 | 49 | 57 | 55 | 79 | 89 | 72 | 128 | 103 | 105 | 111 |
| **Electricity[d]** | **4,751** | **4,975** | **4,923** | **4,907** | **4,962** | **5,126** | **5,382** | **5,724** | **5,517** | **6,810** | **7,224** | **7,506** | **7,358** | **8,173** | **7,700** | **7,781** | **7,712** | **7,606** |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rail | 4,751 | 4,975 | 4,923 | 4,907 | 4,962 | 5,126 | 5,382 | 5,724 | 5,517 | 6,810 | 7,224 | 7,506 | 7,358 | 8,173 | 7,700 | 7,781 | 7,712 | 7,606 |

[a] In 2011, FHWA changed how vehicles are classified, moving form a system based on body-type to one that is based on wheelbase. This change in methodology in FHWA's VM-1 table resulted in large changes in fuel consumption data by vehicle class.

[b] Figures do not include ethanol blended in motor gasoline. Net carbon fluxes associated with ethanol are accounted for in the Land Use, Land-Use Change and Forestry chapter.

[c] Fluctuations in recreational boat gasoline estimates reflect the use of this category to reconcile bottom-up values with EIA total gasoline estimates.

[d] Estimated based on EIA transportation sector energy estimates by fuel type, with bottom-up activity data used for apportionment to modes.

[e] Fluctuations in reported fuel consumption may reflect data collection problems. The residual fuel oil for ships and other boats data is based on EIA's December 2011 Monthly Energy Review data.

[f] VMT and fuel use by vehicle class (VM-1 table) were not available from FHWA for 2011, but trends in overall diesel and gasoline consumption were released in FHWA's Table MF-21 and MF-27. Fuel use in vehicle classes that are predominantly gasoline was estimated to fall by the rate of decrease in gasoline consumption between 2010 and 2011. Fuel use in vehicle classes that were predominantly diesel was estimated to grow by the same rate of diesel fuel consumption increase in 2011. VMT was then distributed to vehicle classes based on these fuel consumption estimates, assuming no relative change in MPG between vehicle classes.

+ Less than 0.05 million gallons or 0.05 million cubic feet

- Unreported or zero

Table A-90: Energy Consumption by Fuel and Vehicle Type (Tbtu)

| Fuel/Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007[a] | 2008[a] | 2009[a] | 2010[a] | 2011[f] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Motor Gasoline[b]** | **13,813** | **14,679** | **14,979** | **15,147** | **15,583** | **15,913** | **16,015** | **16,198** | **16,524** | **16,600** | **16,850** | **16,730** | **16,517** | **16,470** | **15,844** | **15,818** | **15,769** | **15,424** |
| Passenger Cars | 8,725 | 8,437 | 8,569 | 8,568 | 8,848 | 9,075 | 9,038 | 9,113 | 9,289 | 9,004 | 8,968 | 9,268 | 8,901 | 11,158 | 10,731 | 10,687 | 10,642 | 10,395 |
| Light-Duty Trucks | 4,340 | 5,509 | 5,707 | 5,899 | 6,040 | 6,315 | 6,298 | 6,358 | 6,503 | 6,937 | 7,216 | 6,743 | 6,890 | 4,399 | 4,190 | 4,263 | 4,266 | 4,167 |
| Motorcycles | 24 | 25 | 24 | 25 | 26 | 26 | 26 | 24 | 24 | 23 | 24 | 23 | 26 | 59 | 62 | 60 | 53 | 52 |
| Buses | 5 | 5 | 5 | 5 | 5 | 6 | 5 | 5 | 5 | 4 | 6 | 5 | 5 | 10 | 11 | 11 | 11 | 11 |
| Medium- and Heavy-Duty Trucks | 544 | 506 | 494 | 484 | 491 | 498 | 508 | 495 | 501 | 431 | 436 | 492 | 498 | 650 | 661 | 611 | 613 | 618 |
| Recreational Boats[c] | 175 | 197 | 180 | 166 | 174 | -8 | 139 | 204 | 203 | 202 | 200 | 199 | 196 | 193 | 189 | 187 | 184 | 182 |
| **Distillate Fuel Oil (Diesel Fuel)** | **3,555** | **4,383** | **4,599** | **4,802** | **4,955** | **5,251** | **5,442** | **5,417** | **5,596** | **5,711** | **5,918** | **6,194** | **6,359** | **6,440** | **5,996** | **5,450** | **5,674** | **5,891** |
| Passenger Cars | 107 | 106 | 91 | 82 | 76 | 59 | 49 | 50 | 51 | 57 | 58 | 57 | 56 | 56 | 50 | 49 | 51 | 50 |
| Light-Duty Trucks | 155 | 201 | 212 | 220 | 233 | 256 | 272 | 281 | 296 | 368 | 391 | 349 | 362 | 184 | 164 | 164 | 170 | 167 |
| Buses | 108 | 118 | 123 | 125 | 128 | 143 | 138 | 126 | 119 | 129 | 183 | 143 | 145 | 215 | 205 | 191 | 191 | 193 |
| Medium- and Heavy-Duty Trucks | 2,576 | 3,223 | 3,396 | 3,596 | 3,766 | 3,999 | 4,186 | 4,178 | 4,357 | 4,374 | 4,521 | 4,876 | 5,004 | 5,200 | 4,950 | 4,491 | 4,677 | 4,730 |
| Recreational Boats | 26 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 45 | 12 | 47 | 48 | 49 |
| Ships and Other Boats | 102 | 167 | 199 | 198 | 166 | 186 | 191 | 173 | 167 | 163 | 112 | 109 | 101 | 111 | 30 | 18 | 10 | 148 |
| Rail | 480 | 536 | 546 | 547 | 551 | 572 | 569 | 571 | 567 | 579 | 611 | 617 | 647 | 630 | 585 | 490 | 528 | 555 |
| **Jet Fuel[c]** | **2,183** | **2,101** | **2,142** | **2,181** | **2,163** | **2,329** | **2,409** | **2,218** | **2,140** | **2,164** | **2,240** | **2,349** | **2,401** | **2,415** | **2,269** | **2,093** | **1,982** | **1,984** |
| Commercial Aircraft | 1,610 | 1,689 | 1,738 | 1,800 | 1,754 | 1,910 | 1,986 | 1,776 | 1,729 | 1,752 | 1,779 | 1,892 | 1,952 | 1,991 | 1,814 | 1,704 | 1,615 | 1,633 |
| General Aviation Aircraft | 89 | 76 | 82 | 87 | 110 | 131 | 131 | 124 | 127 | 126 | 166 | 206 | 222 | 201 | 230 | 195 | 194 | 194 |
| Military Aircraft | 484 | 337 | 322 | 293 | 300 | 288 | 293 | 318 | 285 | 287 | 295 | 251 | 227 | 224 | 225 | 194 | 173 | 157 |
| **Aviation Gasoline[d]** | **45** | **40** | **37** | **40** | **35** | **39** | **36** | **35** | **34** | **30** | **31** | **35** | **33** | **32** | **28** | **27** | **27** | **27** |
| General Aviation Aircraft | 45 | 40 | 37 | 40 | 35 | 39 | 36 | 35 | 34 | 30 | 31 | 35 | 33 | 32 | 28 | 27 | 27 | 27 |
| **Residual Fuel Oil[d, e]** | **300** | **387** | **315** | **137** | **79** | **176** | **443** | **159** | **228** | **99** | **186** | **256** | **306** | **386** | **265** | **205** | **257** | **268** |
| Ships and Other Boats | 300 | 387 | 315 | 137 | 79 | 176 | 443 | 159 | 228 | 99 | 186 | 256 | 306 | 386 | 265 | 205 | 257 | 268 |
| **Natural Gas[d]** | **680** | **724** | **737** | **780** | **666** | **675** | **672** | **658** | **699** | **627** | **602** | **624** | **625** | **663** | **692** | **715** | **716** | **733** |
| Passenger Cars | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Light-Duty Trucks | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Buses | 0 | 1 | 2 | 3 | 4 | 6 | 8 | 9 | 12 | 14 | 16 | 16 | 16 | 19 | 21 | 22 | 20 | 20 |
| Pipelines | 680 | 721 | 734 | 776 | 661 | 670 | 664 | 649 | 687 | 614 | 586 | 608 | 609 | 645 | 672 | 693 | 696 | 713 |
| **LPG[d]** | **23** | **18** | **16** | **14** | **18** | **14** | **12** | **14** | **14** | **17** | **19** | **28** | **27** | **22** | **40** | **28** | **29** | **31** |
| Buses | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Light-Duty Trucks | 9 | 8 | 7 | 7 | 9 | 8 | 8 | 9 | 10 | 12 | 14 | 21 | 20 | 16 | 29 | 19 | 20 | 21 |
| Medium- and Heavy-Duty Trucks | 14 | 9 | 8 | 7 | 9 | 6 | 4 | 4 | 4 | 5 | 5 | 7 | 8 | 6 | 11 | 9 | 9 | 9 |

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Electricity**[d] | **16** | | **17** | **17** | **17** | **17** | **17** | **18** | **20** | **19** | **23** | **25** | **26** | **25** | **28** | **26** | **27** | **26** | **26** |
| Rail | 16 | | 17 | 17 | 17 | 17 | 17 | 18 | 20 | 19 | 23 | 25 | 26 | 25 | 28 | 26 | 27 | 26 | 26 |
| **Total** | **20,615** | | **22,349** | **22,842** | **23,118** | **23,517** | **24,415** | **25,049** | **24,719** | **25,254** | **25,272** | **25,872** | **26,242** | **26,294** | **26,456** | **25,161** | **24,362** | **24,480** | **24,384** |

[a] In 2011, FHWA changed how vehicles are classified, moving form a system based on body-type to one that is based on wheelbase. This change in methodology in FHWA's VM-1 table resulted in large changes in fuel consumption data by vehicle class.

[b] Figures do not include ethanol blended in motor gasoline. Net carbon fluxes associated with ethanol are accounted for in the Land Use, Land-Use Change and Forestry chapter.

[c] Fluctuations in recreational boat gasoline estimates reflect the use of this category to reconcile bottom-up values with EIA total gasoline estimates.

[d] Estimated based on EIA transportation sector energy estimates, with bottom-up data used for apportionment to modes.

[e] Fluctuations in reported fuel consumption may reflect data collection problems. The residual fuel oil for ships and other boats data is based on EIA's December 2011 Monthly Energy Review data.

[f] VMT and fuel use by vehicle class (VM-1 table) were not available from FHWA for 2011, but trends in overall diesel and gasoline consumption were released in FHWA's Table MF-21 and MF-27. Fuel use in vehicle classes that are predominantly gasoline was estimated to fall by the rate of decrease in gasoline consumption between 2010 and 2011. Fuel use in vehicle classes that were predominantly diesel was estimated to grow by the same rate of diesel fuel consumption increase in 2011. VMT was then distributed to vehicle classes based on these fuel consumption estimates, assuming no relative change in MPG between vehicle classes.

- Unreported or zero

Table A-91. Biofuel Consumption by Fuel Type (million gallons)

| **Fuel Type** | **1990** | | **1995** | **1996** | **1997** | **1998** | **1999** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ethanol** | 712.6 | | 1,327 | 951 | 1,203 | 1,331 | 1,389 | 1,591 | 1,661 | 1,977 | 2,690 | 3,377 | 3,862 | 5,210 | 6,567 | 9,269 | 10,543 | 12,271 | 12,290 |
| **Biodiesel** | NA | | NA | NA | NA | NA | NA | NA | 10 | 16 | 14 | 27 | 91 | 261 | 358 | 316 | 329 | 266 | 878 |

## Estimates of $CH_4$ and $N_2O$ Emissions

Mobile source emissions of greenhouse gases other than $CO_2$ are reported by transport mode (e.g., road, rail, aviation, and waterborne), vehicle type, and fuel type. Emissions estimates of $CH_4$ and $N_2O$ were derived using a methodology similar to that outlined in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997).

Activity data were obtained from a number of U.S. government agencies and other publications. Depending on the category, these basic activity data included fuel consumption and vehicle miles traveled (VMT). These estimates were then multiplied by emission factors, expressed as grams per unit of fuel consumed or per vehicle mile.

### Methodology for On-Road Gasoline and Diesel Vehicles

#### Step 1: Determine Vehicle Miles Traveled by Vehicle Type, Fuel Type, and Model Year

VMT by vehicle type (e.g., passenger cars, light-duty trucks, medium- and heavy-duty trucks,[41] buses, and motorcycles) were obtained from the Federal Highway Administration's (FHWA) *Highway Statistics* (FHWA 1996 through 2013)[42]. As these vehicle categories are not fuel-specific, VMT for each vehicle type was disaggregated by fuel type (gasoline, diesel) so that the appropriate emission factors could be applied. VMT from *Highway Statistics* Table VM-1 (FHWA 1996 through 2013) was allocated to fuel types (gasoline, diesel, other) using historical estimates of fuel shares reported in the Appendix to the *Transportation Energy Data Book* (DOE 1993 through 2012). These fuel shares are drawn from various sources, including the Vehicle Inventory and Use Survey, the National Vehicle Population Profile, and the American Public Transportation Association. The fuel shares were first adjusted proportionately so that the gasoline and diesel shares for each vehicle type summed to 100 percent in order to develop an interim estimate of VMT for each vehicle/fuel type category that summed to the total national VMT estimate. VMT for alternative fuel vehicles (AFVs) was calculated separately, and the methodology is explained in the following section on AFVs. Estimates of VMT from AFVs were then subtracted from the appropriate interim VMT estimates to develop the final VMT estimates by vehicle/fuel type category.[43] The resulting national VMT estimates for gasoline and diesel on-road vehicles are presented in Table A- 92 and Table A- 93, respectively.

Total VMT for each on-road category (i.e., gasoline passenger cars, light-duty gasoline trucks, heavy-duty gasoline vehicles, diesel passenger cars, light-duty diesel trucks, medium- and heavy-duty diesel vehicles, and motorcycles) were distributed across 31 model years shown for 2011 in Table A- 96. Distributions for 1990-2011 are presented in the Inventory Docket. This distribution was derived by weighting the appropriate age distribution of the U.S. vehicle fleet according to vehicle registrations by the average annual age-specific vehicle mileage accumulation of U.S. vehicles. Age distribution values were obtained from EPA's MOBILE6 model for all years before 1999 (EPA 2000) and EPA's MOVES model for years 1999 forward (EPA 2012a).[44] Age-specific vehicle mileage accumulation was obtained from EPA's MOBILE6 model (EPA 2000).

#### Step 2: Allocate VMT Data to Control Technology Type

VMT by vehicle type for each model year was distributed across various control technologies as shown in Table A- 100

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[41] Medium-duty trucks include vehicles with a gross vehicle weight rating (GVWR) of 8,500 to 14,000 lbs. while heavy-duty trucks include those with a GVWR of over 14,000 lbs.

[42] In 2011 FHWA changed how they defined vehicle types for the purposes of reporting VMT for the years 2007-2010. The old approach to vehicle classification was based on body type and split passenger vehicles into "Passenger Cars" and "Other 2 Axle 4-Tire Vehicles". The new approach is a vehicle classification system based on wheelbase. Vehicles with a wheelbase less than or equal to 121 inches are counted as "Light-duty Vehicles –Short Wheelbase". Passenger vehicles with a Wheelbase greater than 121 inches are counted as "Light-duty Vehicles - Long Wheelbase". This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this emission inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

[43] In Inventories through 2002, gasoline-electric hybrid vehicles were considered part of an "alternative fuel and advanced technology" category. However, vehicles are now only separated into gasoline, diesel, or alternative fuel categories, and gas-electric hybrids are now considered within the gasoline vehicle category.

[44] Age distributions were held constant for the period 1990-1998, and reflect a 25-year vehicle age span. EPA (2010) provides a variable age distribution and 31-year vehicle age span beginning in year 1999.

through Table A- 103. The categories "EPA Tier 0" and "EPA Tier 1" were used instead of the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the *Revised 1996 IPCC Guidelines*. EPA Tier 0, EPA Tier 1, EPA Tier 2, and LEV refer to U.S. emission regulations, rather than control technologies; however, each does correspond to particular combinations of control technologies and engine design. EPA Tier 2 and its predecessors EPA Tier 1 and Tier 0 apply to vehicles equipped with three-way catalysts. The introduction of "early three-way catalysts," and "advanced three-way catalysts," as described in the *Revised 1996 IPCC Guidelines*, roughly correspond to the introduction of EPA Tier 0 and EPA Tier 1 regulations (EPA 1998).[45] EPA Tier 2 regulations affect vehicles produced starting in 2004 and are responsible for a noticeable decrease in $N_2O$ emissions compared EPA Tier 1 emissions technology (EPA 1999b).

Control technology assignments for light and heavy-duty conventional fuel vehicles for model years 1972 (when regulations began to take effect) through 1995 were estimated in EPA (1998). Assignments for 1998 through 2007 were determined using confidential engine family sales data submitted to EPA (EPA 2007b). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2007a). This information was used to determine the fraction of sales of each class of vehicle that met EPA Tier 0, EPA Tier 1, Tier 2, and LEV standards. Assignments for 1996 and 1997 were estimated based on the fact that EPA Tier 1 standards for light-duty vehicles were fully phased in by 1996. Tier 2 began initial phase-in by 2004.

#### Step 3: Determine $CH_4$ and $N_2O$ Emission Factors by Vehicle, Fuel, and Control Technology Type

Emission factors for gasoline and diesel on-road vehicles were developed by ICF (2004). These factors were based on EPA and CARB laboratory test results of different vehicle and control technology types. The EPA and CARB tests were designed following the Federal Test Procedure (FTP), which covers three separate driving segments, since vehicles emit varying amounts of GHGs depending on the driving segment. These driving segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions only, and (3) a transient driving cycle that includes hot start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was later analyzed to determine quantities of gases present. The emission characteristics of segment 2 was used to define running emissions, and subtracted from the total FTP emissions to determine start emissions. These were then recombined based upon MOBILE6.2's ratio of start to running emissions for each vehicle class to approximate average driving characteristics.

#### Step 4: Determine the Amount of $CH_4$ and $N_2O$ Emitted by Vehicle, Fuel, and Control Technology Type

Emissions of $CH_4$ and $N_2O$ were then calculated by multiplying total VMT by vehicle, fuel, and control technology type by the emission factors developed in Step 3.

### Methodology for Alternative Fuel Vehicles (AFVs)

#### Step 1: Determine Vehicle Miles Traveled by Vehicle and Fuel Type

VMT for alternative fuel and advanced technology vehicles were calculated from "VMT Projections for Alternative Fueled and Advanced Technology Vehicles through 2025" (Browning 2003). Alternative Fuels include Compressed Natural Gas (CNG), Liquid Natural Gas (LNG), Liquefied Petroleum Gas (LPG), Ethanol, Methanol, and Electric Vehicles (battery powered). Most of the vehicles that use these fuels run on an Internal Combustion Engine (ICE) powered by the alternative fuel, although many of the vehicles can run on either the alternative fuel or gasoline (or diesel), or some combination.[46] The data obtained include vehicle fuel use and total number of vehicles in use from 1992 through 2007. Because AFVs run on different fuel types, their fuel use characteristics are not directly comparable. Accordingly, fuel economy for each vehicle type is expressed in gasoline equivalent terms, i.e., how much gasoline contains the equivalent amount of energy as the alternative fuel. Energy economy ratios (the ratio of the gasoline equivalent fuel economy of a given technology to that of conventional gasoline or diesel vehicles) were taken from full fuel cycle studies done for the California Air Resources Board (Unnasch and Browning, Kassoy 2001). These ratios were used to estimate fuel economy in miles per gasoline gallon equivalent for each alternative fuel and vehicle type. Energy use per fuel type was then divided among the various weight categories and vehicle technologies that use that fuel. Total VMT per vehicle

[45] For further description, see "Definitions of Emission Control Technologies and Standards" section of this annex.

[46] Fuel types used in combination depend on the vehicle class. For light-duty vehicles, gasoline is generally blended with ethanol or methanol; some vehicles are also designed to run on gasoline or an alternative fuel – either natural gas or LPG – but not at the same time, while other vehicles are designed to run on E85 (85% ethanol) or gasoline, or any mixture of the two. Heavy-duty vehicles are more likely to run on a combination of diesel fuel and either natural gas, LPG, ethanol, or methanol.

type for each calendar year was then determined by dividing the energy usage by the fuel economy. Note that for AFVs capable of running on both/either traditional and alternative fuels, the VMT given reflects only those miles driven that were powered by the alternative fuel, as explained in Browning (2003). VMT estimates for AFVs by vehicle category (passenger car, light-duty truck, heavy-duty vehicles) are shown in Table A- 94, while more detailed estimates of VMT by control technology are shown in Table A- 95.

#### Step 2: Determine $CH_4$ and $N_2O$ Emission Factors by Vehicle and Alternative Fuel Type

$CH_4$ and $N_2O$ emission factors for alternative fuel vehicles (AFVs) are calculated according to studies by Argonne National Laboratory (2006) and Lipman & Delucchi (2002), and are reported in ICF (2006a). In these studies, $N_2O$ and $CH_4$ emissions for AFVs were expressed as a multiplier corresponding to conventional vehicle counterpart emissions. Emission estimates in these studies represent the current AFV fleet and were compared against Tier 1 emissions from light-duty gasoline vehicles to develop new multipliers. Alternative fuel heavy-duty vehicles were compared against gasoline heavy-duty vehicles as most alternative fuel heavy-duty vehicles use catalytic after treatment and perform more like gasoline vehicles than diesel vehicles. These emission factors are shown in Table A- 105.

#### Step 3: Determine the Amount of $CH_4$ and $N_2O$ Emitted by Vehicle and Fuel Type

Emissions of $CH_4$ and $N_2O$ were calculated by multiplying total VMT for each vehicle and fuel type (Step 1) by the appropriate emission factors (Step 2).

#### Methodology for Non-Road Mobile Sources

$CH_4$ and $N_2O$ emissions from non-road mobile sources were estimated by applying emission factors to the amount of fuel consumed by mode and vehicle type.

Activity data for non-road vehicles include annual fuel consumption statistics by transportation mode and fuel type, as shown in Table A- 99. Consumption data for ships and other boats (i.e., vessel bunkering) were obtained from DHS (2008) and EIA (1991 through 2012) for distillate fuel, and DHS (2008) and EIA (2012a) for residual fuel; marine transport fuel consumption data for U.S. territories (EIA 2008b, EIA 1991 through 2012) were added to domestic consumption, and this total was reduced by the amount of fuel used for international bunkers.[47] Gasoline consumption by recreational boats was obtained from EPA's NONROAD model (EPA 2012b). Annual diesel consumption for Class I rail was obtained from the Association of American Railroads (AAR) (2008-2012), diesel consumption from commuter rail was obtained from APTA (2007 through 2012) and Gaffney (2007), and consumption by Class II and III rail was provided by Benson (2002 through 2004) and Whorton (2006 through 2012). Diesel consumption by commuter and intercity rail was obtained from DOE (1993 through 2012). Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from EIA (2011), as described in Annex 2.1: Methodology for Estimating Emissions of $CO_2$ from Fossil Fuel Combustion, and were reduced by the amount allocated to international bunker fuels. Pipeline fuel consumption was obtained from EIA (2007 through 2011) (note: pipelines are a transportation source but are stationary, not mobile, sources). Data on fuel consumption by all non-transportation mobile sources[48] were obtained from EPA's NONROAD model (EPA 2011b) and from FHWA (1996 through 2013) for gasoline consumption for trucks used off-road.

Emissions of $CH_4$ and $N_2O$ from non-road mobile sources were calculated by multiplying U.S. default emission factors in the *Revised 1996 IPCC Guidelines* (IPCC/UNEP/OECD/IEA 1997) by activity data for each source type (see Table A- 106).

### Estimates of $NO_x$, CO, and NMVOC Emissions

The emission estimates of $NO_x$, CO, and NMVOCs from mobile combustion (transportation) were obtained from preliminary data (EPA 2010, EPA 2009), which, in final iteration, will be published on the EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends web site. This EPA report provides emission estimates for these gases by fuel type using a procedure whereby emissions were calculated using basic activity data, such as amount of fuel delivered or miles traveled, as indicators of emissions.

[47] See International Bunker Fuels section of the Energy Chapter.

[48] "Non-transportation mobile sources" are defined as any vehicle or equipment not used on the traditional road system, but excluding aircraft, rail and watercraft. This category includes snowmobiles, golf carts, riding lawn mowers, agricultural equipment, and trucks used for off-road purposes, among others.

Table A- 107 through Table A- 109 provides complete emission estimates for 1990 through 2011.

Table A- 92: Vehicle Miles Traveled for Gasoline On-Road Vehicles ($10^9$ Miles)

| Year | Passenger Cars | Light-Duty Trucks | Heavy-Duty Vehicles | Motorcycles |
|---|---|---|---|---|
| 1990 | 1,391.2 | 554.3 | 25.4 | 9.6 |
| 1991 | 1,341.7 | 627.2 | 25.0 | 9.2 |
| 1992 | 1,354.8 | 682.9 | 24.8 | 9.6 |
| 1993 | 1,356.5 | 720.5 | 24.5 | 9.9 |
| 1994 | 1,387.5 | 738.8 | 25.0 | 10.2 |
| 1995 | 1,420.6 | 762.5 | 24.7 | 9.8 |
| 1996 | 1,454.7 | 788.0 | 24.0 | 9.9 |
| 1997 | 1,488.5 | 820.8 | 23.6 | 10.1 |
| 1998 | 1,536.6 | 836.8 | 23.6 | 10.3 |
| 1999 | 1,559.1 | 867.4 | 23.8 | 10.6 |
| 2000 | 1,591.5 | 886.7 | 23.6 | 10.5 |
| 2001 | 1,619.3 | 904.9 | 23.2 | 9.6 |
| 2002 | 1,649.2 | 925.8 | 23.1 | 9.6 |
| 2003 | 1,662.6 | 943.0 | 23.5 | 9.6 |
| 2004 | 1,690.2 | 984.2 | 23.9 | 10.1 |
| 2005 | 1,698.8 | 997.8 | 24.2 | 10.5 |
| 2006 | 1,681.0 | 1,037.5 | 24.4 | 12.0 |
| 2007[a] | 2,092.8 | 561.6 | 33.7 | 21.4 |
| 2008[a] | 2,013.6 | 579.6 | 34.5 | 20.8 |
| 2009[a] | 2,004.6 | 591.2 | 32.1 | 20.8 |
| 2010[a] | 2,014.2 | 595.4 | 31.9 | 18.5 |
| 2011[b] | 1,983.6 | 586.0 | 32.4 | 18.2 |

Source: Derived from FHWA (1996 through 2013).

[a] In 2011, FHWA changed how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This change in methodology in FHWA's VM-1 table resulted in large changes in VMT by vehicle class,

[b] VMT and fuel use by vehicle class (VM-1 table) were not available from FHWA for 2011, but trends in overall diesel and gasoline consumption were released in FHWA's Table MF-21 and MF-27. Fuel use in vehicle classes that are predominantly gasoline was estimated to fall by the rate of decrease in gasoline consumption between 2010 and 2011. Fuel use in vehicle classes that were predominantly diesel was estimated to grow by the same rate of diesel fuel consumption increase in 2011. VMT was then distributed to vehicle classes based on these fuel consumption estimates, assuming no relative change in MPG between vehicle classes.

Table A- 93: Vehicle Miles Traveled for Diesel On-Road Vehicles ($10^9$ Miles)

| Year | Passenger Cars | Light-Duty Trucks | Heavy-Duty Vehicles |
|---|---|---|---|
| 1990 | 16.9 | 19.7 | 125.5 |
| 1991 | 16.3 | 21.6 | 129.3 |
| 1992 | 16.5 | 23.4 | 133.5 |
| 1993 | 17.9 | 24.7 | 140.3 |
| 1994 | 18.3 | 25.3 | 150.5 |
| 1995 | 17.3 | 26.9 | 158.7 |
| 1996 | 14.7 | 27.8 | 164.3 |
| 1997 | 13.5 | 29.0 | 173.4 |
| 1998 | 12.4 | 30.5 | 178.4 |
| 1999 | 9.4 | 32.6 | 185.3 |
| 2000 | 8.0 | 35.2 | 188.0 |
| 2001 | 8.1 | 37.0 | 191.1 |
| 2002 | 8.3 | 38.9 | 196.4 |
| 2003 | 8.3 | 39.7 | 199.1 |
| 2004 | 8.4 | 41.3 | 201.6 |
| 2005 | 8.4 | 41.9 | 202.6 |
| 2006 | 8.3 | 43.5 | 201.0 |
| 2007[a] | 10.3 | 23.4 | 280.1 |
| 2008[a] | 9.9 | 24.2 | 286.4 |
| 2009[a] | 9.8 | 24.7 | 265.8 |
| 2010[a] | 9.9 | 24.9 | 264.3 |
| 2011[b] | 9.8 | 24.5 | 268.5 |

Source: Derived from FHWA (1996 through 2013).

[a] In 2011, FHWA changed how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This change in methodology in FHWA's VM-1 table resulted in large changes in VMT by vehicle class

[b] VMT and fuel use by vehicle class (VM-1 table) were not available from FHWA for 2011, but trends in overall diesel and gasoline consumption were released in FHWA's Table MF-21 and MF-27. Fuel use in vehicle classes that are predominantly gasoline was estimated to fall by the rate of decrease in gasoline consumption between 2010 and 2011. Fuel use in vehicle classes that were predominantly diesel was estimated to grow by the same rate of diesel fuel consumption increase in 2011. VMT was then distributed to vehicle classes based on these fuel consumption estimates, assuming no relative change in MPG between vehicle classes.

Table A- 94: Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles ($10^9$ Miles)

| Year | Passenger Cars | Light-Duty Trucks | Heavy-Duty Vehicles |
|---|---|---|---|
| 1990 | 0.2 | 0.0 | 0.1 |
| 1991 | 0.2 | 0.0 | 0.1 |
| 1992 | 0.3 | 0.0 | 0.1 |
| 1993 | 0.3 | 0.0 | 0.1 |
| 1994 | 0.3 | 0.0 | 0.1 |
| 1995 | 0.4 | 0.0 | 0.1 |
| 1996 | 0.5 | 0.0 | 0.1 |
| 1997 | 0.6 | 0.0 | 0.1 |
| 1998 | 0.6 | 0.0 | 0.1 |
| 1999 | 0.6 | 0.0 | 0.1 |
| 2000 | 0.8 | 0.0 | 0.1 |
| 2001 | 0.9 | 0.0 | 0.1 |
| 2002 | 1.0 | 0.0 | 0.1 |
| 2003 | 1.2 | 0.0 | 0.1 |
| 2004 | 1.3 | 0.0 | 0.1 |
| 2005 | 1.2 | 0.0 | 0.1 |
| 2006 | 1.3 | 0.0 | 0.1 |
| 2007 | 1.3 | 0.0 | 0.1 |
| 2008 | 1.3 | 0.0 | 0.1 |
| 2009 | 1.2 | 0.0 | 0.1 |
| 2010 | 1.3 | 0.0 | 0.1 |
| 2011 | 1.4 | 0.0 | 0.1 |

Source: Derived from Browning (2003).

Table A- 95: Detailed Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles ($10^6$ Miles)

| Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005[a] | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Passenger Cars** | **206.3** | **400.6** | **462.7** | **558.1** | **567.3** | **571.4** | **788.1** | **922.0** | **1,042.4** | **1,172.9** | **1,273.0** | **1,243.1** | **1,296.4** | **1,295.4** | **1,286.4** | **1,242.1** | **1,252.2** | **1,404.4** |
| Methanol-Flex Fuel ICE | 0.0 | 40.9 | 36.4 | 33.2 | 26.2 | 23.5 | 13.2 | 10.1 | 7.8 | 6.4 | 3.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Ethanol-Flex Fuel ICE | 0.0 | 2.2 | 6.7 | 12.3 | 14.7 | 38.2 | 120.4 | 147.9 | 189.1 | 271.2 | 311.5 | 391.7 | 412.8 | 448.6 | 459.9 | 488.4 | 546.0 | 627.6 |
| CNG ICE | 10.6 | 28.0 | 39.6 | 46.3 | 56.7 | 60.4 | 68.9 | 78.1 | 83.0 | 85.0 | 112.1 | 62.6 | 62.5 | 58.4 | 53.0 | 47.3 | 50.4 | 53.6 |
| CNG Bi-fuel | 28.2 | 75.1 | 107.5 | 160.7 | 164.2 | 181.7 | 202.9 | 236.6 | 267.2 | 283.5 | 274.1 | 187.6 | 193.8 | 180.0 | 170.9 | 159.7 | 163.2 | 166.7 |
| LPG ICE | 20.6 | 40.3 | 43.0 | 45.2 | 52.8 | 37.9 | 41.9 | 45.0 | 48.8 | 43.1 | 37.4 | 40.7 | 37.3 | 24.6 | 25.9 | 14.2 | 11.9 | 9.5 |
| LPG Bi-fuel | 146.9 | 201.7 | 215.0 | 231.6 | 211.1 | 171.8 | 197.6 | 224.8 | 237.9 | 221.9 | 199.4 | 207.1 | 186.4 | 121.4 | 129.7 | 88.7 | 83.1 | 71.5 |
| Biodiesel (BD20) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 8.2 | 8.3 | 13.4 | 13.6 | 62.3 | 125.1 | 186.4 | 246.1 | 235.8 | 236.6 | 189.9 | 190.6 |
| NEVs | 0.0 | 5.2 | 6.5 | 13.0 | 18.2 | 28.2 | 62.4 | 88.4 | 98.8 | 114.4 | 124.8 | 104.2 | 99.2 | 99.4 | 99.1 | 97.1 | 97.7 | 98.1 |
| Electric Vehicle | 0.0 | 7.2 | 8.1 | 15.8 | 23.5 | 29.6 | 72.6 | 82.8 | 96.3 | 133.8 | 147.8 | 124.2 | 118.1 | 116.9 | 112.0 | 110.0 | 109.8 | 186.7 |
| **Light-Duty Trucks** | **660.7** | **606.8** | **721.2** | **920.3** | **999.3** | **1,016.8** | **1,162.0** | **1,235.1** | **1,344.2** | **1,447.5** | **1,567.3** | **1,395.2** | **1,504.6** | **1,560.0** | **1,704.4** | **1,708.9** | **1,994.5** | **2,302.9** |
| Ethanol-Flex Fuel ICE | 0.0 | 1.3 | 6.1 | 12.1 | 18.2 | 38.3 | 122.6 | 150.1 | 179.1 | 279.1 | 353.7 | 415.0 | 491.4 | 613.9 | 766.6 | 923.2 | 1,261.7 | 1,605.2 |
| CNG ICE | 10.9 | 29.6 | 42.1 | 107.8 | 130.4 | 143.5 | 145.9 | 145.7 | 153.4 | 158.0 | 162.2 | 65.5 | 65.5 | 64.7 | 63.0 | 58.2 | 60.7 | 66.4 |
| CNG Bi-fuel | 24.2 | 71.0 | 102.9 | 210.4 | 234.6 | 267.1 | 280.1 | 280.1 | 301.2 | 313.4 | 330.0 | 171.4 | 178.6 | 175.4 | 169.6 | 157.5 | 161.6 | 166.1 |
| LPG ICE | 56.9 | 48.5 | 56.5 | 58.2 | 60.3 | 47.8 | 58.4 | 64.4 | 68.2 | 64.9 | 61.5 | 60.1 | 60.1 | 43.8 | 43.8 | 33.0 | 30.3 | 27.7 |
| LPG Bi-fuel | 568.7 | 449.4 | 504.8 | 520.9 | 543.1 | 502.2 | 511.9 | 522.9 | 557.1 | 541.8 | 525.6 | 513.2 | 486.1 | 383.7 | 383.6 | 259.7 | 239.9 | 207.3 |
| Biodiesel (BD20) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 8.2 | 8.4 | 17.1 | 16.9 | 55.9 | 109.4 | 163.8 | 219.2 | 219.0 | 219.8 | 176.5 | 166.2 |
| Electric Vehicle | 0.0 | 7.1 | 8.9 | 10.9 | 12.7 | 17.9 | 35.0 | 63.4 | 68.2 | 73.4 | 78.3 | 60.1 | 58.4 | 58.0 | 57.5 | 55.8 | 61.9 | 62.1 |
| **Medium-Duty Trucks** | **508.0** | **458.4** | **515.2** | **551.3** | **568.0** | **548.6** | **629.6** | **862.5** | **977.7** | **899.7** | **856.6** | **802.6** | **628.8** | **693.1** | **696.0** | **629.8** | **578.6** | **489.7** |
| CNG Bi-fuel | 2.3 | 20.1 | 57.7 | 68.9 | 78.4 | 95.2 | 117.0 | 203.2 | 228.2 | 245.3 | 241.9 | 146.7 | 112.5 | 154.4 | 188.3 | 178.8 | 187.6 | 199.9 |
| LPG ICE | 24.3 | 20.0 | 20.0 | 21.1 | 21.2 | 20.7 | 29.7 | 41.9 | 48.3 | 43.9 | 40.7 | 40.5 | 33.8 | 31.3 | 35.0 | 31.0 | 29.9 | 25.0 |
| LPG Bi-fuel | 481.4 | 418.3 | 437.5 | 461.3 | 468.4 | 432.7 | 475.9 | 609.7 | 671.8 | 585.0 | 535.7 | 517.2 | 326.5 | 298.2 | 268.7 | 215.2 | 211.7 | 127.4 |
| Biodiesel (BD20) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 7.0 | 7.6 | 29.4 | 25.6 | 38.2 | 98.2 | 156.0 | 209.1 | 204.0 | 204.8 | 149.4 | 137.5 |
| **Heavy-Duty Trucks** | **523.9** | **627.0** | **628.4** | **686.0** | **717.0** | **616.4** | **712.3** | **820.5** | **845.2** | **1,041.2** | **1,093.9** | **1,646.0** | **2,880.1** | **3,653.8** | **3,450.0** | **3,670.8** | **3,113.6** | **3,152.7** |
| Neat Methanol ICE | 3.0 | 7.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Neat Ethanol ICE | 0.0 | 2.0 | 3.4 | 3.5 | 0.2 | 2.9 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 1.7 | 12.1 | 26.1 | 27.9 | 28.2 | 29.3 | 30.8 |
| CNG ICE | 12.7 | 32.2 | 34.1 | 44.8 | 56.1 | 54.2 | 83.7 | 149.0 | 146.3 | 183.6 | 187.7 | 408.0 | 491.8 | 557.2 | 647.6 | 843.7 | 900.0 | 985.0 |
| LPG ICE | 36.3 | 46.3 | 47.7 | 50.1 | 52.5 | 39.2 | 48.3 | 57.1 | 60.9 | 73.4 | 70.8 | 69.0 | 81.9 | 78.4 | 76.9 | 74.7 | 74.4 | 74.6 |
| LPG Bi-fuel | 471.9 | 531.9 | 534.9 | 577.4 | 595.1 | 507.1 | 529.7 | 558.0 | 548.5 | 650.2 | 626.7 | 499.2 | 530.0 | 522.5 | 518.1 | 513.4 | 515.2 | 517.1 |
| LNG | 0.0 | 6.9 | 8.2 | 10.2 | 13.1 | 13.1 | 22.2 | 26.9 | 28.6 | 56.8 | 108.1 | 115.9 | 123.2 | 127.5 | 134.0 | 135.0 | 137.7 | 142.9 |
| Biodiesel (BD20) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 28.3 | 29.5 | 60.9 | 77.1 | 100.6 | 552.2 | 1,641.1 | 2,342.2 | 2,045.4 | 2,075.8 | 1,456.9 | 1,402.4 |
| **Buses** | **41.4** | **80.5** | **87.7** | **90.0** | **95.5** | **103.0** | **111.9** | **133.1** | **140.3** | **139.0** | **229.3** | **250.9** | **407.5** | **471.0** | **482.3** | **501.8** | **496.5** | **508.7** |
| Neat Methanol ICE | 1.9 | 3.7 | 1.3 | 1.4 | 1.8 | 1.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Neat Ethanol ICE | 0.1 | 2.2 | 7.4 | 1.9 | 0.1 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 1.0 | 2.4 | 3.2 | 3.2 | 3.4 | 3.8 |
| CNG ICE | 11.2 | 37.5 | 39.9 | 44.1 | 46.4 | 52.6 | 53.4 | 65.0 | 65.5 | 64.3 | 145.2 | 160.0 | 165.1 | 179.8 | 202.5 | 220.2 | 238.0 | 255.9 |
| LPG ICE | 28.2 | 30.9 | 31.4 | 33.4 | 34.0 | 32.6 | 35.6 | 36.9 | 36.4 | 34.1 | 38.9 | 30.3 | 28.9 | 28.9 | 28.7 | 28.4 | 28.4 | 27.7 |
| LNG | 0.0 | 4.3 | 5.1 | 6.3 | 10.1 | 11.9 | 13.3 | 21.0 | 22.3 | 23.6 | 25.7 | 28.6 | 30.0 | 33.5 | 35.0 | 36.0 | 37.5 | 39.0 |
| Biodiesel (BD20) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.5 | 4.7 | 9.9 | 10.5 | 13.1 | 15.6 | 165.1 | 209.1 | 194.0 | 194.8 | 170.0 | 162.1 |
| Electric | 0.0 | 2.0 | 2.6 | 2.9 | 3.1 | 3.6 | 5.1 | 5.6 | 6.3 | 6.6 | 6.4 | 16.2 | 17.3 | 17.1 | 18.4 | 18.5 | 18.5 | 19.4 |
| **Total VMT** | **1,940.3** | **2,173.4** | **2,415.2** | **2,805.7** | **2,947.1** | **2,856.1** | **3,403.9** | **3,973.1** | **4,349.9** | **4,700.4** | **5,020.2** | **5,337.8** | **6,717.4** | **7,673.3** | **7,619.0** | **7,753.4** | **7,435.4** | **7,858.5** |

Source: Derived from Browning (2003).
Note: Throughout the rest of this Inventory, medium-duty trucks are grouped with heavy-duty trucks; they are reported separately here because these two categories may run on a slightly different range of fuel types.
[a] In 2011, EIA changed its reporting methodology for 2005-2010. EIA provided more detail on alternative fuel vehicle use by vehicle class. The fuel use breakdown by vehicle class had previously been based on estimates of the distribution of fuel use by vehicle class. The new data from EIA allowed actual data to be used for fuel use, and resulted in greater share of heavy-duty AFV VMT estimated for 2005-2010. The source of this data is the U.S. Energy Information Administration, Office of Energy Consumption and Efficiency Statistics and the DOE/GSA Federal Automotive Statistical Tool (FAST).
+ Less than 0.05 million vehicle miles traveled
- Unreported or zero

Table A- 96: Age Distribution by Vehicle/Fuel Type for On-Road Vehicles,[a] 2011

| Vehicle Age | LDGV | LDGT | HDGV | LDDV[b] | LDDT | HDDV | MC |
|---|---|---|---|---|---|---|---|
| 0 | 7.1% | 6.1% | 5.7% | 9.9% | 6.2% | 6.0% | 9.7% |
| 1 | 6.2% | 5.5% | 5.2% | 8.6% | 5.7% | 5.5% | 7.6% |
| 2 | 5.2% | 3.9% | 5.0% | 7.2% | 4.0% | 5.4% | 5.4% |
| 3 | 5.8% | 4.8% | 5.5% | 8.0% | 4.9% | 6.0% | 10.1% |
| 4 | 6.4% | 7.1% | 5.6% | 8.9% | 6.4% | 6.2% | 9.1% |
| 5 | 6.5% | 7.1% | 5.6% | 9.0% | 6.1% | 7.4% | 8.6% |
| 6 | 6.3% | 7.4% | 5.5% | 8.7% | 6.3% | 7.0% | 7.6% |
| 7 | 6.0% | 7.0% | 4.3% | 8.3% | 9.1% | 5.5% | 6.4% |
| 8 | 5.9% | 6.5% | 3.4% | 8.1% | 6.5% | 4.2% | 5.4% |
| 9 | 6.0% | 6.0% | 3.0% | 8.4% | 6.9% | 3.8% | 4.8% |
| 10 | 6.0% | 5.6% | 3.5% | 8.3% | 7.0% | 4.1% | 4.1% |
| 11 | 6.0% | 5.1% | 3.8% | 0.0% | 5.8% | 4.9% | 3.3% |
| 12 | 5.2% | 4.4% | 3.8% | 0.0% | 6.1% | 5.0% | 2.5% |
| 13 | 4.2% | 3.8% | 3.1% | 0.0% | 1.5% | 3.9% | 2.1% |
| 14 | 3.5% | 3.2% | 2.4% | 0.0% | 3.5% | 3.0% | 2.0% |
| 15 | 3.0% | 2.8% | 2.6% | 0.0% | 2.4% | 2.8% | 1.8% |
| 16 | 2.4% | 2.3% | 3.0% | 0.0% | 2.2% | 3.1% | 1.3% |
| 17 | 2.0% | 2.1% | 3.0% | 0.0% | 1.9% | 2.7% | 1.5% |
| 18 | 1.5% | 1.7% | 2.2% | 0.0% | 1.4% | 2.0% | 1.3% |
| 19 | 1.1% | 1.3% | 1.7% | 0.0% | 1.0% | 1.3% | 1.0% |
| 20 | 0.8% | 1.0% | 1.6% | 0.0% | 0.7% | 1.3% | 0.8% |
| 21 | 0.7% | 1.0% | 2.0% | 0.0% | 0.7% | 1.5% | 0.7% |
| 22 | 0.6% | 0.9% | 2.7% | 0.0% | 0.6% | 1.6% | 0.5% |
| 23 | 0.5% | 0.8% | 2.6% | 0.0% | 0.4% | 1.4% | 0.4% |
| 24 | 0.3% | 0.7% | 2.2% | 0.0% | 0.4% | 1.1% | 0.4% |
| 25 | 0.3% | 0.6% | 2.9% | 0.0% | 0.5% | 1.1% | 0.3% |
| 26 | 0.2% | 0.5% | 2.2% | 0.9% | 0.4% | 0.8% | 0.3% |
| 27 | 0.1% | 0.4% | 1.3% | 1.0% | 0.4% | 0.5% | 0.3% |
| 28 | 0.1% | 0.2% | 2.0% | 1.1% | 0.4% | 0.4% | 0.2% |
| 29 | 0.1% | 0.2% | 1.1% | 1.4% | 0.4% | 0.2% | 0.1% |
| 30 | 0.1% | 0.2% | 1.6% | 2.1% | 0.2% | 0.3% | 0.2% |
| **Total** | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |

Source: EPA (2010).

[a] The following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles), LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), and MC (motorcycles).
[b] According to EPA's MOVES model, sales of diesel passenger cars in model years 11-25 was very small compared to total passenger car sales, so the calculated fraction of these vehicles in these model years was stored as zero.

Table A- 97: Annual Average Vehicle Mileage Accumulation per Vehicle[a] (miles)

| Vehicle Age | LDGV | LDGT | HDGV | LDDV | LDDT | HDDV | MC[b] |
|---|---|---|---|---|---|---|---|
| 0 | 14,910 | 19,906 | 20,218 | 14,910 | 26,371 | 28,787 | 4,786 |
| 1 | 14,174 | 18,707 | 18,935 | 14,174 | 24,137 | 26,304 | 4,475 |
| 2 | 13,475 | 17,559 | 17,100 | 13,475 | 22,095 | 24,038 | 4,164 |
| 3 | 12,810 | 16,462 | 16,611 | 12,810 | 20,228 | 21,968 | 3,853 |
| 4 | 12,178 | 15,413 | 15,560 | 12,178 | 18,521 | 20,078 | 3,543 |
| 5 | 11,577 | 14,411 | 14,576 | 11,577 | 16,960 | 18,351 | 3,232 |
| 6 | 11,006 | 13,454 | 13,655 | 11,006 | 15,533 | 16,775 | 2,921 |
| 7 | 10,463 | 12,541 | 12,793 | 10,463 | 14,227 | 15,334 | 2,611 |
| 8 | 9,947 | 11,671 | 11,987 | 9,947 | 13,032 | 14,019 | 2,300 |
| 9 | 9,456 | 10,843 | 11,231 | 9,456 | 11,939 | 12,817 | 1,989 |
| 10 | 8,989 | 10,055 | 10,524 | 8,989 | 10,939 | 11,719 | 1,678 |
| 11 | 8,546 | 9,306 | 9,863 | 8,546 | 10,024 | 10,716 | 1,368 |
| 12 | 8,124 | 8,597 | 9,243 | 8,124 | 9,186 | 9,799 | 1,368 |
| 13 | 7,723 | 7,925 | 8,662 | 7,723 | 8,420 | 8,962 | 1,368 |
| 14 | 7,342 | 7,290 | 8,028 | 7,342 | 7,718 | 8,196 | 1,368 |
| 15 | 6,980 | 6,690 | 7,610 | 6,980 | 7,075 | 7,497 | 1,368 |
| 16 | 6,636 | 6,127 | 7,133 | 6,636 | 6,487 | 6,857 | 1,368 |
| 17 | 6,308 | 5,598 | 6,687 | 6,308 | 5,948 | 6,273 | 1,368 |
| 18 | 5,997 | 5,103 | 6,269 | 5,997 | 5,454 | 5,739 | 1,368 |
| 19 | 5,701 | 4,642 | 5,877 | 5,701 | 5,002 | 5,250 | 1,368 |
| 20 | 5,420 | 4,214 | 5,510 | 5,420 | 4,588 | 4,804 | 1,368 |
| 21 | 5,152 | 3,818 | 5,166 | 5,152 | 4,209 | 4,396 | 1,368 |
| 22 | 4,898 | 3,455 | 4,844 | 4,898 | 3,861 | 4,023 | 1,368 |
| 23 | 4,656 | 3,123 | 4,542 | 4,656 | 3,542 | 3,681 | 1,368 |
| 24 | 4,427 | 2,822 | 4,259 | 4,427 | 3,250 | 3,369 | 1,368 |
| 25 | 4,427 | 2,822 | 4,259 | 4,427 | 3,250 | 3,369 | 1,368 |
| 26 | 4,427 | 2,822 | 4,259 | 4,427 | 3,250 | 3,369 | 1,368 |
| 27 | 4,427 | 2,822 | 4,259 | 4,427 | 3,250 | 3,369 | 1,368 |
| 28 | 4,427 | 2,822 | 4,259 | 4,427 | 3,250 | 3,369 | 1,368 |
| 29 | 4,427 | 2,822 | 4,259 | 4,427 | 3,250 | 3,369 | 1,368 |
| 30 | 4,427 | 2,822 | 4,259 | 4,427 | 3,250 | 3,369 | 1,368 |

Source: EPA (2000).
[a] The following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles), LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), and MC (motorcycles).
[b] Because of a lack of data, all motorcycles over 12 years old are considered to have the same emissions and travel characteristics, and therefore are presented in aggregate.

Table A- 98: VMT Distribution by Vehicle Age and Vehicle/Fuel Type,[a] 2011

| Vehicle Age | LDGV | LDGT | HDGV | LDDV[b] | LDDT | HDDV | MC |
|---|---|---|---|---|---|---|---|
| 0 | 10.31% | 10.21% | 10.37% | 13.03% | 11.63% | 11.63% | 15.52% |
| 1 | 8.59% | 8.74% | 8.94% | 10.85% | 9.69% | 9.89% | 11.46% |
| 2 | 6.83% | 5.73% | 7.76% | 8.62% | 6.20% | 8.79% | 7.48% |
| 3 | 7.22% | 6.69% | 8.30% | 9.12% | 7.06% | 8.90% | 13.01% |
| 4 | 7.59% | 9.20% | 7.95% | 9.59% | 8.43% | 8.41% | 10.81% |
| 5 | 7.30% | 8.62% | 7.37% | 9.23% | 7.33% | 9.19% | 9.34% |
| 6 | 6.72% | 8.34% | 6.83% | 8.49% | 6.96% | 7.97% | 7.40% |
| 7 | 6.10% | 7.41% | 5.01% | 7.70% | 9.21% | 5.72% | 5.61% |
| 8 | 5.67% | 6.39% | 3.70% | 7.17% | 6.03% | 3.99% | 4.18% |
| 9 | 5.54% | 5.47% | 3.05% | 7.00% | 5.84% | 3.31% | 3.22% |
| 10 | 5.25% | 4.77% | 3.31% | 6.64% | 5.47% | 3.28% | 2.30% |
| 11 | 5.02% | 4.02% | 3.39% | 0.00% | 4.11% | 3.56% | 1.50% |
| 12 | 4.15% | 3.16% | 3.15% | 0.00% | 3.98% | 3.36% | 1.13% |
| 13 | 3.15% | 2.55% | 2.40% | 0.00% | 0.88% | 2.37% | 0.97% |
| 14 | 2.53% | 1.94% | 1.71% | 0.00% | 1.94% | 1.69% | 0.92% |
| 15 | 2.02% | 1.56% | 1.76% | 0.00% | 1.20% | 1.44% | 0.81% |
| 16 | 1.55% | 1.20% | 1.92% | 0.00% | 1.02% | 1.46% | 0.61% |
| 17 | 1.21% | 0.98% | 1.79% | 0.00% | 0.79% | 1.13% | 0.70% |
| 18 | 0.85% | 0.71% | 1.23% | 0.00% | 0.55% | 0.77% | 0.57% |
| 19 | 0.60% | 0.50% | 0.89% | 0.00% | 0.35% | 0.48% | 0.48% |
| 20 | 0.44% | 0.36% | 0.82% | 0.00% | 0.24% | 0.42% | 0.38% |
| 21 | 0.36% | 0.32% | 0.92% | 0.00% | 0.21% | 0.45% | 0.31% |
| 22 | 0.28% | 0.26% | 1.20% | 0.00% | 0.16% | 0.44% | 0.23% |
| 23 | 0.21% | 0.22% | 1.05% | 0.00% | 0.11% | 0.34% | 0.19% |
| 24 | 0.15% | 0.16% | 0.87% | 0.00% | 0.08% | 0.24% | 0.19% |
| 25 | 0.12% | 0.14% | 1.11% | 0.00% | 0.12% | 0.24% | 0.16% |
| 26 | 0.09% | 0.12% | 0.85% | 0.35% | 0.10% | 0.18% | 0.13% |
| 27 | 0.06% | 0.09% | 0.50% | 0.40% | 0.10% | 0.11% | 0.12% |
| 28 | 0.04% | 0.06% | 0.78% | 0.43% | 0.09% | 0.10% | 0.09% |
| 29 | 0.03% | 0.04% | 0.43% | 0.56% | 0.08% | 0.05% | 0.07% |
| 30 | 0.03% | 0.05% | 0.63% | 0.82% | 0.03% | 0.07% | 0.11% |
| **Total** | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |

Note: Estimated by weighting data in Table A- 96 by data in Table A- 97.

[a] The following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles), LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), and MC (motorcycles).

[b] According to EPA's MOVES model, sales of diesel passenger cars in model years 10-24 was very small compared to total passenger car sales, so the calculated fraction of these vehicles in these model years was stored as zero.

Table A- 99: Fuel Consumption for Off-Road Sources by Fuel Type (million gallons)

| Vehicle Type/Year | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Aircraft[a]** | **16,545** | **15,894** | **16,180** | **16,482** | **16,321** | **17,574** | **18,150** | **16,722** | **16,136** | **16,282** | **16,855** | **17,693** | **18,062** | **18,149** | **17,042** | **15,722** | **14,904** | **14,922** |
| Aviation Gasoline | 374 | 329 | 311 | 330 | 295 | 326 | 302 | 291 | 281 | 251 | 260 | 294 | 278 | 263 | 235 | 221 | 225 | 225 |
| Jet Fuel | 16,171 | 15,565 | 15,869 | 16,152 | 16,026 | 17,248 | 17,848 | 16,431 | 15,855 | 16,031 | 16,596 | 17,398 | 17,784 | 17,886 | 16,806 | 15,501 | 14,679 | 14,697 |
| **Ships and Other Boats** | **4,507** | **5,789** | **5,608** | **4,418** | **3,807** | **4,603** | **6,431** | **4,416** | **4,834** | **4,089** | **4,300** | **4,881** | **5,143** | **5,746** | **4,112** | **3,864** | **4,148** | **5,215** |
| Diesel | 1,043 | 1,546 | 1,786 | 1,784 | 1,557 | 1,707 | 1,750 | 1,630 | 1,592 | 1,711 | 1,347 | 1,470 | 1,409 | 1,489 | 674 | 834 | 787 | 1,790 |
| Gasoline | 1,403 | 1,597 | 1,654 | 1,658 | 1,659 | 1,657 | 1,653 | 1,655 | 1,654 | 1,648 | 1,640 | 1,630 | 1,620 | 1,610 | 1,600 | 1,591 | 1,578 | 1,567 |
| Residual | 2,061 | 2,646 | 2,168 | 976 | 591 | 1,238 | 3,028 | 1,131 | 1,588 | 730 | 1,313 | 1,781 | 2,115 | 2,647 | 1,838 | 1,440 | 1,783 | 1,859 |
| **Construction/ Mining Equipment[b]** | **4,160** | **4,835** | **4,977** | **5,130** | **5,204** | **5,286** | **5,439** | **5,897** | **6,067** | **6,248** | **6,428** | **6,520** | **6,656** | **6,684** | **6,835** | **6,960** | **7,204** | **7,307** |
| Diesel | 3,674 | 4,387 | 4,529 | 4,672 | 4,814 | 4,955 | 5,095 | 5,241 | 5,386 | 5,532 | 5,678 | 5,823 | 5,968 | 6,113 | 6,258 | 6,403 | 6,547 | 6,693 |
| Gasoline | 486 | 448 | 448 | 458 | 390 | 331 | 344 | 657 | 681 | 716 | 751 | 697 | 688 | 571 | 577 | 558 | 656 | 614 |
| **Agricultural Equipment[c]** | **3,134** | **3,698** | **3,780** | **3,936** | **3,949** | **3,835** | **3,875** | **4,107** | **4,220** | **4,324** | **4,648** | **4,715** | **4,948** | **4,862** | **4,517** | **4,641** | **4,739** | **4,928** |
| Diesel | 2,321 | 2,772 | 2,862 | 2,952 | 3,042 | 3,132 | 3,222 | 3,305 | 3,388 | 3,471 | 3,554 | 3,637 | 3,719 | 3,801 | 3,883 | 3,965 | 4,046 | 4,129 |
| Gasoline | 813 | 927 | 918 | 984 | 907 | 703 | 652 | 802 | 832 | 853 | 1,094 | 1,078 | 1,229 | 1,061 | 634 | 676 | 692 | 799 |
| **Rail** | **3,461** | **3,864** | **3,934** | **3,947** | **3,975** | **4,122** | **4,106** | **4,119** | **4,089** | **4,176** | **4,407** | **4,446** | **4,665** | **4,539** | **4,216** | **3,535** | **3,807** | **3,998** |
| Diesel | 3,461 | 3,864 | 3,934 | 3,947 | 3,975 | 4,122 | 4,106 | 4,119 | 4,089 | 4,176 | 4,407 | 4,446 | 4,665 | 4,539 | 4,216 | 3,535 | 3,807 | 3,998 |
| **Other[d]** | **5,916** | **6,525** | **6,598** | **6,624** | **6,710** | **6,677** | **6,826** | **7,657** | **7,840** | **8,049** | **8,263** | **8,281** | **8,396** | **8,256** | **8,387** | **8,482** | **8,830** | **8,795** |
| Diesel | 1,423 | 1,720 | 1,779 | 1,839 | 1,898 | 1,957 | 2,016 | 2,079 | 2,144 | 2,210 | 2,275 | 2,340 | 2,405 | 2,471 | 2,536 | 2,601 | 2,666 | 2,731 |
| Gasoline | 4,493 | 4,805 | 4,819 | 4,785 | 4,812 | 4,720 | 4,810 | 5,578 | 5,696 | 5,840 | 5,988 | 5,941 | 5,991 | 5,785 | 5,851 | 5,881 | 6,164 | 6,063 |
| **Total** | **37,723** | **40,604** | **41,078** | **40,537** | **39,966** | **42,096** | **44,826** | **42,918** | **43,185** | **43,169** | **44,902** | **46,537** | **47,870** | **48,235** | **45,108** | **43,204** | **43,633** | **45,165** |

Sources: AAR (2008 through 2012), APTA (2007 through 2012), BEA (1991 through 2005), Benson (2002 through 2004), DHS (2008), DOC (1991 through 2012), DESC (2012), DOE (1993 through 2012), DOT (1991 through 2012), EIA (2002), EIA (2007b), EIA (2008), EIA (2007 through 2012), EIA (1991 through 2012), EPA (2012b)FAA (2013), FAA (2012), Gaffney (2007), and Whorton (2006 through 2012).

[a] For aircraft, this is aviation gasoline. For all other categories, this is motor gasoline.

[b] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[d] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Table A-100: Control Technology Assignments for Gasoline Passenger Cars (Percent of VMT)

| Model Years | Non-catalyst | Oxidation | EPA Tier 0 | EPA Tier 1 | LEV | EPA Tier 2 |
|---|---|---|---|---|---|---|
| 1973-1974 | 100% | - | - | - | - | - |
| 1975 | 20% | 80% | - | - | - | - |
| 1976-1977 | 15% | 85% | - | - | - | - |
| 1978-1979 | 10% | 90% | - | - | - | - |
| 1980 | 5% | 88% | 7% | - | - | - |
| 1981 | - | 15% | 85% | - | - | - |
| 1982 | - | 14% | 86% | - | - | - |
| 1983 | - | 12% | 88% | - | - | - |
| 1984-1993 | - | - | 100% | - | - | - |
| 1994 | - | - | 60% | 40% | - | - |
| 1995 | - | - | 20% | 80% | - | - |
| 1996 | - | - | 1% | 97% | 2% | - |
| 1997 | - | - | 0.5% | 96.5% | 3% | - |
| 1998 | - | - | <1% | 87% | 13% | - |
| 1999 | - | - | <1% | 67% | 33% | - |
| 2000 | - | - | - | 44% | 56% | - |
| 2001 | - | - | - | 3% | 97% | - |
| 2002 | - | - | - | 1% | 99% | - |
| 2003 | - | - | - | <1% | 87% | 13% |
| 2004 | - | - | - | <1% | 41% | 59% |
| 2005 | - | - | - | - | 38% | 62% |
| 2006 | - | - | - | - | 18% | 82% |
| 2007 | - | - | - | - | 4% | 96% |
| 2008 | - | - | - | - | 2% | 98% |
| 2009-11 | - | - | - | - | - | 100% |

Sources: EPA (1998), EPA (2007a), and EPA (2007b).
Note: Detailed descriptions of emissions control technologies are provided in the following section of this annex.
- Not applicable.

Table A-101: Control Technology Assignments for Gasoline Light-Duty Trucks (Percent of VMT)[a]

| Model Years | Non-catalyst | Oxidation | EPA Tier 0 | EPA Tier 1 | LEV[b] | EPA Tier 2 |
|---|---|---|---|---|---|---|
| 1973-1974 | 100% | - | - | - | - | - |
| 1975 | 30% | 70% | - | - | - | - |
| 1976 | 20% | 80% | - | - | - | - |
| 1977-1978 | 25% | 75% | - | - | - | - |
| 1979-1980 | 20% | 80% | - | - | - | - |
| 1981 | - | 95% | 5% | - | - | - |
| 1982 | - | 90% | 10% | - | - | - |
| 1983 | - | 80% | 20% | - | - | - |
| 1984 | - | 70% | 30% | - | - | - |
| 1985 | - | 60% | 40% | - | - | - |
| 1986 | - | 50% | 50% | - | - | - |
| 1987-1993 | - | 5% | 95% | - | - | - |
| 1994 | - | - | 60% | 40% | - | - |
| 1995 | - | - | 20% | 80% | - | - |
| 1996 | - | - | - | 100% | - | - |
| 1997 | - | - | - | 100% | - | - |
| 1998 | - | - | - | 80% | 20% | - |
| 1999 | - | - | - | 57% | 43% | - |
| 2000 | - | - | - | 65% | 35% | - |
| 2001 | - | - | - | 1% | 99% | - |
| 2002 | - | - | - | 10% | 90% | - |
| 2003 | - | - | - | <1% | 53% | 47% |
| 2004 | - | - | - | - | 72% | 28% |
| 2005 | - | - | - | - | 38% | 62% |
| 2006 | - | - | - | - | 25% | 75% |
| 2007 | - | - | - | - | 14% | 86% |
| 2008-2011 | - | - | - | - | - | 100% |

Sources: EPA (1998), EPA (2007a), and EPA (2007b).
[a] Detailed descriptions of emissions control technologies are provided in the following section of this annex.
[b] The proportion of LEVs as a whole has decreased since 2001, as carmakers have been able to achieve greater emission reductions with certain types of LEVs, such as ULEVs. Because ULEVs emit about half the emissions of LEVs, a carmaker can reduce the total number of LEVs they need to build to meet a specified emission average for all of their vehicles in a given model year.
- Not applicable.

Table A-102: Control Technology Assignments for Gasoline Heavy-Duty Vehicles (Percent of VMT)[a]

| Model Years | Uncontrolled | Non-catalyst | Oxidation | EPA Tier 0 | EPA Tier 1 | LEV[b] | EPA Tier 2 |
|---|---|---|---|---|---|---|---|
| ≤1981 | 100% | - | - | - | - | - | - |
| 1982-1984 | 95% | - | 5% | - | - | - | - |
| 1985-1986 | - | 95% | 5% | - | - | - | - |
| 1987 | - | 70% | 15% | 15% | - | - | - |
| 1988-1989 | - | 60% | 25% | 15% | - | - | - |
| 1990-1995 | - | 45% | 30% | 25% | - | - | - |
| 1996 | - | - | 25% | 10% | 65% | - | - |
| 1997 | - | - | 10% | 5% | 85% | - | - |
| 1998 | - | - | - | - | 96% | 4% | - |
| 1999 | - | - | - | - | 78% | 22% | - |
| 2000 | - | - | - | - | 54% | 46% | - |
| 2001 | - | - | - | - | 64% | 36% | - |
| 2002 | - | - | - | - | 69% | 31% | - |
| 2003 | - | - | - | - | 65% | 30% | 5% |
| 2004 | - | - | - | - | 5% | 37% | 59% |
| 2005 | - | - | - | - | - | 23% | 77% |
| 2006 | - | - | - | - | - | 20% | 80% |
| 2007 | - | - | - | - | - | 10% | 90% |
| 2008-2011 | - | - | - | - | - | 0% | 100% |

Sources: EPA (1998), EPA (2007a), and EPA (2007b).
[a] Detailed descriptions of emissions control technologies are provided in the following section of this annex.
[b] The proportion of LEVs as a whole has decreased since 2000, as carmakers have been able to achieve greater emission reductions with certain types of LEVs, such as ULEVs. Because ULEVs emit about half the emissions of LEVs, a manufacturer can reduce the total number of LEVs they need to build to meet a specified emission average for all of their vehicles in a given model year.
- Not applicable.

Table A-103: Control Technology Assignments for Diesel On-Road Vehicles and Motorcycles

| Vehicle Type/Control Technology | Model Years |
|---|---|
| **Diesel Passenger Cars and Light-Duty Trucks** | |
| Uncontrolled | 1960-1982 |
| Moderate control | 1983-1995 |
| Advanced control | 1996-2011 |
| **Diesel Medium- and Heavy-Duty Trucks and Buses** | |
| Uncontrolled | 1960-1990 |
| Moderate control | 1991-2003 |
| Advanced control | 2004-2006 |
| Aftertreatment | 2007-2011 |
| **Motorcycles** | |
| Uncontrolled | 1960-1995 |
| Non-catalyst controls | 1996-2011 |

Source: EPA (1998) and Browning (2005)
Note: Detailed descriptions of emissions control technologies are provided in the following section of this annex.

Table A-104: Emission Factors for $CH_4$ and $N_2O$ for On-Road Vehicles

| Vehicle Type/Control Technology | $N_2O$ (g/mi) | $CH_4$ (g/mi) |
|---|---|---|
| **Gasoline Passenger Cars** | | |
| EPA Tier 2 | 0.0036 | 0.0173 |
| Low Emission Vehicles | 0.0150 | 0.0105 |
| EPA Tier 1[a] | 0.0429 | 0.0271 |
| EPA Tier 0[a] | 0.0647 | 0.0704 |
| Oxidation Catalyst | 0.0504 | 0.1355 |
| Non-Catalyst Control | 0.0197 | 0.1696 |
| Uncontrolled | 0.0197 | 0.1780 |
| **Gasoline Light-Duty Trucks** | | |
| EPA Tier 2 | 0.0066 | 0.0163 |
| Low Emission Vehicles | 0.0157 | 0.0148 |
| EPA Tier 1[a] | 0.0871 | 0.0452 |
| EPA Tier 0[a] | 0.1056 | 0.0776 |
| Oxidation Catalyst | 0.0639 | 0.1516 |
| Non-Catalyst Control | 0.0218 | 0.1908 |
| Uncontrolled | 0.0220 | 0.2024 |

| | | |
|---|---|---|
| **Gasoline Heavy-Duty Vehicles** | | |
| EPA Tier 2 | 0.0134 | 0.0333 |
| Low Emission Vehicles | 0.0320 | 0.0303 |
| EPA Tier 1[a] | 0.1750 | 0.0655 |
| EPA Tier 0[a] | 0.2135 | 0.2630 |
| Oxidation Catalyst | 0.1317 | 0.2356 |
| Non-Catalyst Control | 0.0473 | 0.4181 |
| Uncontrolled | 0.0497 | 0.4604 |
| **Diesel Passenger Cars** | | |
| Advanced | 0.0010 | 0.0005 |
| Moderate | 0.0010 | 0.0005 |
| Uncontrolled | 0.0012 | 0.0006 |
| **Diesel Light-Duty Trucks** | | |
| Advanced | 0.0015 | 0.0010 |
| Moderate | 0.0014 | 0.0009 |
| Uncontrolled | 0.0017 | 0.0011 |
| **Diesel Medium- and Heavy-Duty Trucks and Buses** | | |
| Aftertreatment | 0.0048 | 0.0051 |
| Advanced | 0.0048 | 0.0051 |
| Moderate | 0.0048 | 0.0051 |
| Uncontrolled | 0.0048 | 0.0051 |
| **Motorcycles** | | |
| Non-Catalyst Control | 0.0069 | 0.0672 |
| Uncontrolled | 0.0087 | 0.0899 |

Source: ICF (2006b and 2004).

[a] The categories "EPA Tier 0" and "EPA Tier 1" were substituted for the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the *Revised 1996 IPCC Guidelines*. Detailed descriptions of emissions control technologies are provided at the end of this annex.

Table A-105: Emission Factors for $CH_4$ and $N_2O$ for Alternative Fuel Vehicles (g/mi)

| | $N_2O$ | $CH_4$ |
|---|---|---|
| **Light Duty Vehicles** | | |
| Methanol | 0.067 | 0.018 |
| CNG | 0.050 | 0.737 |
| LPG | 0.067 | 0.037 |
| Ethanol | 0.067 | 0.055 |
| Biodiesel (BD20) | 0.001 | 0.0005 |
| **Medium- and Heavy-Duty Trucks** | | |
| Methanol | 0.175 | 0.066 |
| CNG | 0.175 | 1.966 |
| LNG | 0.175 | 1.966 |
| LPG | 0.175 | 0.066 |
| Ethanol | 0.175 | 0.197 |
| Biodiesel (BD20) | 0.005 | 0.005 |
| **Buses** | | |
| Methanol | 0.175 | 0.066 |
| CNG | 0.175 | 1.966 |
| Ethanol | 0.175 | 0.197 |
| Biodiesel (BD20) | 0.005 | 0.005 |

Source: Developed by ICF (2006a) using ANL (2006) and Lipman and Delucchi (2002).

Table A-106: Emission Factors for $CH_4$ and $N_2O$ Emissions from Non-Road Mobile Combustion (g/kg fuel)

| Vehicle Type/Fuel Type | $N_2O$ | $CH_4$ |
|---|---|---|
| **Ships and Boats** | | |
| Residual | 0.16 | 0.03 |
| Gasoline | 0.08 | 0.23 |
| Diesel | 0.14 | 0.02 |
| **Rail** | | |
| Diesel | 0.08 | 0.25 |
| **Agricultural Equipment[a]** | | |
| Gasoline | 0.08 | 0.45 |
| Diesel | 0.08 | 0.45 |

| | | |
|---|---|---|
| **Construction/Mining Equipment[c]** | | |
| Gasoline | 0.08 | 0.18 |
| Diesel | 0.08 | 0.18 |
| **Other Non-Road** | | |
| All "Other" Categories[c] | 0.08 | 0.18 |
| **Aircraft** | | |
| Jet Fuel | 0.10 | 0.087 |
| Aviation Gasoline | 0.04 | 2.64 |

Source: IPCC/UNEP/OECD/IEA (1997) and ICF (2009).

[a] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[b] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[c] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Table A-107: $NO_x$ Emissions from Mobile Combustion (Gg)

| Fuel Type/Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010[e] | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gasoline On-Road** | **5,746** | **4,560** | **4,322** | **4,268** | **4,090** | **3,924** | **3,812** | **3,715** | **3,761** | **3,541** | **3,322** | **3,102** | **2,897** | **2,693** | **2,488** | **2,212** | **2,212** | **2,212** |
| Passenger Cars | 3,847 | 2,752 | 2,533 | 2,447 | 2,316 | 2,158 | 2,084 | 2,027 | 2,052 | 1,932 | 1,812 | 1,692 | 1,581 | 1,469 | 1,357 | 1,207 | 1,207 | 1,207 |
| Light-Duty Trucks | 1,364 | 1,325 | 1,318 | 1,334 | 1,294 | 1,267 | 1,303 | 1,285 | 1,301 | 1,225 | 1,149 | 1,073 | 1,002 | 931 | 860 | 765 | 765 | 765 |
| Medium- and Heavy-Duty Trucks and Buses | 515 | 469 | 459 | 475 | 467 | 485 | 411 | 390 | 395 | 372 | 349 | 326 | 304 | 283 | 261 | 232 | 232 | 232 |
| Motorcycles | 20 | 14 | 13 | 13 | 13 | 13 | 13 | 14 | 14 | 13 | 12 | 11 | 11 | 10 | 9 | 8 | 8 | 8 |
| **Diesel On-Road** | **2,956** | **3,493** | **3,600** | **3,708** | **3,729** | **3,671** | **3,803** | **3,338** | **3,379** | **3,182** | **2,984** | **2,787** | **2,603** | **2,419** | **2,235** | **1,987** | **1,987** | **1,987** |
| Passenger Cars | 39 | 19 | 15 | 13 | 11 | 10 | 7 | 6 | 6 | 6 | 5 | 5 | 5 | 4 | 4 | 3 | 3 | 3 |
| Light-Duty Trucks | 20 | 12 | 11 | 10 | 9 | 8 | 6 | 5 | 6 | 5 | 5 | 5 | 4 | 4 | 4 | 3 | 3 | 3 |
| Medium- and Heavy-Duty Trucks and Buses | 2,897 | 3,462 | 3,575 | 3,685 | 3,709 | 3,653 | 3,791 | 3,326 | 3,367 | 3,171 | 2,974 | 2,778 | 2,594 | 2,411 | 2,228 | 1,981 | 1,981 | 1,981 |
| **Alternative Fuel On-Road[a]** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** |
| **Non-Road** | **2,160** | **2,483** | **2,553** | **2,552** | **2,565** | **2,588** | **2,584** | **2,643** | **2,879** | **2,960** | **3,041** | **3,122** | **2,988** | **2,853** | **2,718** | **2,007** | **2,007** | **2,007** |
| Ships and Boats | 402 | 488 | 507 | 483 | 469 | 428 | 506 | 544 | 595 | 612 | 629 | 646 | 618 | 590 | 562 | 415 | 415 | 415 |
| Rail | 338 | 433 | 455 | 457 | 469 | 444 | 451 | 485 | 531 | 546 | 561 | 576 | 551 | 527 | 502 | 371 | 371 | 371 |
| Aircraft[b] | 25 | 31 | 32 | 36 | 40 | 41 | 40 | 39 | 43 | 44 | 45 | 47 | 45 | 43 | 41 | 30 | 30 | 30 |
| Agricultural Equipment[c] | 437 | 478 | 486 | 487 | 487 | 497 | 484 | 480 | 521 | 535 | 550 | 565 | 540 | 516 | 491 | 363 | 363 | 363 |
| Construction/Mining Equipment[d] | 641 | 697 | 708 | 707 | 705 | 765 | 697 | 690 | 748 | 769 | 790 | 811 | 776 | 741 | 706 | 521 | 521 | 521 |
| Other[e] | 318 | 357 | 364 | 382 | 394 | 413 | 407 | 406 | 441 | 453 | 465 | 478 | 457 | 437 | 416 | 307 | 307 | 307 |
| **Total** | **10,862** | **10,536** | **10,475** | **10,528** | **10,384** | **10,182** | **10,199** | **9,696** | **10,019** | **9,683** | **9,347** | **9,012** | **8,488** | **7,965** | **7,441** | **6,206** | **6,206** | **6,206** |

[a] $NO_x$ emissions from alternative fuel on-road vehicles are included under gasoline and diesel on-road.
[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.
[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[e] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.
[e] Criteria Air Pollutant emissions for 2010 and 2011 were unavailable. Values from 2009 are used as proxy estimates.
Note: Totals may not sum due to independent rounding.
IE = Included Elsewhere

Table A-108: CO Emissions from Mobile Combustion (Gg)

| Fuel Type/Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010[e] | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gasoline On-Road** | **98,328** | **74,673** | **69,941** | **67,509** | **65,245** | **61,210** | **60,657** | **56,716** | **54,143** | **50,554** | **46,965** | **43,374** | **40,492** | **37,610** | **34,727** | **34,199** | **34,199** | **34,199** |
| Passenger Cars | 60,757 | 42,065 | 38,327 | 36,825 | 35,686 | 32,921 | 32,867 | 31,600 | 30,166 | 28,166 | 26,166 | 24,166 | 22,560 | 20,954 | 19,348 | 19,054 | 19,054 | 19,054 |
| Light-Duty Trucks | 29,237 | 27,048 | 26,610 | 25,748 | 24,754 | 23,343 | 24,532 | 22,574 | 21,550 | 20,121 | 18,693 | 17,264 | 16,117 | 14,969 | 13,822 | 13,612 | 13,612 | 13,612 |
| Medium- and Heavy-Duty Trucks and Buses | 8,093 | 5,404 | 4,867 | 4,787 | 4,642 | 4,782 | 3,104 | 2,411 | 2,302 | 2,149 | 1,997 | 1,844 | 1,721 | 1,599 | 1,476 | 1,454 | 1,454 | 1,454 |
| Motorcycles | 240 | 155 | 138 | 150 | 163 | 164 | 154 | 131 | 125 | 117 | 109 | 100 | 94 | 87 | 80 | 79 | 79 | 79 |
| **Diesel On-Road** | **1,696** | **1,424** | **1,370** | **1,301** | **1,202** | **1,122** | **1,088** | **869** | **830** | **775** | **720** | **665** | **621** | **576** | **532** | **524** | **524** | **524** |
| Passenger Cars | 35 | 18 | 15 | 13 | 10 | 10 | 7 | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Light-Duty Trucks | 22 | 16 | 14 | 13 | 12 | 9 | 6 | 5 | 5 | 5 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 |
| Medium- and Heavy-Duty Trucks and Buses | 1,639 | 1,391 | 1,341 | 1,276 | 1,179 | 1,103 | 1,075 | 858 | 819 | 765 | 711 | 656 | 613 | 569 | 525 | 517 | 517 | 517 |
| **Alternative Fuel On-Road[a]** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** |
| **Non-Road** | **19,337** | **21,533** | **21,971** | **21,351** | **21,375** | **21,050** | **21,814** | **22,266** | **20,448** | **19,850** | **19,252** | **18,652** | **17,859** | **17,067** | **16,274** | **8,633** | **8,633** | **8,633** |
| Ships and Boats | 1,559 | 1,781 | 1,825 | 1,828 | 1,828 | 2,019 | 1,825 | 1,832 | 1,682 | 1,633 | 1,584 | 1,534 | 1,469 | 1,404 | 1,339 | 710 | 710 | 710 |
| Rail | 85 | 93 | 94 | 89 | 83 | 98 | 90 | 90 | 82 | 80 | 78 | 75 | 72 | 69 | 66 | 35 | 35 | 35 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aircraft[b] | 217 | 224 | 225 | 250 | 274 | 285 | 245 | 233 | 214 | 208 | 202 | 196 | 187 | 179 | 171 | 91 | 91 | 91 |
| Agricultural Equipment[c] | 581 | 628 | 638 | 636 | 633 | 630 | 626 | 621 | 570 | 554 | 537 | 520 | 498 | 476 | 454 | 241 | 241 | 241 |
| Construction/Mining Equipment[d] | 1,090 | 1,132 | 1,140 | 1,097 | 1,081 | 1,074 | 1,047 | 1,041 | 956 | 928 | 900 | 872 | 835 | 798 | 761 | 404 | 404 | 404 |
| Other[e] | 15,805 | 17,676 | 18,049 | 17,452 | 17,476 | 16,943 | 17,981 | 18,449 | 16,943 | 16,447 | 15,951 | 15,455 | 14,798 | 14,141 | 13,484 | 7,153 | 7,153 | 7,153 |
| **Total** | **119,360** | **97,630** | **93,283** | **90,161** | **87,822** | **83,382** | **83,559** | **79,852** | **75,421** | **71,178** | **66,936** | **62,692** | **58,972** | **55,253** | **51,533** | **43,355** | **43,355** | **43,355** |

[a] $NO_x$ emissions from alternative fuel on-road vehicles are included under gasoline and diesel on-road.
[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.
[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[e] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.
Note: Totals may not sum due to independent rounding.
[e] Criteria Air Pollutant emissions for 2010 and 2011 were unavailable. Values from 2009 are used as proxy estimates.

IE = Included Elsewhere

Table A-109: NMVOCs Emissions from Mobile Combustion (Gg)

| Fuel Type/Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010[e] | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Gasoline On-Road** | **8,110** | **5,819** | **5,361** | **5,167** | **5,066** | **4,924** | **4,615** | **4,285** | **4,255** | **4,023** | **3,791** | **3,558** | **3,358** | **3,158** | **2,958** | **2,878** | **2,878** | **2,878** |
| Passenger Cars | 5,120 | 3,394 | 3,049 | 2,928 | 2,894 | 2,811 | 2,610 | 2,393 | 2,376 | 2,247 | 2,117 | 1,987 | 1,875 | 1,764 | 1,652 | 1,607 | 1,607 | 1,607 |
| Light-Duty Trucks | 2,374 | 2,019 | 1,947 | 1,881 | 1,812 | 1,734 | 1,750 | 1,664 | 1,652 | 1,562 | 1,472 | 1,382 | 1,304 | 1,226 | 1,149 | 1,118 | 1,118 | 1,118 |
| Medium- and Heavy-Duty Trucks and Buses | 575 | 382 | 343 | 336 | 335 | 351 | 232 | 206 | 205 | 193 | 182 | 171 | 162 | 152 | 142 | 138 | 138 | 138 |
| Motorcycles | 42 | 24 | 21 | 22 | 25 | 28 | 23 | 22 | 22 | 21 | 19 | 18 | 17 | 16 | 15 | 15 | 15 | 15 |
| **Diesel On-Road** | **406** | **304** | **283** | **263** | **249** | **230** | **216** | **207** | **206** | **195** | **183** | **172** | **163** | **153** | **143** | **139** | **139** | **139** |
| Passenger Cars | 16 | 8 | 7 | 6 | 5 | 5 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 |
| Light-Duty Trucks | 14 | 9 | 9 | 8 | 7 | 6 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 |
| Medium- and Heavy-Duty Trucks and Buses | 377 | 286 | 268 | 249 | 237 | 219 | 209 | 201 | 199 | 188 | 178 | 167 | 157 | 148 | 139 | 135 | 135 | 135 |
| **Alternative Fuel On-Road[a]** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** | **IE** |
| **Non-Road** | **2,415** | **2,622** | **2,663** | **2,497** | **2,425** | **2,432** | **2,399** | **2,379** | **2,773** | **2,716** | **2,658** | **2,600** | **2,516** | **2,430** | **2,346** | **1,134** | **1,134** | **1,134** |
| Ships and Boats | 608 | 739 | 765 | 765 | 762 | 769 | 744 | 730 | 851 | 833 | 816 | 798 | 772 | 746 | 720 | 348 | 348 | 348 |
| Rail | 33 | 36 | 37 | 35 | 33 | 38 | 35 | 35 | 41 | 40 | 39 | 39 | 37 | 36 | 35 | 17 | 17 | 17 |
| Aircraft[b] | 28 | 28 | 28 | 32 | 35 | 38 | 24 | 19 | 22 | 22 | 21 | 21 | 20 | 20 | 19 | 9 | 9 | 9 |
| Agricultural Equipment[c] | 85 | 86 | 86 | 83 | 81 | 81 | 76 | 72 | 84 | 83 | 81 | 79 | 77 | 74 | 71 | 35 | 35 | 35 |
| Construction/Mining Equipment[d] | 149 | 152 | 153 | 142 | 137 | 141 | 130 | 125 | 146 | 143 | 140 | 137 | 132 | 128 | 123 | 60 | 60 | 60 |
| Other[e] | 1,512 | 1,580 | 1,593 | 1,440 | 1,377 | 1,366 | 1,390 | 1,397 | 1,629 | 1,595 | 1,561 | 1,527 | 1,477 | 1,427 | 1,378 | 666 | 666 | 666 |
| **Total** | **10,932** | **8,745** | **8,306** | **7,926** | **7,740** | **7,586** | **7,229** | **6,871** | **7,234** | **6,934** | **6,633** | **6,330** | **6,037** | **5,742** | **5,447** | **4,151** | **4,151** | **4,151** |

[a] $NO_x$ emissions from alternative fuel on-road vehicles are included under gasoline and diesel on-road.
[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.
[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[e] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.
[e] Criteria Air Pollutants emissions for 2010 and 2011 were unavailable. Values from 2009 are used as proxy estimates.
Note: Totals may not sum due to independent rounding.
IE = Included Elsewhere

## Definitions of Emission Control Technologies and Standards

The $N_2O$ and $CH_4$ emission factors used depend on the emission standards in place and the corresponding level of control technology for each vehicle type. Table A- 100 through Table A- 103 show the years in which these technologies or standards were in place and the penetration level for each vehicle type. These categories are defined below.

### Uncontrolled

Vehicles manufactured prior to the implementation of pollution control technologies are designated as uncontrolled. Gasoline passenger cars and light-duty trucks (pre-1973), gasoline heavy-duty vehicles (pre-1984), diesel vehicles (pre-1983), and motorcycles (pre-1996) are assumed to have no control technologies in place.

### Gasoline Emission Controls

Below are the control technologies and emissions standards applicable to gasoline vehicles.

#### *Non-catalyst*

These emission controls were common in gasoline passenger cars and light-duty gasoline trucks during model years (1973-1974) but phased out thereafter, in heavy-duty gasoline vehicles beginning in the mid-1980s, and in motorcycles beginning in 1996. This technology reduces hydrocarbon (HC) and carbon monoxide (CO) emissions through adjustments to ignition timing and air-fuel ratio, air injection into the exhaust manifold, and exhaust gas recirculation (EGR) valves, which also helps meet vehicle $NO_x$ standards.

#### *Oxidation Catalyst*

This control technology designation represents the introduction of the catalytic converter, and was the most common technology in gasoline passenger cars and light-duty gasoline trucks made from 1975 to 1980 (cars) and 1975 to 1985 (trucks). This technology was also used in some heavy-duty gasoline vehicles between 1982 and 1997. The two-way catalytic converter oxidizes HC and CO, significantly reducing emissions over 80 percent beyond non-catalyst-system capacity. One reason unleaded gasoline was introduced in 1975 was due to the fact that oxidation catalysts cannot function properly with leaded gasoline.

#### *EPA Tier 0*

This emission standard from the Clean Air Act was met through the implementation of early "three-way" catalysts, therefore this technology was used in gasoline passenger cars and light-duty gasoline trucks sold beginning in the early 1980s, and remained common until 1994. This more sophisticated emission control system improves the efficiency of the catalyst by converting CO and HC to $CO_2$ and $H_2O$, reducing $NO_x$ to nitrogen and oxygen, and using an on-board diagnostic computer and oxygen sensor. In addition, this type of catalyst includes a fuel metering system (carburetor or fuel injection) with electronic "trim" (also known as a "closed-loop system"). New cars with three-way catalysts met the Clean Air Act's amended standards (enacted in 1977) of reducing HC to 0.41 g/mile by 1980, CO to 3.4 g/mile by 1981 and $NO_x$ to 1.0 g/mile by 1981.

#### *EPA Tier 1*

This emission standard created through the 1990 amendments to the Clean Air Act limited passenger car $NO_x$ emissions to 0.4 g/mi, and HC emissions to 0.25 g/mi. These bounds respectively amounted to a 60 and 40 percent reduction from the EPA Tier 0 standard set in 1981. For light-duty trucks, this standard set emissions at 0.4 to 1.1 g/mi for $NO_x$, and 0.25 to 0.39 g/mi for HCs, depending on the weight of the truck. Emission reductions were met through the use of more advanced emission control systems, and applied to light-duty gasoline vehicles beginning in 1994. These advanced emission control systems included advanced three-way catalysts, electronically controlled fuel injection and ignition timing, EGR, and air injection.

#### *EPA Tier 2*

This emission standard was specified in the 1990 amendments to the Clean Air Act, limiting passenger car $NO_x$ emissions to 0.07 g/mi on average and aligning emissions standards for passenger cars and light-duty trucks. Manufacturers can meet this average emission level by producing vehicles in 11 emission “Bins”, the three highest of

which expire in 2006. These new emission levels represent a 77 to 95% reduction in emissions from the EPA Tier 1 standard set in 1994. Emission reductions were met through the use of more advanced emission control systems and lower sulfur fuels and are applied to vehicles beginning in 2004. These advanced emission control systems include improved combustion, advanced three-way catalysts, electronically controlled fuel injection and ignition timing, EGR, and air injection.

#### *Low Emission Vehicles (LEV)*

This emission standard requires a much higher emission control level than the Tier 1 standard. Applied to light-duty gasoline passenger cars and trucks beginning in small numbers in the mid-1990s, LEV includes multi-port fuel injection with adaptive learning, an advanced computer diagnostics systems and advanced and close coupled catalysts with secondary air injection. LEVs as defined here include transitional low-emission vehicles (TLEVs), low emission vehicles, ultra-low emission vehicles (ULEVs) and super ultra-low emission vehicles (SULEVs). In this analysis, all categories of LEVs are treated the same due to the fact that there are very limited $CH_4$ or $N_2O$ emission factor data for LEVs to distinguish among the different types of vehicles. Zero emission vehicles (ZEVs) are incorporated into the alternative fuel and advanced technology vehicle assessments.

### Diesel Emission Controls

Below are the three levels of emissions control for diesel vehicles.

#### *Moderate control*

Improved injection timing technology and combustion system design for light- and heavy-duty diesel vehicles (generally in place in model years 1983 to 1995) are considered moderate control technologies. These controls were implemented to meet emission standards for diesel trucks and buses adopted by the EPA in 1985 to be met in 1991 and 1994.

#### *Advanced control*

EGR and modern electronic control of the fuel injection system are designated as advanced control technologies. These technologies provide diesel vehicles with the level of emission control necessary to comply with standards in place from 1996 through 2006.

#### *Aftertreatment*

Use of diesel particulate filters (DPFs), oxidation catalysts and NOx absorbers or selective catalytic reduction (SCR) systems are designated as aftertreatment control. These technologies provide diesel vehicles with a level of emission control necessary to comply with standards in place from 2007 on.

## Supplemental Information on GHG Emissions from Transportation and Other Mobile Sources

This section of this Annex includes supplemental information on the contribution of transportation and other mobile sources to U.S. greenhouse gas emissions. In the main body of the Inventory report, emission estimates are generally presented by greenhouse gas, with separate discussions of the methodologies used to estimate $CO_2$, $N_2O$, $CH_4$, and HFC emissions. Although the inventory is not required to provide detail beyond what is contained in the body of this report, the IPCC allows presentation of additional data and detail on emission sources. The purpose of this sub-annex, within the annex that details the calculation methods and data used for non- $CO_2$ calculations, is to provide all transportation estimates presented throughout the repot in one place.

This section of this Annex reports total greenhouse gas emissions from transportation and other (non-transportation) mobile sources in $CO_2$ equivalents, with information on the contribution by greenhouse gas and by mode, vehicle type, and fuel type. In order to calculate these figures, additional analyses were conducted to develop estimates of $CO_2$ from non-transportation mobile sources (e.g., agricultural equipment, construction/mining equipment, recreational vehicles), and to provide more detailed breakdowns of emissions by source.

### Estimation of $CO_2$ from Non-Transportation Mobile Sources

The estimates of $N_2O$ and $CH_4$ from fuel combustion presented in the Energy chapter of the inventory include both transportation sources and other mobile sources. Other mobile sources include construction/mining equipment, agricultural equipment, vehicles used off-road, and other sources that have utility associated with their movement but do not have a primary purpose of transporting people or goods (e.g., snowmobiles, riding lawnmowers, etc.). Estimates of $CO_2$ from non-transportation mobile sources, based on EIA fuel consumption estimates, are included in the agricultural,

industrial, and commercial sectors. In order to provide comparable information on transportation and mobile sources, Table A- 110 provides estimates of $CO_2$ from these other mobile sources, developed from EPA's NONROAD model and FHWA's *Highway Statistics*. These other mobile source estimates were developed using the same fuel consumption data utilized in developing the $N_2O$ and $CH_4$ estimates.

Table A- 110: $CO_2$ Emissions from Non-Transportation Mobile Sources (Tg $CO_2$ Eq.)

| Fuel Type/Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Agricultural Equipment[a] | 31.0 | 36.6 | 37.4 | 38.9 | 39.2 | 38.3 | 38.8 | 41.0 | 42.1 | 43.1 | 46.1 | 46.8 | 49.0 | 48.4 | 45.4 | 46.7 | 47.6 | 49.4 |
| Construction/Mining Equipment[b] | 42.0 | 48.9 | 50.4 | 52.0 | 52.8 | 53.7 | 55.3 | 59.5 | 61.2 | 63.0 | 64.9 | 65.9 | 67.3 | 67.8 | 69.3 | 70.6 | 73.0 | 74.1 |
| Other Sources[c] | 54.5 | 59.8 | 60.6 | 60.9 | 61.7 | 61.4 | 62.8 | 70.2 | 72.0 | 73.9 | 76.0 | 76.2 | 77.6 | 76.7 | 77.7 | 78.6 | 81.8 | 81.6 |
| **Total** | **127.6** | **145.4** | **148.4** | **151.8** | **153.7** | **153.4** | **156.9** | **170.7** | **175.3** | **180.0** | **187.0** | **188.9** | **193.9** | **193.0** | **192.4** | **195.9** | **202.4** | **205.1** |

[a] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[b] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[c] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

### Estimation of HFC Emissions from Transportation Sources

In addition to $CO_2$, $N_2O$ and $CH_4$ emissions, transportation sources also result in emissions of HFCs. 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. There are three categories of transportation-related HFC emissions; Mobile AC represents the emissions from air conditioning units in passenger cars and light-duty trucks, Comfort Cooling represents the emissions from air conditioning units in passenger trains and buses, and Refrigerated Transport represents the emissions from units used to cool freight during transportation.

Table A- 111 below presents these HFC emissions. Table A- 112 presents all transportation and mobile source greenhouse gas emissions, including HFC emissions.

Table A- 111: HFC Emissions from Transportation Sources

| Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mobile AC** | **-** | **16.7** | **23.9** | **31.3** | **36.4** | **41.3** | **46.0** | **49.9** | **53.1** | **55.5** | **58.1** | **59.4** | **58.3** | **54.7** | **50.7** | **45.9** | **44.1** | **42.7** |
| Passenger Cars | - | 10.1 | 14.1 | 18.1 | 20.2 | 22.2 | 24.3 | 25.9 | 27.2 | 28.0 | 28.7 | 28.4 | 27.1 | 24.6 | 22.1 | 19.3 | 18.6 | 18.3 |
| Light-Duty Trucks | - | 6.5 | 9.8 | 13.3 | 16.2 | 19.0 | 21.7 | 24.0 | 25.8 | 27.5 | 29.4 | 31.0 | 31.2 | 30.1 | 28.6 | 26.6 | 25.4 | 24.5 |
| **Comfort Cooling for Trains and Buses** | **-** | **0.0** | **0.0** | **0.1** | **0.1** | **0.1** | **0.1** | **0.2** | **0.2** | **0.2** | **0.2** | **0.2** | **0.3** | **0.3** | **0.4** | **0.4** | **0.4** | **0.4** |
| School and Tour Buses | - | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 |
| Transit Buses | - | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Rail | - | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| **Refrigerated Transport** | **-** | **2.3** | **3.8** | **5.4** | **6.9** | **8.3** | **9.6** | **10.5** | **11.2** | **12.0** | **12.8** | **13.2** | **13.6** | **13.8** | **13.8** | **13.9** | **13.9** | **14.0** |
| Medium- and Heavy-Duty Trucks | - | 1.7 | 2.9 | 4.1 | 5.3 | 6.4 | 7.4 | 8.1 | 8.7 | 10.0 | 10.7 | 11.1 | 11.4 | 11.5 | 11.6 | 11.6 | 11.6 | 11.7 |
| Rail | - | 0.5 | 0.9 | 1.3 | 1.5 | 1.8 | 2.0 | 2.2 | 2.4 | 1.9 | 2.1 | 2.1 | 2.2 | 2.2 | 2.2 | 2.2 | 2.3 | 2.3 |
| Ships and Other Boats | - | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| **Total** | **-** | **19.0** | **27.8** | **36.8** | **43.4** | **49.7** | **55.7** | **60.5** | **64.5** | **67.7** | **71.1** | **72.9** | **72.2** | **68.8** | **64.9** | **60.2** | **58.4** | **57.1** |

Note: Totals may not sum due to independent rounding.
+ Less than 0.05 Tg $CO_2$ Eq.
- Unreported or zero

**Contribution of Transportation and Mobile Sources to Greenhouse Gas Emissions, by Mode/Vehicle Type/Fuel Type**

Table A- 112 presents estimates of greenhouse gas emissions from an expanded analysis including all transportation and additional mobile sources, as well as emissions from electricity generation by the consuming category, in $CO_2$ equivalents. In total, transportation and non-transportation mobile sources emitted 2,115.4 Tg $CO_2$ Eq. in 2011, an increase of 24 percent from 1990. Transportation sources account for 1,908.4 Tg $CO_2$ Eq. while non-transportation mobile sources account for 207.0 Tg $CO_2$ Eq. These estimates include HFC emissions for mobile AC, comfort cooling for trains and buses, and refrigerated transport. These estimates were generated using the estimates of $CO_2$ emissions from transportation sources reported in the Carbon Dioxide Emissions from Fossil Fuel Combustion section, and $CH_4$ emissions and $N_2O$ emissions reported in the Mobile Combustion section of the Energy chapter; information on HFCs from mobile air conditioners, comfort cooling for trains and buses, and refrigerated transportation from Chapter 4; and estimates of $CO_2$ emitted from non-transportation mobile sources reported in Table A- 108 above.

Although all emissions reported here are based on estimates reported throughout this inventory, some additional calculations were performed in order to provide a detailed breakdown of emissions by mode and vehicle category. In the case of $N_2O$ and $CH_4$, additional calculations were performed to develop emissions estimates by type of aircraft and type of heavy-duty vehicle (i.e., medium- and heavy-duty trucks or buses) to match the level of detail for $CO_2$ emissions. $N_2O$ and $CH_4$ estimates were developed for individual aircraft types by multiplying the emissions estimates for aircraft for each fuel type (jet fuel and aviation gasoline) by the portion of fuel used by each aircraft type (from FAA 2013, 2012). Similarly, $N_2O$ and $CH_4$ estimates were developed for medium- and heavy-duty trucks and buses by multiplying the emission estimates for heavy-duty vehicles for each fuel type (gasoline, diesel) from the Mobile Combustion section in the Energy chapter, by the portion of fuel used by each vehicle type (from DOE 1993 through 2012). Otherwise, the table and figure are drawn directly from emission estimates presented elsewhere in the inventory, and are dependent on the methodologies presented in Annex 2.1 (for $CO_2$), Chapter 4, and Annex 3.8 (for HFCs), and earlier in this Annex (for $CH_4$ and $N_2O$).

Transportation sources include on-road vehicles, aircraft, boats and ships, rail, and pipelines (note: pipelines are a transportation source but are stationary, not mobile sources). In addition, transportation-related greenhouse gas emissions also include HFC released from mobile air conditioners and refrigerated transportation, and the release of $CO_2$ from lubricants (such as motor oil) used in transportation. Together, transportation sources were responsible for 1,908.4 Tg $CO_2$ Eq. in 2011.

On-road vehicles were responsible for about 73 percent of all transportation and non-transportation mobile GHG emissions in 2011. Although passenger cars make up the largest component of on-road vehicle greenhouse gas emissions, light-duty and medium- and heavy-duty trucks have been the primary sources of growth in on-road vehicle emissions. Between 1990 and 2011, greenhouse gas emissions from passenger cars increased by 18 percent, while emissions from light-duty trucks increased one percent[49]. Meanwhile, greenhouse gas emissions from medium- and heavy-duty trucks increased 76 percent, reflecting the increased volume of total freight movement and an increasing share transported by trucks.

Greenhouse gas emissions from aircraft decreased 8 percent between 1990 and 2011. Emissions from military aircraft decreased 67 percent and commercial aircraft emissions rose 26 percent between 1990 and 2007 then dropped 18 percent from 2007 to 2011.

Non-transportation mobile sources, such as construction/mining equipment, agricultural equipment, and industrial/commercial equipment, emitted approximately 207.0 Tg $CO_2$ Eq. in 2011. Together, these sources emitted more greenhouse gases than ships and boats, and rail combined. Emissions from non-transportation mobile sources increased rapidly, growing approximately 61 percent between 1990 and 2011. $CH_4$ and $N_2O$ emissions from these sources are included in the "Mobile Combustion" section and $CO_2$ emissions are included in the relevant economic sectors.

[49] In 2011 FHWA changed how they defined vehicle types for the purposes of reporting VMT for the years 2007-2010. The old approach to vehicle classification was based on body type and split passenger vehicles into "Passenger Cars" and "Other 2 Axle 4-Tire Vehicles". The new approach is a vehicle classification system based on wheelbase. Vehicles with a wheelbase less than or equal to 121 inches are counted as "Light-duty Vehicles –Short Wheelbase". Passenger vehicles with a Wheelbase greater than 121 inches are counted as "Light-duty Vehicles - Long Wheelbase". This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this emission inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

### Contribution of Transportation and Mobile Sources to Greenhouse Gas Emissions, by Gas

Table A- 113 presents estimates of greenhouse gas emissions from transportation and other mobile sources broken down by greenhouse gas. As this table shows, $CO_2$ accounts for the vast majority of transportation greenhouse gas emissions (approximately 96 percent in 2011). Emissions of $CO_2$ from transportation and mobile sources increased by 352.9 Tg $CO_2$ Eq. between 1990 and 2011. In contrast, the combined emissions of $CH_4$ and $N_2O$ decreased by 28.2 Tg $CO_2$ Eq. over the same period, due largely to the introduction of control technologies designed to reduce criteria pollutant emissions.[50] Meanwhile, HFC emissions from mobile air conditioners and refrigerated transport increased from virtually no emissions in 1990 to 57.1 Tg $CO_2$ Eq. in 2011 as these chemicals were phased in as substitutes for ozone depleting substances. It should be noted, however, that the ozone depleting substances that HFCs replaced are also powerful greenhouse gases, but are not included in national greenhouse gas inventories due to their mandated phase out.

### Greenhouse Gas Emissions from Freight and Passenger Transportation

Table A- 114 and Table A- 115 present greenhouse gas estimates from transportation, broken down into the passenger and freight categories. Passenger modes include light-duty vehicles, buses, passenger rail, aircraft (general aviation and commercial aircraft), recreational boats, and mobile air conditioners, and are illustrated in Table A- 114. Freight modes include medium- and heavy-duty trucks, freight rail, refrigerated transport, waterborne freight vessels, pipelines, and commercial aircraft and are illustrated in Table A- 115. Commercial aircraft do carry some freight, in addition to passengers, and for this Inventory, the emissions have been split between passenger and freight transportation. (In previous Inventories, all commercial aircraft emissions were considered passenger transportation.) The amount of commercial aircraft emissions to allocate to the passenger and freight categories was calculated using BTS data on freight shipped by commercial aircraft, and the total number of passengers enplaned. Each passenger was considered to weigh an average of 150 pounds, with a luggage weight of 50 pounds. The total freight weight and total passenger weight carried were used to determine percent shares which were used to split the total commercial aircraft emissions estimates. The remaining transportation and mobile emissions were from sources not considered to be either freight or passenger modes (e.g., construction/mining and agricultural equipment, lubricants).

The estimates in these tables are derived from the estimates presented in Table A- 112. In addition, estimates of fuel consumption from DOE (1993 through 2011) were used to allocate rail emissions between passenger and freight categories.

In 2011, passenger transportation modes emitted 1,302.1 Tg $CO_2$ Eq., while freight transportation modes emitted 535.8 Tg $CO_2$ Eq. Between 1990 and 2011, the percentage growth of greenhouse gas emissions from freight sources was 52 percent, while emissions from passenger sources grew by 13 percent. This difference in growth is due largely to the rapid increase in emissions associated with medium- and heavy-duty trucks.

[50] The decline in CFC emissions is not captured in the official transportation estimates.

Table A- 112: Total U.S. Greenhouse Gas Emissions from Transportation and Mobile Sources (Tg $CO_2$ Eq.)

| Mode / Vehicle Type / Fuel Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | Percent Change 1990-2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Transportation Total[a]** | **1,574.6** | **1752.3** | **1808.3** | **1846.7** | **1890.9** | **1963.5** | **2020.4** | **1999.3** | **2038.2** | **2038.2** | **2085.1** | **2108.0** | **2109.4** | **2111.5** | **1993.8** | **1918.3** | **1920.5** | **1908.4** | **21%** |
| **On-Road Vehicles** | **1,235.2** | **1371.3** | **1415.2** | **1452.4** | **1503.0** | **1559.8** | **1575.1** | **1585.7** | **1624.5** | **1637.1** | **1673.6** | **1682.9** | **1679.7** | **1680.8** | **1602.9** | **1558.2** | **1565.1** | **1540.8** | **25%** |
| **Passenger Cars** | **657.4** | **646.0** | **657.8** | **660.8** | **682.6** | **697.3** | **695.3** | **701.2** | **714.9** | **693.6** | **691.0** | **709.5** | **682.9** | **847.4** | **807.0** | **798.7** | **793.3** | **773.4** | **18%** |
| Gasoline | 649.4 | 627.9 | 636.9 | 636.7 | 656.8 | 670.7 | 667.3 | 671.6 | 683.9 | 661.3 | 658.0 | 676.9 | 651.6 | 818.6 | 781.2 | 775.7 | 770.9 | 751.5 | 16% |
| Diesel | 7.9 | 7.9 | 6.7 | 6.1 | 5.6 | 4.4 | 3.7 | 3.7 | 3.7 | 4.2 | 4.3 | 4.2 | 4.1 | 4.1 | 3.7 | 3.6 | 3.8 | 3.7 | -53% |
| AFVs | + | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 366% |
| HFCs from Mobile AC | + | 10.1 | 14.1 | 18.1 | 20.2 | 22.2 | 24.3 | 25.9 | 27.2 | 28.0 | 28.7 | 28.4 | 27.1 | 24.6 | 22.1 | 19.3 | 18.6 | 18.3 | N/A |
| **Light-Duty Trucks** | **336.6** | **436.6** | **455.2** | **473.7** | **487.8** | **509.9** | **512.1** | **518.6** | **529.8** | **565.2** | **588.1** | **551.3** | **564.0** | **366.4** | **347.0** | **349.5** | **348.6** | **339.8** | **1%** |
| Gasoline | 324.5 | 414.6 | 429.2 | 443.7 | 453.8 | 471.4 | 469.8 | 473.2 | 481.4 | 509.7 | 528.9 | 493.0 | 504.7 | 321.7 | 304.4 | 309.5 | 309.3 | 301.6 | -7% |
| Diesel | 11.5 | 14.9 | 15.7 | 16.3 | 17.3 | 19.0 | 20.1 | 20.8 | 21.9 | 27.2 | 29.0 | 25.9 | 26.8 | 13.6 | 12.1 | 12.1 | 12.6 | 12.3 | 8% |
| AFVs | 0.6 | 0.5 | 0.5 | 0.5 | 0.6 | 0.5 | 0.5 | 0.6 | 0.7 | 0.7 | 0.9 | 1.3 | 1.2 | 1.0 | 1.8 | 1.2 | 1.3 | 1.4 | 136% |
| HFCs from Mobile AC | + | 6.5 | 9.8 | 13.3 | 16.2 | 19.0 | 21.7 | 24.0 | 25.8 | 27.5 | 29.4 | 31.0 | 31.2 | 30.1 | 28.6 | 26.6 | 25.4 | 24.5 | N/A |
| **Medium- and Heavy-Duty Trucks** | **231.1** | **277.8** | **290.8** | **306.2** | **320.6** | **339.2** | **354.6** | **353.8** | **368.1** | **365.9** | **377.7** | **408.4** | **418.6** | **444.7** | **427.0** | **389.2** | **403.0** | **407.3** | **76%** |
| Gasoline | 39.5 | 36.8 | 36.0 | 35.3 | 35.9 | 36.3 | 37.0 | 36.1 | 36.5 | 31.6 | 31.9 | 35.8 | 36.3 | 47.6 | 48.1 | 44.3 | 44.4 | 44.7 | 13% |
| Diesel | 190.7 | 238.6 | 251.4 | 266.2 | 278.8 | 296.0 | 309.9 | 309.3 | 322.6 | 323.8 | 334.7 | 361.0 | 370.4 | 385.0 | 366.5 | 332.6 | 346.3 | 350.2 | 84% |
| AFVs | 0.9 | 0.6 | 0.6 | 0.5 | 0.6 | 0.5 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.6 | 0.5 | 0.8 | 0.7 | 0.7 | 0.7 | -17% |
| HFCs from Refrigerated Transport | + | 1.7 | 2.9 | 4.1 | 5.3 | 6.4 | 7.4 | 8.1 | 8.7 | 10.0 | 10.7 | 11.1 | 11.4 | 11.5 | 11.6 | 11.6 | 11.6 | 11.7 | N/A |
| **Buses** | **8.4** | **9.2** | **9.6** | **9.9** | **10.2** | **11.4** | **11.2** | **10.3** | **10.0** | **10.8** | **15.0** | **12.1** | **12.3** | **18.0** | **17.4** | **16.5** | **16.4** | **16.6** | **98%** |
| Gasoline | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.3 | 0.3 | 0.5 | 0.4 | 0.4 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 125% |
| Diesel | 8.0 | 8.7 | 9.1 | 9.2 | 9.5 | 10.6 | 10.2 | 9.3 | 8.8 | 9.5 | 13.5 | 10.6 | 10.8 | 15.9 | 15.2 | 14.1 | 14.1 | 14.3 | 78% |
| AFVs | + | 0.1 | 0.1 | 0.2 | 0.3 | 0.3 | 0.5 | 0.5 | 0.6 | 0.7 | 0.9 | 0.9 | 0.8 | 1.0 | 1.1 | 1.2 | 1.1 | 1.1 | 39375% |
| HFCs from Comfort Cooling | + | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | N/A |
| **Motorcycles** | **1.8** | **1.8** | **1.8** | **1.8** | **1.9** | **1.9** | **1.9** | **1.7** | **1.7** | **1.7** | **1.8** | **1.7** | **1.9** | **4.3** | **4.5** | **4.3** | **3.8** | **3.7** | **111%** |
| Gasoline | 1.8 | 1.8 | 1.8 | 1.8 | 1.9 | 1.9 | 1.9 | 1.7 | 1.7 | 1.7 | 1.8 | 1.7 | 1.9 | 4.3 | 4.5 | 4.3 | 3.8 | 3.7 | 111% |
| **Aircraft** | **160.1** | **153.3** | **158.9** | **161.9** | **160.3** | **172.6** | **178.3** | **164.3** | **158.5** | **160.0** | **165.6** | **173.8** | **177.5** | **178.4** | **167.5** | **154.5** | **146.5** | **146.7** | **-8%** |
| **General Aviation Aircraft** | **9.6** | **8.2** | **8.6** | **9.1** | **10.5** | **12.3** | **12.1** | **11.5** | **11.6** | **11.3** | **14.3** | **17.5** | **18.5** | **16.9** | **18.8** | **16.1** | **16.0** | **16.0** | **67%** |
| Jet Fuel | 6.4 | 5.4 | 6.0 | 6.3 | 8.0 | 9.5 | 9.6 | 9.0 | 9.2 | 9.2 | 12.1 | 15.0 | 16.2 | 14.6 | 16.8 | 14.3 | 14.1 | 14.1 | 120% |
| Aviation Gasoline | 3.2 | 2.8 | 2.6 | 2.8 | 2.5 | 2.8 | 2.6 | 2.5 | 2.4 | 2.1 | 2.2 | 2.5 | 2.4 | 2.2 | 2.0 | 1.9 | 1.9 | 1.9 | -40% |
| **Commercial Aircraft** | **115.7** | **121.0** | **126.8** | **131.3** | **127.9** | **139.4** | **144.9** | **129.5** | **126.1** | **127.8** | **129.8** | **138.0** | **142.4** | **145.2** | **132.3** | **124.3** | **117.8** | **119.1** | **3%** |
| Jet Fuel | 115.7 | 121.0 | 126.8 | 131.3 | 127.9 | 139.4 | 144.9 | 129.5 | 126.1 | 127.8 | 129.8 | 138.0 | 142.4 | 145.2 | 132.3 | 124.3 | 117.8 | 119.1 | 3% |
| **Military Aircraft** | **34.8** | **24.1** | **23.5** | **21.4** | **21.9** | **21.0** | **21.3** | **23.2** | **20.8** | **20.9** | **21.5** | **18.3** | **16.5** | **16.3** | **16.4** | **14.1** | **12.6** | **11.5** | **-67%** |
| Jet Fuel | 34.8 | 24.1 | 23.5 | 21.4 | 21.9 | 21.0 | 21.3 | 23.2 | 20.8 | 20.9 | 21.5 | 18.3 | 16.5 | 16.3 | 16.4 | 14.1 | 12.6 | 11.5 | -67% |
| **Ships and Boats[b]** | **45.1** | **58.6** | **54.4** | **39.8** | **33.7** | **29.8** | **61.0** | **42.7** | **47.6** | **37.3** | **40.1** | **45.2** | **48.4** | **55.2** | **37.1** | **34.1** | **37.3** | **48.5** | **7%** |
| Gasoline | 12.6 | 14.1 | 12.9 | 11.9 | 12.5 | -0.4 | 10.0 | 14.6 | 14.6 | 14.4 | 14.4 | 14.2 | 14.1 | 14.0 | 13.6 | 13.5 | 13.3 | 13.1 | 5% |
| Distillate Fuel | 9.6 | 14.9 | 17.4 | 17.4 | 15.1 | 16.7 | 17.1 | 15.8 | 15.4 | 15.3 | 11.5 | 11.4 | 10.9 | 11.7 | 3.2 | 4.9 | 4.4 | 14.8 | 54% |
| Residual Fuel | 22.9 | 29.5 | 24.0 | 10.4 | 6.0 | 13.4 | 33.8 | 12.2 | 17.4 | 7.6 | 14.2 | 19.6 | 23.4 | 29.5 | 20.2 | 15.7 | 19.6 | 20.5 | -11% |
| HFCs from Refrigerated Transport | + | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | N/A |
| **Rail** | **86.4** | **119.6** | **129.9** | **139.9** | **146.7** | **153.6** | **158.8** | **161.1** | **160.3** | **161.1** | **164.4** | **163.7** | **161.6** | **152.7** | **141.1** | **126.3** | **125.2** | **125.6** | **45%** |
| Distillate Fuel | 35.8 | 40.0 | 40.7 | 40.9 | 41.1 | 42.7 | 42.5 | 42.6 | 42.3 | 43.2 | 45.6 | 46.0 | 48.3 | 47.0 | 43.6 | 36.6 | 39.4 | 41.4 | 16% |
| Electricity | 3.1 | 3.1 | 3.1 | 3.1 | 3.2 | 3.2 | 3.5 | 3.7 | 3.5 | 4.3 | 4.6 | 4.8 | 4.6 | 5.1 | 4.7 | 4.5 | 4.5 | 4.3 | 40% |

| | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Other Emissions from Rail Electricity Use | 47.5 | 76.0 | 85.2 | 94.7 | 100.9 | 105.9 | 110.7 | 112.6 | 112.1 | 111.6 | 112.2 | 110.7 | 106.5 | 98.3 | 90.5 | 82.9 | 79.0 | 77.7 | 64% |
| HFCs from Comfort Cooling | + | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | N/A |
| HFCs from Refrigerated Transport | + | 0.5 | 0.9 | 1.3 | 1.5 | 1.8 | 2.0 | 2.2 | 2.4 | 1.9 | 2.1 | 2.1 | 2.2 | 2.2 | 2.2 | 2.2 | 2.3 | 2.3 | N/A |
| **Pipelines[c]** | **36.0** | **38.2** | **38.9** | **41.2** | **35.0** | **35.5** | **35.2** | **34.4** | **36.4** | **32.5** | **31.1** | **32.2** | **32.3** | **34.2** | **35.6** | **36.7** | **36.9** | **37.8** | **5%** |
| Natural Gas | 36.0 | 38.2 | 38.9 | 41.2 | 35.0 | 35.5 | 35.2 | 34.4 | 36.4 | 32.5 | 31.1 | 32.2 | 32.3 | 34.2 | 35.6 | 36.7 | 36.9 | 37.8 | 5% |
| **Other Transportation** | **11.8** | **11.3** | **11.0** | **11.6** | **12.1** | **12.2** | **12.1** | **11.1** | **10.9** | **10.1** | **10.2** | **10.2** | **9.9** | **10.2** | **9.5** | **8.5** | **9.5** | **9.0** | **-24%** |
| Lubricants | 11.8 | 11.3 | 11.0 | 11.6 | 12.1 | 12.2 | 12.1 | 11.1 | 10.9 | 10.1 | 10.2 | 10.2 | 9.9 | 10.2 | 9.5 | 8.5 | 9.5 | 9.0 | -24% |
| **Non-Transportation Mobile Total** | **128.8** | **146.8** | **149.8** | **153.2** | **155.2** | **154.9** | **158.3** | **172.3** | **177.0** | **181.7** | **188.7** | **190.7** | **195.8** | **194.8** | **194.2** | **197.7** | **204.3** | **207.0** | **61%** |
| **Agricultural Equipment[d]** | **31.4** | **37.0** | **37.8** | **39.4** | **39.6** | **38.7** | **39.2** | **41.4** | **42.5** | **43.6** | **46.6** | **47.3** | **49.6** | **49.0** | **45.9** | **47.2** | **48.2** | **50.0** | **59%** |
| Gasoline | 7.3 | 8.3 | 8.2 | 8.8 | 8.1 | 6.2 | 5.8 | 7.1 | 7.4 | 7.6 | 9.8 | 9.6 | 11.0 | 9.6 | 5.7 | 6.1 | 6.2 | 7.2 | -2% |
| Diesel | 24.1 | 28.7 | 29.7 | 30.6 | 31.5 | 32.5 | 33.4 | 34.3 | 35.1 | 36.0 | 36.8 | 37.7 | 38.6 | 39.4 | 40.3 | 41.1 | 41.9 | 42.8 | 78% |
| **Construction/ Mining Equipment[e]** | **42.4** | **49.4** | **50.9** | **52.4** | **53.3** | **54.2** | **55.8** | **60.1** | **61.8** | **63.6** | **65.4** | **66.5** | **67.9** | **68.4** | **69.9** | **71.2** | **73.6** | **74.8** | **76%** |
| Gasoline | 4.4 | 4.0 | 4.0 | 4.1 | 3.5 | 2.9 | 3.1 | 5.8 | 6.1 | 6.4 | 6.7 | 6.2 | 6.2 | 5.1 | 5.2 | 5.0 | 5.9 | 5.5 | 26% |
| Diesel | 38.0 | 45.4 | 46.9 | 48.3 | 49.8 | 51.3 | 52.7 | 54.2 | 55.7 | 57.2 | 58.8 | 60.3 | 61.8 | 63.3 | 64.8 | 66.3 | 67.8 | 69.3 | 82% |
| **Other Equipment[f]** | **55.0** | **60.4** | **61.1** | **61.4** | **62.3** | **62.0** | **63.4** | **70.9** | **72.7** | **74.5** | **76.7** | **76.9** | **78.3** | **77.4** | **78.4** | **79.3** | **82.5** | **82.3** | **50%** |
| Gasoline | 40.3 | 42.6 | 42.7 | 42.4 | 42.6 | 41.7 | 42.5 | 49.3 | 50.5 | 51.7 | 53.1 | 52.7 | 53.4 | 51.8 | 52.2 | 52.4 | 54.9 | 54.0 | 34% |
| Diesel | 14.7 | 17.8 | 18.4 | 19.0 | 19.6 | 20.3 | 20.9 | 21.5 | 22.2 | 22.9 | 23.5 | 24.2 | 24.9 | 25.6 | 26.2 | 26.9 | 27.6 | 28.3 | 92% |
| **Transportation and Non-Transportation Mobile Total** | **1,703.4** | **1899.1** | **1958.1** | **1999.9** | **2046.1** | **2118.4** | **2178.8** | **2171.6** | **2215.2** | **2219.9** | **2273.9** | **2298.7** | **2305.2** | **2306.2** | **2188.0** | **2116.0** | **2124.8** | **2115.4** | **24%** |

[a] Not including emissions from international bunker fuels.
[b] Fluctuations in emission estimates reflect data collection problems.
[c] Includes only $CO_2$ from natural gas used to power pipelines; does not include emissions from electricity use or non-$CO_2$ gases.
[d] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[e] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[f] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.
+ Less than 0.05 Tg $CO_2$ Eq.
- Unreported or zero
NA = Not Applicable, as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.

Table A- 113: Transportation and Mobile Source Emissions by Gas (Tg $CO_2$ Eq.)

| | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | Percent Change 1990-2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CO2 | 1,607 | 1,746 | 1,787 | 1,809 | 1,843 | 1,905 | 1,956 | 1,945 | 1,990 | 1,995 | 2,048 | 2,076 | 2,090 | 2,108 | 2,005 | 1,948 | 1,965 | 1,960 | 22% |
| N2O | 43 | 54 | 54 | 55 | 55 | 54 | 53 | 50 | 46 | 43 | 40 | 37 | 34 | 29 | 25 | 23 | 20 | 18 | -58% |
| CH4 | 4.7 | 4.3 | 4.1 | 3.9 | 3.8 | 3.5 | 3.3 | 3.3 | 2.9 | 2.7 | 2.6 | 2.5 | 2.3 | 2.2 | 2.0 | 1.9 | 1.9 | 1.8 | -61% |
| HFC | + | 19.0 | 27.8 | 36.8 | 43.4 | 49.7 | 55.7 | 60.5 | 64.5 | 67.7 | 71.1 | 72.9 | 72.2 | 68.8 | 64.9 | 60.2 | 58.4 | 57.1 | N/A |

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total** | **1,655** | **1,823** | **1,873** | **1,905** | **1,945** | **2,012** | **2,068** | **2,059** | **2,103** | **2,108** | **2,162** | **2,188** | **2,199** | **2,208** | **2,097** | **2,033** | **2,046** | **2,038** | | **23%** |

- Unreported or zero

NA = Not Applicable, as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.

Figure A-4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2009 (Tg $CO_2$ Eq.)

**To be provided:**

**Figure A-4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2011 (Tg CO2 Eq.)**

Table A- 114: Greenhouse Gas Emissions from Passenger Transportation (Tg $CO_2$ Eq.)

| Vehicle Type | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | Percent Change 1990-2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **On-Road Vehicles** | **1,004.1** | **1,093.5** | **1,124.4** | **1,146.2** | **1,182.4** | **1,220.5** | **1,220.5** | **1,231.9** | **1,256.3** | **1,271.2** | **1,295.9** | **1,274.5** | **1,261.1** | **1,236.1** | **1,175.9** | **1,169.0** | **1,162.1** | **1,133.5** | **13%** |
| Passenger Cars | 657.4 | 646.0 | 657.8 | 660.8 | 682.6 | 697.3 | 695.3 | 701.2 | 714.9 | 693.6 | 691.0 | 709.5 | 682.9 | 847.4 | 807.0 | 798.7 | 793.3 | 773.4 | 18% |
| Light-Duty Trucks | 336.6 | 436.6 | 455.2 | 473.7 | 487.8 | 509.9 | 512.1 | 518.6 | 529.8 | 565.2 | 588.1 | 551.3 | 564.0 | 366.4 | 347.0 | 349.5 | 348.6 | 339.8 | 1% |
| Buses | 8.4 | 9.2 | 9.6 | 9.9 | 10.2 | 11.4 | 11.2 | 10.3 | 10.0 | 10.8 | 15.0 | 12.1 | 12.3 | 18.0 | 17.4 | 16.5 | 16.4 | 16.6 | 98% |
| Motorcycles | 1.8 | 1.8 | 1.8 | 1.8 | 1.9 | 1.9 | 1.9 | 1.7 | 1.7 | 1.7 | 1.8 | 1.7 | 1.9 | 4.3 | 4.5 | 4.3 | 3.8 | 3.7 | 111% |
| **Aircraft** | **105.3** | **108.3** | **113.5** | **117.7** | **116.3** | **127.5** | **131.9** | **118.6** | **115.9** | **117.0** | **122.4** | **133.5** | **138.6** | **140.9** | **132.5** | **123.2** | **117.0** | **118.2** | **12%** |
| General Aviation | 9.6 | 8.2 | 8.6 | 9.1 | 10.5 | 12.3 | 12.1 | 11.5 | 11.6 | 11.3 | 14.3 | 17.5 | 18.5 | 16.9 | 18.8 | 16.1 | 16.0 | 16.0 | 67% |
| Commercial Aircraft | 95.7 | 100.0 | 104.9 | 108.6 | 105.8 | 115.2 | 119.8 | 107.1 | 104.3 | 105.7 | 108.0 | 116.0 | 120.0 | 124.1 | 113.8 | 107.1 | 101.0 | 102.1 | 7% |
| **Recreational Boats** | **14.5** | **16.4** | **15.3** | **14.4** | **15.0** | **2.2** | **12.7** | **17.4** | **17.4** | **17.4** | **17.4** | **17.4** | **17.3** | **17.3** | **14.5** | **16.9** | **16.8** | **16.8** | **15%** |
| **Passenger Rail** | **4.4** | **4.5** | **4.4** | **4.6** | **4.7** | **4.8** | **5.2** | **5.4** | **5.1** | **5.8** | **6.0** | **6.2** | **6.0** | **6.6** | **6.3** | **6.2** | **6.2** | **5.9** | **36%** |
| **Total** | **1,128.2** | **1,222.7** | **1,257.7** | **1,282.9** | **1,318.5** | **1,355.1** | **1,370.3** | **1,373.3** | **1,394.8** | **1,411.5** | **1,441.8** | **1,431.6** | **1,423.0** | **1,400.9** | **1,329.2** | **1,315.3** | **1,302.1** | **1,274.4** | **13%** |

Note: Data from DOE (1993 through 2011) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates.

Table A- 115: Greenhouse Gas Emissions from Domestic Freight Transportation (Tg $CO_2$ Eq.)

| By Mode | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | Percent Change 1990-2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trucking | 231.1 | 277.8 | 290.8 | 306.2 | 320.6 | 339.2 | 354.6 | 353.8 | 368.1 | 365.9 | 377.7 | 408.4 | 418.6 | 444.7 | 427.0 | 389.2 | 403.0 | 407.3 | 76% |
| Freight Rail | 34.5 | 39.1 | 40.2 | 40.7 | 41.1 | 42.9 | 42.8 | 43.1 | 43.1 | 43.7 | 46.2 | 46.7 | 49.0 | 47.8 | 44.4 | 37.2 | 40.0 | 42.0 | 22% |
| Ships and Other Boats | 30.6 | 42.2 | 39.0 | 25.4 | 18.6 | 27.5 | 48.3 | 25.4 | 30.1 | 19.9 | 22.7 | 27.9 | 31.1 | 37.9 | 22.6 | 17.1 | 20.5 | 31.7 | 4% |
| Pipelines | 36.0 | 38.2 | 38.9 | 41.2 | 35.0 | 35.5 | 35.2 | 34.4 | 36.4 | 32.5 | 31.1 | 32.2 | 32.3 | 34.2 | 35.6 | 36.7 | 36.9 | 37.8 | 5% |
| Commercial Aircraft | 20.0 | 20.9 | 22.0 | 22.7 | 22.1 | 24.1 | 25.1 | 22.4 | 21.8 | 22.1 | 21.8 | 22.0 | 22.4 | 21.1 | 18.6 | 17.2 | 16.8 | 17.0 | -15% |
| **Total** | 352.3 | 418.2 | 431.0 | 436.1 | 437.5 | 469.2 | 506.0 | 479.1 | 499.6 | 484.1 | 499.5 | 537.2 | 553.5 | 585.7 | 548.1 | 497.5 | 517.2 | 535.8 | 52% |

Note: Data from DOE (1993 through 2011) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates.

## 3.3. Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption – TO BE UPDATED

**IPCC Tier 3B Method**: Commercial aircraft jet fuel burn and carbon dioxide (CO2) emissions estimates were developed by the U.S. Federal Aviation Administration (FAA) using radar-informed data from the FAA Enhanced Traffic Management System (ETMS) for 2000 through 2011 as modeled with the Aviation Environmental Design Tool (AEDT). This bottom-up approach is built from modeling dynamic aircraft performance for each flight occurring within an individual calendar year. The analysis incorporates data on the aircraft type, date, flight identifier, departure time, arrival time, departure airport, arrival airport, ground delay at each airport, and real-world flight trajectories. To generate results for a given flight within AEDT, the radar-informed aircraft data is correlated with engine and aircraft performance data to calculate fuel burn and exhaust emissions. Information on exhaust emissions for in-production aircraft engines comes from the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank (EDB). This bottom-up approach is in accordance with the Tier 3B method from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

**International Bunkers**: The IPCC guidelines define international aviation (International Bunkers) as emissions from flights that depart in one country and arrive in a different country. Bunker fuel emissions estimates for commercial aircraft were developed for this report for 2000 through 2011 using the same radar-informed data modeled with AEDT. Since this process builds estimates from flight-specific information, the emissions estimates for commercial aircraft can include emissions associated with the U.S. territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands). However, to allow for the alignment of emissions estimates for commercial aircraft with other data that is provided without the U.S. territories, this annex includes emissions estimates for commercial aircraft both with and without the U.S. territories included.

**Analysis Scope and Next Steps**: Previous reports included data for inventory years 2000 through 2005 that were modeled using the FAA's System for assessing Aviation's Global Emissions (SAGE). That tool was incorporated into AEDT; and, for this report inventory years 2000 and 2005 were regenerated using radar-informed data and the same AEDT model version that were used to generate the 2010 and 2011 inventories. Data for years 2001 through 2004 have been estimated from the previously reported SAGE data.[51]

The radar-informed method that will be used to estimate emissions for commercial aircraft for all years 2000 through 2011 is not possible for 1990 through 1999 because the radar data set is not available for years prior to 2000. FAA is developing OAG schedule-informed inventories modeled with AEDT and great circle trajectories for 1990, 2000 and 2010 to generate the best possible jet fuel burn estimate for 1990.

**Methane Emissions**: Contributions of methane ($CH_4$) emissions from commercial aircraft are reported as zero. The U.S. Environmental Protection Agency by publishing that "…methane is no longer considered to be an emission from aircraft gas turbine engines burning Jet A at higher power settings and is, in fact, consumed in net at these higher powers."[52] In accordance with the following statements in the 2006 IPCC Guidelines (IPCC 2006), the FAA does not calculate $CH_4$ emissions for either the domestic or international bunker commercial aircraft jet fuel emissions inventories. "Methane ($CH_4$) may be emitted by gas turbines during idle and by older technology engines, but recent data suggest that little or no $CH_4$ is emitted by modern engines." "Current scientific understanding does not allow other gases (e.g., $N_2O$ and $CH_4$) to be included in calculation of cruise emissions." (IPCC 1999).

**Results**: The graph and table below, four jet fuel burn values are reported for each calendar year. These values are comprised of domestic and international fuel burn totals for the US 50 States and the US 50 States + Territories. Data are presented for domestic defined as jet fuel burn from any commercial aircraft flight departing and landing in the US 50 States and for the US 50 States + Territories. The data presented as international is respective of the two different domestic definitions, and represents flights departing from the specified domestic area and landing anywhere in the world outside of that area.

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[51] Additional information on the AEDT modeling process is available at <http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models>

[52] Recommended Best Practice for Quantifying Speciated Organic Gas Emissions from Aircraft Equipped with Turbofan, Turbojet and Turboprop Engines, EPA-420-R-09-901, May 27, 2009, Available at <http://www.epa.gov/otaq/aviation.htm>.

Note that the graph and table present less fuel burn for the international US 50 States + Territories than for the international US 50 States. This is because the flights between the 50 states and US Territories are "international" when only the 50 states are defined as domestic, but they are "domestic" for the US 50 States + Territories definition.

Figure A- 5: Commercial Aviation Fuel Burn for the United States and Territories

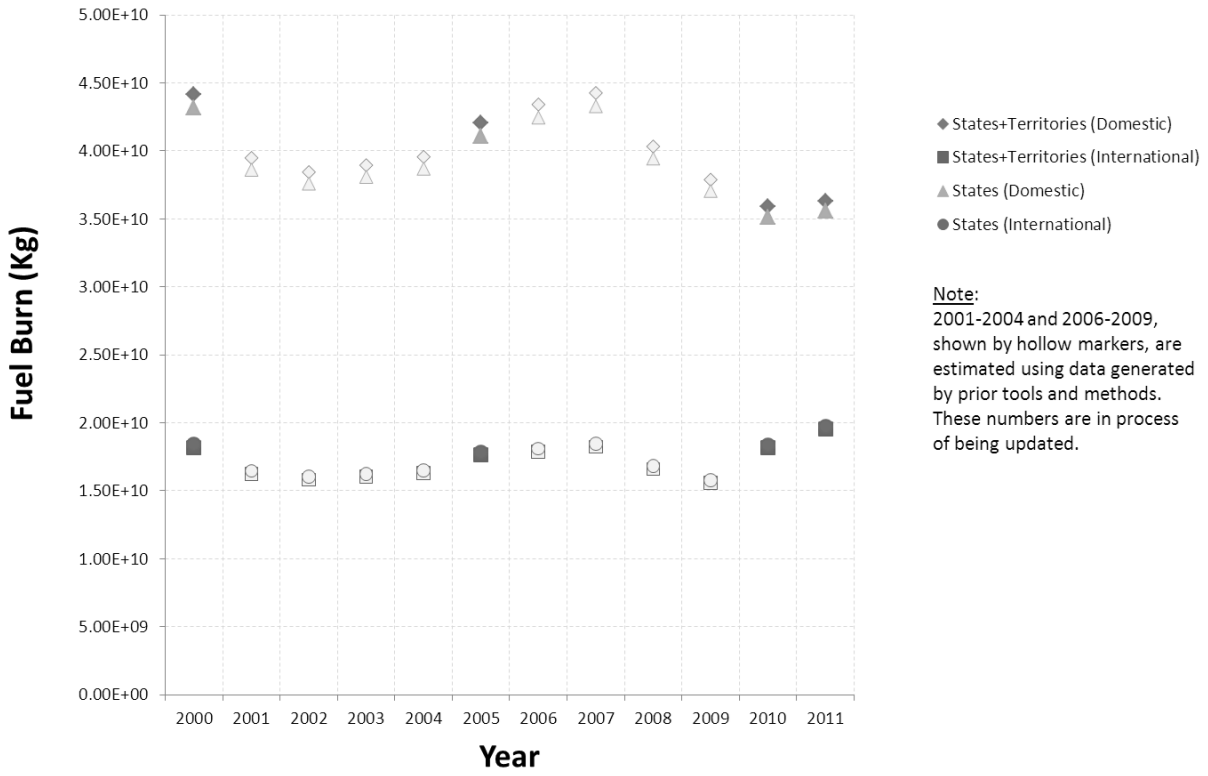



Table A- 116: Commercial Aviation Fuel Burn for the United States and Territories

| Year | Region | Fuel Burn (Kg) | $CO_2$ Emissions (Tg) |
|---|---|---|---|
| 2000 | Domestic US 50 States and US Territories | 139,330,609,451 | 139.33 |
| | International US 50 States and US Territories | 57,362,743,109 | 57.36 |
| | Domestic US 50 States | 136,267,605,638 | 136.27 |
| | International US 50 States | 58,090,395,128 | 58.09 |
| 2001 | Domestic US 50 States and US Territories | 124,601,857,298 | 124.60 |
| | International US 50 States and US Territories | 51,298,880,836 | 51.30 |
| | Domestic US 50 States | 121,862,646,111 | 121.86 |
| | International US 50 States | 51,949,612,168 | 51.95 |
| 2002 | Domestic US 50 States and US Territories | 121,309,990,597 | 121.31 |
| | International US 50 States and US Territories | 49,943,611,490 | 49.94 |
| | Domestic US 50 States | 118,643,146,856 | 118.64 |
| | International US 50 States | 50,577,151,097 | 50.58 |
| 2003 | Domestic US 50 States and US Territories | 122,908,897,280 | 122.91 |
| | International US 50 States and US Territories | 50,601,885,172 | 50.60 |

| Year | Region | Fuel Burn (Kg) | $CO_2$ Emissions (Tg) |
|---|---|---|---|
| | Domestic US 50 States | 120,206,903,637 | 120.21 |
| | International US 50 States | 51,243,775,046 | 51.24 |
| 2004 | Domestic US 50 States and US Territories | 124,846,395,967 | 124.85 |
| | International US 50 States and US Territories | 51,399,557,987 | 51.40 |
| | Domestic US 50 States | 122,101,808,913 | 122.10 |
| | International US 50 States | 52,051,566,418 | 52.05 |
| 2005 | Domestic US 50 States and US Territories | 132,723,160,436 | 132.72 |
| | International US 50 States and US Territories | 55,633,717,996 | 55.63 |
| | Domestic US 50 States | 129,665,323,866 | 129.67 |
| | International US 50 States | 56,376,609,705 | 56.38 |
| 2006 | Domestic US 50 States and US Territories | 136,998,086,760 | 137.00 |
| | International US 50 States and US Territories | 56,402,437,972 | 56.40 |
| | Domestic US 50 States | 133,986,360,451 | 133.99 |
| | International US 50 States | 57,117,908,426 | 57.12 |
| 2007 | Domestic US 50 States and US Territories | 139,669,201,455 | 139.67 |
| | International US 50 States and US Territories | 57,502,142,241 | 57.50 |
| | Domestic US 50 States | 136,598,754,133 | 136.60 |
| | International US 50 States | 58,231,562,552 | 58.23 |
| 2008 | Domestic US 50 States and US Territories | 127,254,161,326 | 127.25 |
| | International US 50 States and US Territories | 52,390,840,709 | 52.39 |
| | Domestic US 50 States | 124,456,642,654 | 124.46 |
| | International US 50 States | 53,055,423,658 | 53.06 |
| 2009 | Domestic US 50 States and US Territories | 119,541,787,912 | 119.54 |
| | International US 50 States and US Territories | 49,215,638,242 | 49.22 |
| | Domestic US 50 States | 116,913,815,827 | 116.91 |
| | International US 50 States | 49,839,943,437 | 49.84 |
| 2010 | Domestic US 50 States and US Territories | 113,304,643,683 | 113.30 |
| | International US 50 States and US Territories | 57,398,769,606 | 57.40 |
| | Domestic US 50 States | 110,793,703,538 | 110.79 |
| | International US 50 States | 58,048,834,984 | 58.05 |
| 2011 | Domestic US 50 States and US Territories | 114,593,293,653 | 114.59 |
| | International US 50 States and US Territories | 61,685,398,768 | 61.69 |
| | Domestic US 50 States | 112,282,521,479 | 112.28 |
| | International US 50 States | 62,238,822,604 | 62.24 |

Note: These data are estimated using data generated by prior tools and methods. These numbers are in process of being updated.

## 3.4. Methodology for Estimating $CH_4$ Emissions from Coal Mining

The methodology for estimating $CH_4$ emissions from coal mining consists of two distinct steps. The first step addresses emissions from underground mines. For these mines, emissions are estimated on a mine-by-mine basis and then are summed to determine total emissions. The second step of the analysis involves estimating $CH_4$ emissions for surface mines and post-mining activities. In contrast to the methodology for underground mines, which uses mine-specific data, the surface mine and post-mining activities analysis consists of multiplying basin-specific coal production by basin-specific emission factors.

#### Step 1: Estimate $CH_4$ Liberated and $CH_4$ Emitted from Underground Mines

Underground mines generate $CH_4$ from ventilation systems and from degasification systems. Some mines recover and use $CH_4$ generated from degasification systems, thereby reducing emissions to the atmosphere. Total $CH_4$ emitted from underground mines equals the $CH_4$ liberated from ventilation systems, plus the $CH_4$ liberated from degasification systems, minus $CH_4$ recovered and used.

##### *Step 1.1: Estimate $CH_4$ Liberated from Ventilation Systems*

All coal mines with detectable $CH_4$ emissions[53] use ventilation systems to ensure that $CH_4$ levels remain within safe concentrations. Many coal mines do not have detectable levels of $CH_4$, while others emit several million cubic feet per day (MMCFD) from their ventilation systems. On a quarterly basis, the U.S. Mine Safety and Health Administration (MSHA) measures $CH_4$ emissions levels at underground mines. MSHA maintains a database of measurement data from all underground mines with detectable levels of $CH_4$ in their ventilation air. Based on the four quarterly measurements, MSHA estimates average daily $CH_4$ liberated at each of the underground mines with detectable emissions.

For the years 1990 through 1996, 1998 through 2006, and 2008 through 2011, MSHA emissions data were obtained for a large but incomplete subset of all mines with detectable emissions. This subset includes mines emitting at least 0.1 MMCFD for some years and at least 0.5 MMCFD for other years, as shown in Table A- 117. Well over 90 percent of all ventilation emissions were concentrated in these subsets. For 1997 and 2007, the complete MSHA databases for all 586 mines (in 1997) and 730 mines (in 2007) with detectable $CH_4$ emissions were obtained. These mines were assumed to account for 100 percent of $CH_4$ liberated from underground mines. Using the complete database from 1997, the proportion of total emissions accounted for by mines emitting less than 0.1 MMCFD or 0.5 MMCFD was estimated (see Table A- 117). The proportion was then applied to the years 1990 through 2006 to account for the less than 5 percent of ventilation emissions coming from mines without MSHA data.

For 1990 through 1999, average daily $CH_4$ emissions were multiplied by the number of days in the year (i.e., coal mine assumed in operation for all four quarters) to determine the annual emissions for each mine. For 2000 through 2011, MSHA provided quarterly emissions. The average daily $CH_4$ emissions were multiplied by the number of days corresponding to the number of quarters the mine vent was operating. For example, if the mine vent was operational in one out of the four quarters, the average daily $CH_4$ emissions were multiplied by 92 days. Total ventilation emissions for a particular year were estimated by summing emissions from individual mines.

During 2009-2011, one coal mine destroyed a portion of its $CH_4$ emissions from ventilation systems using thermal oxidation technology.

[53] MSHA records coal mine methane readings with concentrations of greater than 50 ppm (parts per million) methane. Readings below this threshold are considered non-detectable.

Table A- 117: Mine-Specific Data Used to Estimate Ventilation Emissions

| Year | Individual Mine Data Used |
|---|---|
| 1990 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 1991 | 1990 Emissions Factors Used Instead of Mine-Specific Data |
| 1992 | 1990 Emissions Factors Used Instead of Mine-Specific Data |
| 1993 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 1994 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 1995 | All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total)* |
| 1996 | All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total)* |
| 1997 | All Mines with Detectable Emissions (Assumed to Account for 100% of Total) |
| 1998 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 1999 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 2000 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 2001 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 2002 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 2003 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 2004 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 2005 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 2006 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)* |
| 2007 | All Mines with Detectable Emissions (Assumed to Account for 100% of Total) |
| 2008 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)** |
| 2009 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)** |
| 2010 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)** |
| 2011 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)** |

* Factor derived from a complete set of individual mine data collected for 1997.
** Factor derived from a complete set of individual mine data collected for 2007.

### *Step 1.2: Estimate $CH_4$ Liberated from Degasification Systems*

Coal mines use several different types of degasification systems to remove $CH_4$, including vertical wells and horizontal boreholes to recover $CH_4$ prior to mining of the coal seam. Gob wells and cross-measure boreholes recover $CH_4$ from the overburden (i.e., gob area) after mining of the seam (primarily in longwall mines).

MSHA collects information about the presence and type of degasification systems in some mines, but does not collect quantitative data on the amount of $CH_4$ liberated. Thus, the methodology estimated degasification emissions on a mine-by-mine basis based on other sources of available data. Many of the coal mines employing degasification systems have provided EPA with information regarding $CH_4$ liberated from their degasification systems. For these mines, this reported information was used as the estimate. In other cases in which mines sell $CH_4$ recovered from degasification systems to a pipeline, gas sales were used to estimate $CH_4$ liberated from degasification systems (see Step 1.3). Finally, for those mines that do not sell $CH_4$ to a pipeline and have not provided information to EPA, $CH_4$ liberated from degasification systems was estimated based on the type of system employed. For example, for coal mines employing gob wells and horizontal boreholes, the methodology assumes that degasification emissions account for 40 percent of total $CH_4$ liberated from the mine.

### *Step 1.3: Estimate $CH_4$ Recovered from Degasification Systems and Utilized (Emissions Avoided)*

In 2011, fourteen active coal mines had $CH_4$ recovery and use projects. All fourteen mines sold the recovered $CH_4$ to a pipeline. One of the mines that sold gas to a pipeline also used $CH_4$ to fuel a thermal coal dryer. In order to calculate emissions avoided from pipeline sales, information was needed regarding the amount of gas recovered and the number of years in advance of mining that wells were drilled. Several state agencies provided gas sales data, which were used to estimate emissions avoided for these projects. Additionally, coal mine operators provided information on gas sales and/or the number of years in advance of mining. Emissions avoided were attributed to the year in which the coal seam was mined. For example, if a coal mine recovered and sold $CH_4$ using a vertical well drilled five years in advance of mining, the emissions avoided associated with those gas sales (cumulative production) were attributed to the well at the time it was mined through (e.g., five years of gas production). Where individual well data is not available, estimated percentages of the operator's annual gas sales within the field around the coal mine are attributed to emissions avoidance. For some mines, individual well data were used to assign gas sales to the appropriate emissions avoided year. In most cases, coal mine operators provided this information, which was then used to estimate emissions avoided for a particular year. Additionally, several state agencies provided production data for individual wells.

### Step 2: Estimate $CH_4$ Emitted from Surface Mines and Post-Mining Activities

Mine-specific data were not available for estimating $CH_4$ emissions from surface coal mines or for post-mining activities. For surface mines and post-mining activities, basin-specific coal production was multiplied by a basin-specific emission factor to determine $CH_4$ emissions.

#### *Step 2.1: Define the Geographic Resolution of the Analysis and Collect Coal Production Data*

The first step in estimating $CH_4$ emissions from surface mining and post-mining activities was to define the geographic resolution of the analysis and to collect coal production data at that level of resolution. The analysis was conducted by coal basin as defined in Table A- 118, which presents coal basin definitions by basin and by state.

The Energy Information Administration's (EIA) Annual Coal Report includes state- and county-specific underground and surface coal production by year. To calculate production by basin, the state level data were grouped into coal basins using the basin definitions listed in Table A- 118. For two states—West Virginia and Kentucky—county-level production data was used for the basin assignments because coal production occurred from geologically distinct coal basins within these states. Table A- 119 presents the coal production data aggregated by basin.

#### *Step 2.2: Estimate Emissions Factors for Each Emissions Type*

Emission factors for surface mined coal were developed from the *in situ* $CH_4$ content of the surface coal in each basin. Based on an analysis presented in EPA (1993), surface mining emission factors were estimated to be from 1 to 3 times the average *in situ* $CH_4$ content in the basin. For this analysis, the surface mining emission factor was determined to be twice the *in situ* $CH_4$ content in the basin. Furthermore, the post-mining emission factors used were estimated to be 25 to 40 percent of the average *in situ* $CH_4$ content in the basin. For this analysis, the post-mining emission factor was determined to be 32.5 percent of the *in situ* $CH_4$ content in the basin. Table A- 120 presents the average *in situ* content for each basin, along with the resulting emission factor estimates.

#### *Step 2.3: Estimate $CH_4$ Emitted*

The total amount of $CH_4$ emitted was calculated by multiplying the coal production in each basin by the appropriate emission factors.

Total annual $CH_4$ emissions are equal to the sum of underground mine emissions plus surface mine emissions plus post-mining emissions.

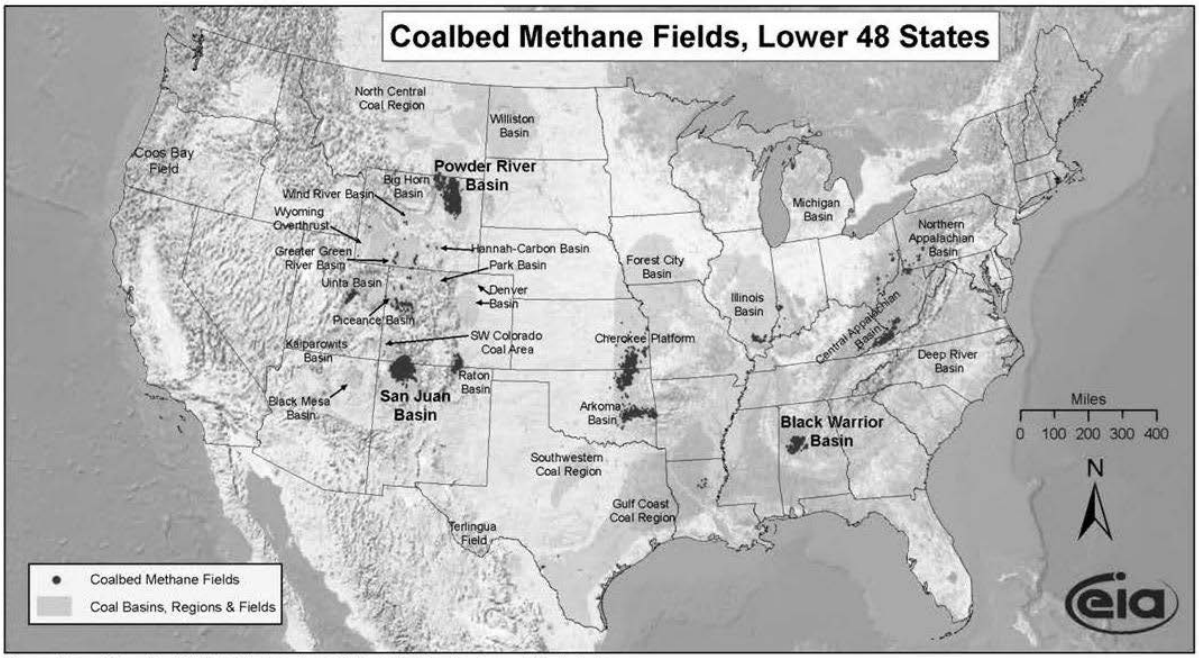
Table A- 116 lists each of the major coal mine basins in the U.S. and the states in which they are located. As shown in Figure A- 6. Several coal basins span several states. Table A- 117 shows annual underground, surface, and total coal production (in short tons) for each coal basin. Table A- 118 shows the surface, post-surface, and post-underground emission factors used for estimating $CH_4$ emissions for each of the categories. Table A- 121 presents annual estimates of $CH_4$ emissions for ventilation and degasification systems, and $CH_4$ used and emitted by underground coal mines. Table A- 122 presents annual estimates of total $CH_4$ emissions from underground, post-underground, surface, and post-surface activities. Table A- 123 provides the total net $CH_4$ emissions by state.

Table A- 118: Coal Basin Definitions by Basin and by State

| Basin | States |
|---|---|
| Northern Appalachian Basin | Maryland, Ohio, Pennsylvania, West Virginia North |
| Central Appalachian Basin | Kentucky East, Tennessee, Virginia, West Virginia South |
| Warrior Basin | Alabama, Mississippi |
| Illinois Basin | Illinois, Indiana, Kentucky West |
| South West and Rockies Basin | Arizona, California, Colorado, New Mexico, Utah |
| North Great Plains Basin | Montana, North Dakota, Wyoming |
| West Interior Basin | Arkansas, Iowa, Kansas, Louisiana, Missouri, Oklahoma, Texas |
| Northwest Basin | Alaska, Washington |
| **State** | **Basin** |
| Alabama | Warrior Basin |
| Alaska | Northwest Basin |
| Arizona | South West and Rockies Basin |
| Arkansas | West Interior Basin |
| California | South West and Rockies Basin |
| Colorado | South West and Rockies Basin |
| Illinois | Illinois Basin |
| Indiana | Illinois Basin |
| Iowa | West Interior Basin |

| | |
|---|---|
| Kansas | West Interior Basin |
| Kentucky East | Central Appalachian Basin |
| Kentucky West | Illinois Basin |
| Louisiana | West Interior Basin |
| Maryland | Northern Appalachian Basin |
| Mississippi | Warrior Basin |
| Missouri | West Interior Basin |
| Montana | North Great Plains Basin |
| New Mexico | South West and Rockies Basin |
| North Dakota | North Great Plains Basin |
| Ohio | Northern Appalachian Basin |
| Oklahoma | West Interior Basin |
| Pennsylvania. | Northern Appalachian Basin |
| Tennessee | Central Appalachian Basin |
| Texas | West Interior Basin |
| Utah | South West and Rockies Basin |
| Virginia | Central Appalachian Basin |
| Washington | Northwest Basin |
| West Virginia South | Central Appalachian Basin |
| West Virginia North | Northern Appalachian Basin |
| Wyoming | North Great Plains Basin |

Figure A- 6: Locations of U.S Coal Basins




Source: Energy Information Administration based on data from USGS and various published studies
Updated: April 8, 2009

Table A-119: Annual Coal Production (Thousand Short Tons)

| Basin | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Underground Coal Production** | **423,556** | **396,249** | **372,766** | **380,627** | **357,384** | **352,785** | **367,558** | **368,611** | **359,020** | **351,791** | **357,074** | **332,061** | **337,155** | **345,607** |
| N. Appalachia | 103,865 | 98,103 | 105,374 | 107,025 | 98,643 | 98,369 | 106,915 | 111,151 | 107,827 | 106,024 | 105,228 | 99,629 | 103,109 | 105,752 |
| Cent. Appalachia | 198,412 | 166,495 | 150,584 | 152,457 | 137,224 | 130,724 | 128,559 | 123,083 | 117,738 | 110,103 | 114,998 | 98,689 | 96,354 | 94,034 |
| Warrior | 17,531 | 17,605 | 15,895 | 15,172 | 14,916 | 15,375 | 16,114 | 13,295 | 10,737 | 11,462 | 12,281 | 11,505 | 12,513 | 10,879 |
| Illinois | 69,167 | 69,009 | 53,720 | 54,364 | 54,016 | 51,780 | 56,320 | 59,180 | 61,726 | 61,924 | 64,609 | 67,186 | 72,178 | 81,089 |
| S. West/Rockies | 32,754 | 42,994 | 45,742 | 51,193 | 52,121 | 56,111 | 59,039 | 60,865 | 59,670 | 58,815 | 55,781 | 50,416 | 44,368 | 45,139 |
| N. Great Plains | 1,722 | 2,018 | 1,210 | 0 | 0 | 32 | 201 | 572 | 840 | 2,869 | 3,669 | 4,248 | 8,208 | 8,179 |
| West Interior | 105 | 25 | 241 | 416 | 464 | 394 | 410 | 465 | 482 | 594 | 508 | 388 | 425 | 535 |
| Northwest | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Surface Coal Production** | **602,753** | **636,726** | **700,608** | **745,306** | **735,912** | **717,869** | **743,553** | **762,191** | **802,975** | **793,689** | **813,321** | **740,175** | **764,709** | **754,871** |
| N. Appalachia | 60,761 | 39,372 | 34,908 | 35,334 | 30,088 | 27,370 | 28,174 | 28,873 | 28,376 | 26,121 | 30,413 | 26,552 | 26,082 | 26,382 |
| Cent. Appalachia | 94,343 | 106,250 | 110,479 | 116,983 | 111,340 | 99,419 | 103,968 | 112,222 | 118,388 | 116,226 | 118,962 | 97,778 | 89,788 | 90,778 |
| Warrior | 11,413 | 7,036 | 4,252 | 4,796 | 6,320 | 8,437 | 9,742 | 11,599 | 11,889 | 11,410 | 11,172 | 10,731 | 11,406 | 10,939 |
| Illinois | 72,000 | 40,376 | 33,631 | 40,894 | 39,380 | 36,675 | 34,016 | 33,702 | 33,362 | 33,736 | 34,266 | 34,837 | 32,911 | 34,943 |
| S. West/Rockies | 43,863 | 46,643 | 49,587 | 52,180 | 50,006 | 41,237 | 42,558 | 42,756 | 36,798 | 34,310 | 34,283 | 32,167 | 28,889 | 31,432 |
| N. Great Plains | 249,356 | 331,367 | 407,670 | 438,367 | 441,346 | 444,007 | 466,224 | 474,056 | 518,136 | 523,695 | 538,387 | 496,290 | 507,995 | 502,734 |
| West Interior | 64,310 | 59,116 | 54,170 | 50,613 | 50,459 | 53,411 | 51,706 | 52,263 | 52,021 | 46,867 | 44,361 | 39,960 | 46,136 | 55,514 |
| Northwest | 6,707 | 6,566 | 5,911 | 6,138 | 6,973 | 7,313 | 7,165 | 6,720 | 4,005 | 1,324 | 1,477 | 1,860 | 2,151 | 2,149 |
| **Total Coal Production** | **1,026,309** | **1,032,975** | **1,073,374** | **1,125,933** | **1,093,296** | **1,070,654** | **1,111,111** | **1,130,802** | **1,161,995** | **1,145,478** | **1,170,395** | **1,072,236** | **1,101,864** | **1,100,478** |
| N. Appalachia | 164,626 | 137,475 | 140,282 | 142,360 | 128,731 | 125,739 | 135,089 | 140,024 | 136,203 | 132,143 | 135,641 | 126,181 | 129,191 | 132,134 |
| Cent. Appalachia | 292,755 | 272,745 | 261,063 | 269,440 | 248,564 | 230,143 | 232,527 | 235,305 | 236,126 | 226,328 | 233,960 | 196,467 | 186,142 | 184,812 |
| Warrior | 28,944 | 24,641 | 20,147 | 19,967 | 21,236 | 23,812 | 25,856 | 24,894 | 22,626 | 22,872 | 23,453 | 22,236 | 23,919 | 21,818 |
| Illinois | 141,167 | 109,385 | 87,351 | 95,258 | 93,396 | 88,455 | 90,336 | 92,882 | 95,088 | 95,660 | 98,875 | 102,023 | 105,089 | 116,032 |
| S. West/Rockies | 76,617 | 89,637 | 95,329 | 103,373 | 102,127 | 97,348 | 101,597 | 103,621 | 96,468 | 93,125 | 90,064 | 82,583 | 73,257 | 76,571 |
| N. Great Plains | 251,078 | 333,385 | 408,880 | 438,367 | 441,346 | 444,039 | 466,425 | 474,628 | 518,976 | 526,564 | 542,056 | 500,538 | 516,203 | 510,913 |
| West Interior | 64,415 | 59,141 | 54,411 | 51,028 | 50,923 | 53,805 | 52,116 | 52,728 | 52,503 | 47,462 | 44,869 | 40,348 | 46,561 | 56,049 |
| Northwest | 6,707 | 6,566 | 5,911 | 6,138 | 6,973 | 7,313 | 7,165 | 6,720 | 4,005 | 1,324 | 1,477 | 1,860 | 2,151 | 2,149 |

Source for 1990-2010 data: EIA (1990 through 2010), Annual Coal Report. U.S. Department of Energy, Washington, DC, Table 1. Source for 2011 data: spreadsheet for the 2011 Annual Coal Report.
Note: Totals may not sum due to independent rounding.

Table A-120: Coal Underground, Surface, and Post-Mining $CH_4$ Emission Factors ($ft^3$ per Short Ton)

| Basin | Surface Average *in situ* Content | Underground Average *In situ* Content | Surface Mine Factors | Post-Mining Surface Factors | Post Mining Underground |
|---|---|---|---|---|---|
| Northern Appalachia | 59.5 | 138.4 | 119.0 | 19.3 | 45.0 |
| Central Appalachia (WV) | 24.9 | 136.8 | 49.8 | 8.1 | 44.5 |
| Central Appalachia (VA) | 24.9 | 399.1 | 49.8 | 8.1 | 129.7 |
| Central Appalachia (E KY) | 24.9 | 61.4 | 49.8 | 8.1 | 20.0 |
| Warrior | 30.7 | 266.7 | 61.4 | 10.0 | 86.7 |
| Illinois | 34.3 | 64.3 | 68.6 | 11.1 | 20.9 |
| Rockies (Piceance Basin) | 33.1 | 196.4 | 66.2 | 10.8 | 63.8 |
| Rockies (Uinta Basin) | 16.0 | 99.4 | 32.0 | 5.2 | 32.3 |
| Rockies (San Juan Basin) | 7.3 | 104.8 | 14.6 | 2.4 | 34.1 |
| Rockies (Green River Basin) | 33.1 | 247.2 | 66.2 | 10.8 | 80.3 |
| Rockies (Raton Basin) | 33.1 | 127.9 | 66.2 | 10.8 | 41.6 |
| N. Great Plains (WY, MT) | 20.0 | 15.8 | 40.0 | 6.5 | 5.1 |
| N. Great Plains (ND) | 5.6 | 15.8 | 11.2 | 1.8 | 5.1 |
| West Interior (Forest City, Cherokee Basins) | 34.3 | 64.3 | 68.6 | 11.1 | 20.9 |

| | | | | | |
|---|---|---|---|---|---|
| West Interior (Arkoma Basin) | 74.5 | 331.2 | 149.0 | 24.2 | 107.6 |
| West Interior (Gulf Coast Basin) | 11.0 | 127.9 | 22.0 | 3.6 | 41.6 |
| Northwest (AK) | 16.0 | 160.0 | 32.0 | 1.8 | 52.0 |
| Northwest (WA) | 16.0 | 47.3 | 32.0 | 5.2 | 15.4 |

Sources: 1986 USBM Circular 9067, *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*, 1983 U.S. DOE Report (DOE/METC/83-76), *Methane Recovery from Coalbeds: A Potential Energy Source*, 1986-88 Gas Research Institute Topical Reports, A Geologic Assessment of Natural Gas from Coal Seams; *Surface Mines Emissions Assessment*, U.S. EPA Draft Report, November 2005.

Table A-121: Underground Coal Mining $CH_4$ Emissions (Billion Cubic Feet)

| Activity | 1990 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ventilation Output | 112 | 96 | 94 | 92 | 87 | 84 | 79 | 76 | 83 | 75 | 79 | 81 | 100 | 114 | 117 | 97 |
| Adjustment Factor for Mine Data* | 97.8% | 100.0% | 97.8% | 97.8% | 97.8% | 97.8% | 97.8% | 97.8% | 97.8% | 97.8% | 97.8% | 100.0% | 99.0% | 99.0% | 99% | 99% |
| Adjusted Ventilation Output | 114 | 96 | 96 | 94 | 89 | 86 | 80 | 77 | 84 | 77 | 80 | 81 | 101 | 115 | 118 | 98 |
| Degasification System Liberated | 54 | 43 | 49 | 40 | 45 | 49 | 51 | 50 | 45 | 48 | 54 | 45 | 49 | 49 | 58 | 48 |
| Total Underground Liberated | 168 | 139 | 146 | 134 | 134 | 135 | 131 | 127 | 130 | 124 | 134 | 126 | 150 | 163 | 177 | 146 |
| Recovered & Used | (14) | (28) | (35) | (31) | (37) | (41) | (43) | (38) | (40) | (37) | (46) | (37) | (40) | (40) | (49) | (41) |
| **Total** | **154** | **111** | **110** | **103** | **98** | **95** | **88** | **89** | **90** | **87** | **88** | **88** | **110** | **123** | **128** | **105** |

* Refer to Table A-117.

Note: Totals may not sum due to independent rounding.

Table A-122: Total Coal Mining $CH_4$ Emissions (Billion Cubic Feet)

| Activity | 1990 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Underground Mining | 154 | 111 | 110 | 103 | 98 | 95 | 88 | 89 | 90 | 87 | 88 | 88 | 110 | 123 | 128 | 105 |
| Surface Mining | 30 | 30 | 31 | 31 | 30 | 33 | 32 | 31 | 32 | 33 | 35 | 34 | 35 | 32 | 32 | 32 |
| Post-Mining (Underground) | 19 | 18 | 18 | 17 | 17 | 17 | 16 | 16 | 16 | 16 | 15 | 15 | 15 | 14 | 14 | 14 |
| Post-Mining (Surface) | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 6 | 5 | 5 | 5 |
| **Total** | **208** | **164** | **165** | **156** | **149** | **149** | **140** | **141** | **144** | **141** | **144** | **143** | **166** | **174** | **179** | **156** |

Note: Totals may not sum due to independent rounding.

Table A-123: Total Coal Mining $CH_4$ Emissions by State (Million Cubic Feet)

| State | 1990 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alabama | 32,272 | 26,426 | 26,440 | 25,677 | 23,342 | 21,896 | 18,686 | 19,288 | 18,246 | 15,912 | 14,699 | 17,159 | 21,120 | 22,231 | 21,490 | 19,054 |
| Alaska | 63 | 54 | 50 | 58 | 61 | 56 | 43 | 40 | 56 | 54 | 53 | 49 | 55 | 69 | 80 | 80 |
| Arizona | 192 | 199 | 192 | 200 | 223 | 228 | 217 | 205 | 216 | 205 | 139 | 135 | 136 | 127 | 132 | 138 |
| Arkansas | 7 | 3 | 4 | 4 | 2 | 2 | 2 | 1 | 1 | 1 | 4 | 144 | 237 | 119 | 130 | 349 |
| California | 1 | - | + | + | + | + | + | + | + | + | + | + | - | - | - | - |
| Colorado | 10,325 | 9,189 | 9,181 | 9,390 | 10,808 | 11,117 | 12,082 | 13,216 | 12,582 | 13,608 | 13,102 | 13,180 | 12,998 | 14,100 | 16,554 | 11,276 |
| Illinois | 10,502 | 8,534 | 7,847 | 7,810 | 8,542 | 7,270 | 5,972 | 4,744 | 5,798 | 6,586 | 6,954 | 4,493 | 7,759 | 7,322 | 8,707 | 7,665 |
| Indiana | 2,795 | 2,742 | 2,878 | 2,650 | 2,231 | 3,373 | 3,496 | 3,821 | 3,531 | 3,702 | 4,029 | 4,347 | 5,452 | 6,155 | 6,293 | 6,562 |
| Iowa | 30 | - | + | + | + | + | + | + | + | + | + | + | - | - | - | - |
| Kansas | 57 | 29 | 27 | 33 | 16 | 14 | 16 | 12 | 6 | 14 | 34 | 33 | 18 | 15 | 11 | 3 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kentucky | 10,956 | | 10,451 | 10,005 | 9,561 | 9,105 | 9,363 | 8,464 | 8,028 | 7,926 | 7,494 | 9,135 | 9,278 | 10,641 | 12,617 | 12,847 | 11,175 |
| Louisiana | 81 | | 91 | 82 | 76 | 94 | 95 | 97 | 103 | 97 | 106 | 105 | 80 | 98 | 94 | 101 | 214 |
| Maryland | 519 | | 267 | 251 | 225 | 331 | 340 | 401 | 391 | 411 | 421 | 435 | 261 | 325 | 273 | 294 | 325 |
| Mississippi | - | | - | 0 | 1 | 57 | 43 | 165 | 264 | 256 | 254 | 271 | 253 | 203 | 246 | 286 | 196 |
| Missouri | 211 | | 32 | 30 | 31 | 35 | 29 | 20 | 43 | 46 | 48 | 31 | 19 | 20 | 36 | 37 | 37 |
| Montana | 1,749 | | 1,906 | 1,992 | 1,911 | 1,783 | 1,820 | 1,738 | 1,719 | 1,853 | 1,870 | 1,931 | 2,016 | 2,076 | 1,804 | 1,898 | 1,834 |
| Mew Mexico | 451 | | 459 | 489 | 497 | 464 | 630 | 1,280 | 1,864 | 2,052 | 3,001 | 2,970 | 2,660 | 3,479 | 3,904 | 4,014 | 4,253 |
| North Dakota | 380 | | 385 | 389 | 405 | 407 | 397 | 401 | 401 | 390 | 390 | 396 | 385 | 386 | 390 | 377 | 368 |
| Ohio | 5,065 | | 4,349 | 4,350 | 3,914 | 3,519 | 3,619 | 2,831 | 2,649 | 3,183 | 3,385 | 3,413 | 2,672 | 3,959 | 4,746 | 3,889 | 4,183 |
| Oklahoma | 285 | | 385 | 395 | 469 | 454 | 620 | 660 | 620 | 849 | 877 | 658 | 774 | 970 | 646 | 459 | 387 |
| Pennsylvania | 22,735 | | 30,026 | 30,888 | 24,867 | 24,830 | 22,252 | 19,668 | 20,281 | 20,020 | 18,289 | 18,727 | 19,519 | 21,044 | 23,216 | 23,697 | 18,061 |
| Tennessee | 296 | | 148 | 116 | 119 | 99 | 142 | 142 | 124 | 136 | 140 | 117 | 120 | 105 | 84 | 82 | 74 |
| Texas | 1,426 | | 1,364 | 1,345 | 1,357 | 1,240 | 1,152 | 1,157 | 1,215 | 1,173 | 1,175 | 1,165 | 1,073 | 998 | 898 | 1,048 | 1,174 |
| Utah | 3,587 | | 3,566 | 3,859 | 3,633 | 2,816 | 2,080 | 2,709 | 3,408 | 5,253 | 4,787 | 5,445 | 3,678 | 5,524 | 5,449 | 5,628 | 3,651 |
| Virginia | 46,137 | | 16,851 | 13,978 | 13,321 | 12,065 | 11,506 | 11,227 | 11,906 | 11,389 | 8,790 | 9,830 | 10,118 | 9,334 | 8,144 | 9,163 | 8,614 |
| Washington | 186 | | 167 | 173 | 153 | 159 | 172 | 217 | 232 | 210 | 196 | 96 | + | - | - | - | - |
| West Virginia | 49,039 | | 33,554 | 35,566 | 33,599 | 30,563 | 33,985 | 31,405 | 28,474 | 29,465 | 30,612 | 29,510 | 29,654 | 37,406 | 41,241 | 41,525 | 36,404 |
| Wyoming | 8,496 | | 12,994 | 14,549 | 15,607 | 15,725 | 17,147 | 17,352 | 17,497 | 18,435 | 18,784 | 20,752 | 20,974 | 21,601 | 19,903 | 20,419 | 20,272 |
| **Total** | **207,844** | | **164,171** | **165,075** | **155,568** | **149,371** | **149,348** | **140,449** | **140,544** | **143,581** | **140,698** | **144,004** | **143,076** | **165,945** | **173,826** | **178,974** | **156,348** |

- Zero Cubic Feet

+ Does not exceed 0.5 Million Cubic Feet

Note: The emission estimates provided above are inclusive of emissions from underground mines, surface mines and post-mining activities. The following states have neither underground nor surface mining and thus report no emissions as a result of coal mining: Connecticut, Delaware, Florida, Georgia, Hawaii, Idaho, Maine, Massachusetts, Michigan, Minnesota, Nebraska, Nevada, New Hampshire, New Jersey, New York, North Carolina, Oregon, Rhode Island, South Carolina, South Dakota, Vermont, and Wisconsin.

## 3.5. Methodology for Estimating $CH_4$ and $CO_2$ Emissions from Natural Gas Systems

As described in the main body text on Natural Gas, the GHG Inventory methodology involves the calculation of $CH_4$ and $CO_2$ emissions for over 100 emissions sources, and then the summation of emissions for each natural gas sector stage.

**Step 1: Calculate Potential Methane**

Potential Methane Factors

The primary basis for potential $CH_4$ factors, and emission factors for non-combustion-related $CO_2$ emissions from the U.S. natural gas industry, is a detailed study by the Gas Research Institute and EPA (EPA/GRI 1996). The EPA/GRI study developed over 80 $CH_4$ emission factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system. Since the time of this study, practices and technologies have changed. While this study still represents best available data in many cases, using these emission factors alone to represent actual emissions without adjusting for emissions controls would in many cases overestimate emissions. For this reason, "potential emissions" are calculated using the data, and then current data on voluntary and regulatory emission reduction activities (step 3) are deducted to calculate actual emissions. See main body text on Natural Gas systems for more information.

For certain $CH_4$ emissions sources, new data and information allows for net emissions to be calculated directly: liquids unloading, condensate storage tanks, and centrifugal compressors. For these sources, EPA has developed emissions factors that directly reflect the use of control technologies. For liquids unloading, separate emissions estimates were developed for wells with plunger lifts, and wells without plunger lifts. Likewise, for condensate tanks, emissions estimates were developed for tanks with and without control devices. Finally, for centrifugal compressors, separate emissions estimates were developed for compressors with wet and dry seals.

For potential methane factors and emission factors used in the Inventory, see Tables A-1 to A-4.

Methane compositions from GTI 2001 are adjusted year to year using gross production for National Energy Modeling System (NEMS) oil and gas supply module regions from the EIA. Therefore, emission factors may vary from year to year due to slight changes in the $CH_4$ composition for each NEMS oil and gas supply module region.

*1990-2011 Inventory updates to potential emission factors and emission factors*

This year's Inventory included an update to emission factors for liquids unloading. Region- and unloading technology- specific emission factors were developed based on API/ANGA 2012. API/ANGA 2012 collected survey data on liquids unloading from over 50,000 wells. The data showed far more widespread use of control technologies than EPA was capturing in its Inventory, and also presented calculated emissions from liquids unloading for wells with and without plunger lifts. Using the API/ANGA data and regional methane contents, EPA developed liquids unloading emissions factors for wells with plunger lifts, and for wells without plunger lifts for each NEMS region. In this new methodology, the emission factors used for liquids unloading are not potential factors, but are factors for actual emissions because control technologies are taken into account through the use of separate emission factors for wells with plunger lifts. The updated factors are included in Table A-1.

In addition, consistent with the analysis for the final oil and gas NSPS, EPA rounded the potential emission factor for completions and workovers with hydraulic fracturing, from 9,175 Mscf gas per completion/workover to 9,000 Mscf gas per completion/workover.

Activity Data

Activity data were taken from the following sources: DrillingInfo, Inc (DrillingInfo 2012), American Gas Association (AGA 1991–1998); Bureau of Ocean Energy Management, Regulation and Enforcement (previous Minerals and Management Service) (BOEMRE 2010a-d); Monthly Energy Review (EIA 2011f); Natural Gas Liquids Reserves Report (EIA 2005); Natural Gas Monthly (EIA 2011b,c,e); the Natural Gas STAR Program annual emissions savings (EPA 2012); Oil and Gas Journal (OGJ 1997–2011); Pipeline and Hazardous Materials Safety Administration (PHMSA 2011); Federal Energy Regulatory Commission (FERC 2011) and other Energy Information Administration publications (EIA 2001, 2004, 2010a,d). Data for estimating emissions from hydrocarbon production tanks were incorporated (EPA 1999). Coalbed $CH_4$ well activity factors were taken from the Wyoming Oil and Gas Conservation Commission (Wyoming 2009) and the Alabama State Oil and Gas Board (Alabama 2010). Activity data are presented in Tables A-1 through A-4.

For many sources, recent direct activity data are not available. For these sources, a set of industry activity data drivers was developed and is used to update activity data. Drivers include statistics on gas production, number of wells,

system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations. For example, recent data on various types of field separation equipment in the production stage (i.e., heaters, separators, and dehydrators) are unavailable. EPA determined that each of these types of field separation equipment relate to the number of non-associated gas wells. Using the number of each type of field separation equipment estimated by GRI/EPA in 1992, and the number of non-associated gas wells in 1992, EPA developed a factor that is used to estimate the number of each type of field separation equipment throughout the time series. The key activity drivers are presented in Table A-5.

*1990-2011 Inventory updates to activity data sources*

Across the 1990-2011 time series, both the underlying data source and the methodology used to generate the well counts for each of the categories (e.g., associated gas wells) was updated from previous years' Inventories. EPA used DI Desktop, a production database maintained by DrillingInfo, Inc. (DrillingInfo) (DrillingInfo 2012), covering U.S. oil and natural gas wells to populate activity data for associated gas wells, non-associated gas wells, gas wells with hydraulic fracturing, and completions with hydraulic fracturing. Updating the well count data source using the DI Desktop data allowed for developing a more transparent, consistent, and reproducible methodology for obtaining well counts. Previously, several different data sources were used in a piecemeal fashion to aggregate well counts for each category. For this year's Inventory, EPA queried DI Desktop for relevant data on an individual well basis—including location, natural gas and liquids (i.e., oil and condensate) production by year, drill type (e.g., horizontal or vertical), and date of completion or first production. Associated gas wells were identified as any well within DI Desktop that EPA classified as producing "oil" or "oil and gas" based on the production type description and that had non-zero natural gas and liquids production. Non-associated gas wells were identified as any well that met either of the following criteria: (1) classified as "oil" or "oil and gas" producing and had zero liquids production, but non-zero natural gas production; or (2) classified as "gas" producing and had non-zero gas production. Both oil and condensate are included in the liquids production data in DI Desktop; therefore, the count of associated gas wells may include wells that produce gas and condensate only. Gas wells with hydraulic fracturing were assumed to be the subset of the non-associated gas wells that were horizontally drilled and/or located in an unconventional formation (i.e., shale, tight sands, or coalbed). Unconventional formations were identified based on well basin, reservoir, and field data reported in DI Desktop referenced against a formation type crosswalk developed by EIA (EIA 2012a). Gas well completions with hydraulic fracturing were identified as a subset of the gas wells with hydraulic fracturing that had a date of completion or first production in the specified year.

Certain states required state-specific steps to count wells more accurately than the output of the standardized DI Desktop queries. For Kentucky, operators were not required to report production data until 1997; therefore, DI Desktop does not contain data until 1997. The 1990-1996 time series well counts were populated by assigning the same well count values across all categories as were calculated from DI Desktop for the year 1997. In addition, Kentucky institutes a one-year lag in making oil and gas production data publicly available. The version of DI Desktop used for developing well counts does not include Kentucky data after 2009. The Kentucky Department for Natural Resources reports 2010 data that EPA used to calculate counts of associated and non-associated gas wells in 2010 (Kentucky 2012). To populate each other well category count in 2010, EPA used the ratio of category count to total non-associated gas wells count from DI Desktop from the year 2009. The 2011 well counts were populated by assigning the same well count values across all categories as were calculated for 2010. For Michigan, operators report data on the basis of "production reporting units" (PRUs) which are groups of wells on a common lease, for which a single production value is reported for the entire group. DI Desktop associates this production value with a single well. For the time series 1990-2011, DI Desktop query logic was altered specifically for Michigan to allocate PRU production equally among all wells composing the PRU to more accurately count individual producing wells. Illinois and Indiana are not included in DI Desktop; therefore, EPA used EIA data for non-associated gas well counts over the entire time series for these states (EIA 2012b). EIA does not report well counts for other categories (e.g., associated gas wells, hydraulically fractured gas wells). To populate each other well category count in a given year, EPA used the ratio of category count to total non-associated gas wells count from DI Desktop from nearby gas producing states of Ohio, Michigan, and Kentucky in that year. Note that the methodology to account for Illinois and Indiana is not anticipated to have a significant impact on the overall Inventory as both of these states have very low gas production compared to other gas producing states.

The methodological update for liquids unloading required updated activity data for use with the new emission factors. The API/ANGA data showed that both wells with and without hydraulic fracturing can have liquids unloading issues, while the Inventory previously only included wells without hydraulic fracturing in its estimates for liquids unloading. This year's Inventory applies liquids unloading emission factors to both wells with and without hydraulic fracturing, using the percentages of wells venting for liquids unloading with plunger lifts, and wells venting without plunger lifts in each region, from the API/ANGA data. API/ANGA data were collected in 2010 and 2011. To determine this activity data element for the time series, for each region, EPA held constant the percentage of wells requiring liquids unloading determined from the API/ANGA data across the 1990-2011 time series. EPA then estimated no plunger lifts

and no artificial lifts in operation in any region in 1990, and then increased this estimate linearly up to the percentage indicated by the API/ANGA data for that region in 2010.

For well completions with hydraulic fracturing, the annual numbers of well completions were updated using DI Desktop data (DrillingInfo 2012). Previous Inventories used data from state websites and had incomplete coverage of completions. In general, completions in tight sands and most shale formations were omitted, due to lack of data. In addition, a refracture rate of 1 percent (i.e., 1 percent of all wells with hydraulic fracturing are assumed to be refractured in a given year) was applied. Previous inventories used a refracture rate of 10 percent. This update is consistent with the analysis for the final oil and gas NSPS.

**Step 2: Compile Reductions Data**

The emissions calculated in Step 1 above represent expected emissions from an activity in the absence of emissions controls (with the exceptions of liquids unloading, centrifugal compressors, and condensate tanks, as noted above), and do not take into account any use of technologies or practices that reduce emissions. To take into account use of such technologies, data are collected on voluntary and regulatory reductions. Voluntary reductions included in the Inventory are those reported to GasSTAR for activities such as voluntary reduced emissions completions, replacing a high bleed pneumatic device with a low bleed device, and replacing wet seals with dry seals at reciprocating compressors. Regulatory actions reducing emissions include state regulations requiring controls at completions with hydraulic fracturing, and NESHAP regulations for dehydrator vents and condensate tanks.

Voluntary reductions. Industry partners report $CH_4$ emission reductions by project to the Natural Gas STAR Program. The reductions from the implementation of specific technologies and practices (e.g., reduced emission completions, vapor recovery units, and centrifugal compressors) are calculated by the reporting partners using actual measurement data or equipment-specific emission factors. Natural Gas STAR Partners do not report reductions when they are required due to regulation. Therefore, the Inventory assumes there is no overlap between the reductions reported through Natural Gas STAR and reductions due to state regulations. The reductions undergo quality assurance and quality control checks to identify errors, inconsistencies, or irregular data before being incorporated into the Inventory. In general, the Inventory uses aggregated Gas STAR reductions by natural gas system stage (i.e., production, processing, transmission and storage, and distribution). In response to stakeholder feedback during the Inventory development process, EPA is providing aggregate emissions reductions data by Gas STAR technology for several sources, as shown in Table A-6 of the Annex. For those sources, EPA has also used data on potential emissions, and the Gas STAR data on reductions, to calculate net emissions, as shown in Table A-12 of the Annex. For Inventory sources with emission factors that already take into account the use of control technologies (i.e., liquids unloading, and condensate storage tanks) Natural Gas STAR reported reductions for those activities are not incorporated into the Inventory, as this would double count reductions. $CH_4$ emission reductions from the Natural Gas STAR Program are summarized in Table A-129.

Federal regulations. The 1990 Clean Air Act (CAA) sets the limits on the amount of hazardous air pollutants (HAPs) that can be emitted in the United States. The NESHAP regulations set the standards to limit emissions of HAPs. The emission sources are required to use the Maximum Achievable Control Technology, giving the operators flexibility to choose the type of control measure(s) to implement. In regards to the oil and natural gas industry, the NESHAP regulation addresses HAPs from the oil and natural gas production sectors and the natural gas transmission and storage sectors of the industry. Though the regulation deals specifically with HAPs reductions, methane emissions are also incidentally reduced.

The NESHAP regulation requires that glycol dehydration unit vents and storage tanks that have HAP emissions and exceed a gas throughput and liquids throughput value, respectively, be connected to a closed loop emission control system that reduces emissions by 95 percent. Also, gas processing plants exceeding the threshold natural gas throughput limit are required to routinely implement Leak Detection and Repair (LDAR) programs. The emissions reductions achieved as a result of NESHAP regulations were calculated using data provided in the Federal Register Background Information Document (BID) for this regulation. The BID provides the levels of control measures in place before the enactment of regulation. The emissions reductions were estimated by analyzing the portion of the industry without control measures already in place that would be impacted by the regulation. $CH_4$ emission reductions from federal regulations, such as NESHAP, are summarized in Table A-130. In addition to the NESHAP applicable to natural gas, future Inventories will reflect the 2012 NSPS for oil and gas. The regulation, which targets VOCs, is expected to achieve a 95 percent reduction in VOCs from hydraulically fractured gas wells completions and workovers, with CH4 reduction co-benefits. The rule also has VOC reduction requirements for compressors, storage vessels, pneumatic controllers, and equipment leaks at processing plants, which will also impact $CH_4$ emissions.

State Regulations. Additionally, some states, such as Wyoming and Colorado, require that natural gas produced during hydraulically fractured well completions be controlled, and not vented. In these states, emissions from natural gas well completions and re-completions are either recovered for sale or flared.

*1990-2011 Inventory Update to State Regulations*

The method for reducing potential emissions estimates for hydraulic fracturing completions and workovers due to reductions resulting from state regulations was updated. As part of the analysis of the proposed New Source Performance Standard (NSPS) OOOO rule, EPA re-estimated the percentage of gas well completions and workovers with hydraulic fracturing impacted by State regulations. This analysis is documented in the Technical Support Document (TSD) for the NSPS. The analysis considered regulations in Wyoming, adopted in 2008, and Colorado, adopted in 2009. By dividing the number of completions in these States by a more comprehensive estimate of the number of well completions than was used in the 2012 Inventory, EPA determined that 15.1 percent of the total U.S. 2010 completions were covered by State regulations. In 2008, when only the Wyoming regulations were in place, the estimated percentage of completions covered drops to 9.6 percent. The 1990-2011 Inventory updates the percentage of reductions from state regulations to be consistent with the NSPS analysis. Previous inventories incorrectly deducted these state reductions throughout the entire time series beginning in 1990, and overestimated the fraction of well completions occurring in state with regulations requiring controls for completions and workovers with hydraulic fracturing.

As in previous Inventories, voluntary reductions reported to Natural Gas STAR are also deducted from potential emissions totals.

**Step 3: Calculate Net Emissions**

For methane, the reductions described above in Step 2 are summed and deducted from the potential CH4 emissions calculated in Step 1. These net emissions are reported in the Natural Gas Systems inventory text.

The same procedure for estimating $CH_4$ emissions holds true for estimating non-energy related $CO_2$ emissions, except the emission estimates are not adjusted for reductions due to the Natural Gas STAR program or regulations.

Produced natural gas is composed of primarily $CH_4$, but as shown in Table A-13, the natural gas contains, in some cases, as much as 8 percent $CO_2$. The same vented and fugitive natural gas that led to $CH_4$ emissions also contains a certain volume of $CO_2$. Accordingly, the $CO_2$ emissions for each sector can be estimated using the same activity data for these vented and fugitive sources. The emission factors used to estimate $CH_4$ were also used to calculate non-combustion $CO_2$ emissions. The Gas Technology Institute's (GTI, formerly GRI) Unconventional Natural Gas and Gas Composition Databases (GTI 2001) were used to adapt the $CH_4$ emission factors into non-combustion related $CO_2$ emission factors. Additional information about $CO_2$ content in transmission quality natural gas was obtained from numerous U.S. transmission companies to help further develop the non-combustion $CO_2$ emission factors. For the $CO_2$ content used to develop $CO_2$ emission factors from $CH_4$ potential factors, see Table A-13.

In the processing sector, the $CO_2$ content of the natural gas remains the same as the $CO_2$ content in the production sector for the equipment upstream of the acid gas removal unit because produced natural gas is usually only minimally treated after being produced and then transported to natural gas processing plants via gathering pipelines. The $CO_2$ content in gas for the remaining equipment that is downstream of the acid gas removal is the same as in pipeline quality gas. The EPA/GRI study estimates the average $CH_4$ content of natural gas in the processing sector to be 87 percent $CH_4$. Consequently, the processing sector $CO_2$ emission factors were developed using $CH_4$ emission factors, proportioned to reflect the $CO_2$ content of either produced natural gas or pipeline quality gas using the same methodology as the production sector. The detailed source emission estimates for $CH_4$ and $CO_2$ from the processing sector are presented in Table A-132 and Table A-15, respectively.

For the transmission sector, $CO_2$ content in natural gas transmission pipelines was estimated for the top 20 transmission pipeline companies in the United States (separate analyses identified the top 20 companies based on gas throughput and total pipeline miles). The weighted average $CO_2$ content in the transmission pipeline quality gas in both cases—total gas throughput and total miles of pipeline—was estimated to be about 1 percent. To estimate the $CO_2$ emissions for the transmission sector the $CH_4$ emission factors were proportioned from the 93.4 percent $CH_4$ reported in EPA/GRI (1996) to reflect the 1 percent $CO_2$ content found in transmission quality natural gas. The detailed source emissions estimates for $CH_4$ and $CO_2$ for the transmission sector are presented in Table A-133 and Table A-16, respectively.

The natural gas in the distribution sector of the system has the same characteristics as the natural gas in the transmission sector. The $CH_4$ content (93.4 percent) and $CO_2$ content (1 percent) are identical due to the absence of any further treatment between sector boundaries. Thus, the $CH_4$ emissions factors were converted to $CO_2$ emission factors using the same methodology as discussed for the transmission sector. The detailed source emission estimates for $CH_4$ and $CO_2$ for the distribution sector are presented in Table A-134 and Table A-17, respectively.

Three exceptions to this methodology are $CO_2$ emissions from flares, $CO_2$ from acid gas removal units, and $CO_2$ from condensate tanks. In the case of flare emissions, a direct $CO_2$ emission factor from EIA (1996) was used. This emission factor was applied to the portion of offshore gas that is not vented and all of the gas reported as vented and flared onshore by EIA. The amount of $CO_2$ emissions from an acid gas unit in a processing plant is equal to the difference in $CO_2$ concentrations between produced natural gas and pipeline quality gas applied to the throughput of the plant. This methodology was applied to the national gas throughput using national average $CO_2$ concentrations in produced gas (3.45 percent) and transmission quality gas (1 percent). Data were unavailable to use annual values for $CO_2$ concentration. For condensate tanks, a series of E&P Tank (EPA 1999) simulations provide the total $CO_2$ vented per barrel of condensate throughput from fixed roof tank flash gas for condensate gravities of API 45 degree and higher. The ratios of emissions to throughput were used to estimate the $CO_2$ emission factor for condensate passing through fixed roof tanks.

The detailed emission estimates for $CH_4$ and $CO_2$ from the production sector are presented in Table A-131 and Table A-14, respectively.

Tables A-124 through A-127 display the 2010 activity data, $CH_4$ emission factors, and calculated potential $CH_4$ emissions for each stage.

The tables provide references for emission factors and activity data in footnotes (i.e., lettered footnotes). The tables also provide information on which method was used for supplying activity data for 2011 (i.e., numbered footnotes).

Key to table notations on data sources for Table A-1:

Table A-124: 2011 Data and Calculated $CH_4$ Potential Emissions (Mg) for the Natural Gas Production Stage, by NEMS Region

| | *2011 EPA Inventory Values* | | | | |
|---|---|---|---|---|---|
| **Activity** | **Activity Data** | | **Emission Factor (Potential)[aa]** | | **Calculated Potential (Mg)[bb]** |
| **North East** | | | | | |
| ***Gas Wells*** | | | | | |
| NE - Associated Gas Wells[cc,dd] | 36,102 | wells[a,1] | NA | | NA |
| NE - Non-associated Gas Wells (less wells with hydraulic fracturing) | 114,978 | wells[a,1] | 7.31 | scfd/well[b] | 5,906.6 |
| NE - Gas Wells with Hydraulic Fracturing | 37,566 | wells[a,1] | 7.50 | scfd/well[b] | 1,979.6 |
| ***Field Separation Equipment*** | | | | | |
| Heaters | 305 | heaters[b,2] | 14.61 | scfd/heater[b] | 31.3 |
| Separators | 108,306 | separators[b,2] | 0.92 | scfd/separator[b] | 703.3 |
| Dehydrators | 21,267 | dehydrators[b,2] | 22.36 | scfd/dehydrator[b] | 3,342.3 |
| Meters/Piping | 7,546 | meters[c,2] | 9.26 | scfd/meter[b] | 491.4 |
| ***Gathering Compressors*** | | | | | |
| Small Reciprocating Compressors | 153 | compressors[b,2] | 275 | scfd/compressor[b] | 295.1 |
| Large Reciprocating Compressors | 24 | compressors[b,2] | 15,630 | scfd/compressor[b] | 2,637.0 |
| Large Reciprocating Stations | 3 | stations[b,2] | 8,477 | scfd/station[b] | 178.8 |
| Pipeline Leaks | 75,384 | miles[c,2] | 54.64 | scfd/mile[b] | 28,954.1 |
| ***Drilling and Well Completion*** | | | | | |
| Gas Well Completions without Hydraulic Fracturing[ee] | 273 | completions/yr[d,2] | 753 | scf/completion[b] | 4.0 |
| Gas Well Completions with Hydraulic Fracturing | 1,555 | completions/yr[a,1] | 7,477,623 | scf/completion[e] | 223,976.7 |
| Well Drilling | 5,077 | wells[f,1] | 2,614 | scf/well[g] | 255.6 |
| ***Normal Operations*** | | | | | |
| Pneumatic Device Vents | 74,136 | controllers[b,2] | 355 | scfd/device[b] | 184,826.6 |
| Chemical Injection Pumps | 763 | active pumps[b,2] | 255 | scfd/pump[b] | 1,366.9 |
| Kimray Pumps | 6,224,853 | MMscf/yr[b,2] | 1,020 | scf/MMscf[b] | 122,253.7 |
| Dehydrator Vents | 6,986,367 | MMscf/yr[b,2] | 283 | scf/MMscf[b] | 38,119.9 |
| ***Condensate Tank Vents*** | | | | | |
| Condensate Tanks without Control Devices | 0.5 | MMbbl/yr[h,1] | 21.87 | scf/bbl[i,ff] | 210.6 |
| Condensate Tanks with Control Devices | 0.5 | MMbbl/yr[h,1] | 4.37 | scf/bbl[i,ff] | 42.1 |
| ***Compressor Exhaust Vented*** | | | | | |
| Gas Engines | - | MMHPhr[b,2] | 0.25 | scf/HPhr[b] | - |
| ***Well Workovers*** | | | | | |
| Workovers without hydraulic fracturing | 5,002 | workovers/yr[a,2] | 2,522 | scf/workover[b] | 243.0 |

| Activity | Activity Data | | Emission Factor (Potential)[aa] | | Calculated Potential (Mg)[bb] |
|---|---|---|---|---|---|
| | | | 7,4 | | |
| Refractures | 376 | refractures/yr[a,2] | 77,623 | scf/refracture[e] | 54,102.4 |
| ***Liquids Unloading*** | | | | | |
| Liquids Unloading (with plunger lifts) | 6,644 | wells[i] | 254,851 | scfy/well[j,gg] | 32,611.6 |
| Liquids Unloading (without plunger lifts) | 17,182 | wells[a,j,2] | 134,603 | scfy/well[j,gg] | 44,543.5 |
| ***Blowdowns*** | | | | | |
| Vessel Blowdown | 129,879 | vessels[b,2] | 80.18 | scfy/vessel[b] | 200.6 |
| Pipeline Blowdown | 75,384 | miles (gathering)[c,2] | 318 | scfy/mile[b] | 461.2 |
| Compressor Blowdown | 153 | compressors[b,2] | 3,879 | scfy/compressor[b] | 11.4 |
| Compressor Starts | 153 | compressors[b,2] | 8,679 | scfy/compressor[b] | 25.5 |
| ***Upsets*** | | | | | |
| Pressure Relief Valves | 360,968 | PRV[b,2] | 34.95 | scfy/PRV[b] | 243.0 |
| Mishaps | 18,846 | miles[c,2] | 688 | scf/mile[b] | 249.6 |
| ***Midcontinent*** | | | | | |
| ***Gas Wells*** | | | | | |
| MC - Associated Gas Wells[cc,dd] | 11,535 | wells[a,1] | NA | | NA |
| MC - Non-associated Gas Wells (less wells with hydraulic fracturing) | 68,613 | wells[a,1] | 7.70 | scfd/well[b] | 3,713.0 |
| MC - Gas Wells with Hydraulic Fracturing | 21,678 | wells[a,1] | 8.35 | scfd/well[b] | 1,272.8 |
| ***Field Separation Equipment*** | | | | | |
| Heaters | 36,658 | heaters[b,2] | 15.39 | scfd/heater[b] | 3,967.1 |
| Separators | 39,277 | separators[b,2] | 0.97 | scfd/separator[b] | 268.7 |
| Dehydrators | 12,588 | dehydrators[b,2] | 98.70 | scfd/dehydrator[b] | 8,734.0 |
| Meters/Piping | 118,865 | meters[c,2] | 9.76 | scfd/meter[b] | 8,154.9 |
| ***Gathering Compressors*** | | | | | |
| Small Reciprocating Compressors | 10,203 | compressors[b,2] | 290 | scfd/compressor[b] | 20,799.2 |
| Large Reciprocating Compressors | 16 | compressors[b,2] | 16,468 | scfd/compressor[b] | 1,852.3 |
| Large Reciprocating Stations | 2 | stations[b,2] | 8,931 | scfd/station[b] | 125.6 |
| Pipeline Leaks | 70,347 | miles[c,2] | 57.57 | scfd/mile[b] | 28,467.9 |
| ***Drilling and Well Completion*** | | | | | |
| Gas Well Completions without Hydraulic Fracturing[ee] | 161 | completions/yr[d,2] | 794 | scf/completion[b] | 2.5 |
| Gas Well Completions with Hydraulic Fracturing | 1,662 | completions/yr[a,1] | 8,331,516 | scf/completion[e] | 266,692.8 |
| Well Drilling | 3,005 | wells[f,1] | 2,754 | scf/well[g] | 159.4 |
| ***Normal Operations*** | | | | | |
| Pneumatic Device Vents | 140,041 | controllers[b,2] | 374 | scfd/device[b] | 367,848.4 |
| Chemical Injection Pumps | 12,821 | active pumps[b,2] | 269 | scfd/pump[b] | 24,209.1 |
| Kimray Pumps | 3,684,499 | MMscf/yr[b,2] | 1,074 | scf/MMscf[b] | 76,241.4 |
| Dehydrator Vents | 4,135,240 | MMscf/yr[b,2] | 298 | scf/MMscf[b] | 23,772.8 |
| ***Condensate Tank Vents*** | | | | | |
| Condensate Tanks without Control Devices | 16.0 | MMbbl/yr[h,1] | 303 | scf/bbl[i,ff] | 93,296.8 |
| Condensate Tanks with Control Devices | 16.0 | MMbbl/yr[h,1] | 60.55 | scf/bbl[i,ff] | 18,659.4 |
| ***Compressor Exhaust Vented*** | | | | | |
| Gas Engines | 17,314 | MMHPhr[b,2] | 0.26 | scf/HPhr[b] | 86,676.6 |
| ***Well Workovers*** | | | | | |
| Workovers without Hydraulic Fracturing | 2,985 | workovers/yr[a,2] | 2,657 | scf/workover[b] | 152.8 |
| Refractures | 217 | refractures/yr[a,2] | 8,331,516 | scf/refracture[e] | 34,785.6 |
| ***Liquids Unloading*** | | | | | |
| Liquids Unloading (with plunger lifts) | 2,103 | wells[a,j,2] | 1,177,705 | scfy/well[j,gg] | 47,701.5 |
| Liquids Unloading (without plunger lifts) | 3,734 | wells[a,j,2] | 196,460 | scfy/well[j,gg] | 14,128.8 |
| ***Blowdowns*** | | | | | |
| Vessel Blowdown | 88,523 | vessels[b,2] | 84.48 | scfy/vessel[b] | 144.0 |
| Pipeline Blowdown | 70,347 | miles (gathering)[c,2] | 335 | scfy/mile[b] | 453.4 |
| Compressor Blowdown | 10,203 | compressors[b,2] | 4,087 | scfy/compressor[b] | 803.2 |
| Compressor Starts | 10,203 | compressors[b,2] | 9,144 | scfy/compressor[b] | 1,796.9 |

| Activity | Activity Data | | Emission Factor (Potential)[aa] | | Calculated Potential (Mg)[bb] |
|---|---|---|---|---|---|
| ***Upsets*** | | | | | |
| Pressure Relief Valves | 213,657 | PRV [b,2] | 36.82 | scfy/PRV[b] | 151.5 |
| Mishaps | 17,587 | miles [c,2] | 725 | scf/mile[b] | 245.4 |
| ***Rocky Mountain*** | | | | | |
| ***Gas Wells*** | | | | | |
| RM - Associated Gas Wells[cc,dd] | 29,566 | wells [a,1] | NA | | NA |
| RM - Non-associated Gas Wells (less wells with hydraulic fracturing) | 22,985 | wells [a,1] | 35.16 | scfd/well[b] | 5,681.8 |
| RM - Gas Wells with Hydraulic Fracturing | 60,948 | wells [a,1] | 39.52 | scfd/well[b] | 16,933.6 |
| ***Field Separation Equipment*** | | | | | |
| Heaters | 38,273 | heaters [b,2] | 56.89 | scfd/heater[b] | 15,305.4 |
| Separators | 41,883 | separators [b,2] | 120 | scfd/separator[b] | 35,408.7 |
| Dehydrators | 11,702 | dehydrators [b,2] | 89.82 | scfd/dehydrator[b] | 7,388.7 |
| Meters/Piping | 97,825 | meters [c,2] | 52.14 | scfd/meter[b] | 35,858.8 |
| ***Gathering Compressors*** | | | | | |
| Small Reciprocating Compressors | 9,317 | compressors [b,2] | 264 | scfd/compressor[b] | 17,284.0 |
| Large Reciprocating Compressors | 32 | compressors [b,2] | 14,986 | scfd/compressor[b] | 3,371.3 |
| Large Reciprocating Stations | 4 | stations [b,2] | 8,128 | scfd/station[b] | 228.6 |
| Pipeline Leaks | 108,372 | miles [c,2] | 52.39 | scfd/mile[b] | 39,911.0 |
| ***Drilling and Well Completion*** | | | | | |
| Gas Well Completions without Hydraulic Fracturing[ee] | 150 | completions/yr [d,2] | 707 | scf/completion[b] | 2.0 |
| Gas Well Completions with Hydraulic Fracturing | 1,344 | completions/yr [a,1] | 7,691,035 | scf/completion[e] | 199,085.8 |
| Well Drilling | 2,794 | wells [f,1] | 2,506 | scf/well[g] | 134.9 |
| ***Normal Operations*** | | | | | |
| Pneumatic Device Vents | 122,878 | controllers [b,2] | 340 | scfd/device[b] | 293,732.2 |
| Chemical Injection Pumps | 14,940 | active pumps [b,2] | 244 | scfd/pump[b] | 25,672.2 |
| Kimray Pumps | 3,425,048 | MMscf/yr [b,2] | 978 | scf/MMscf[b] | 64,497.7 |
| Dehydrator Vents | 3,844,050 | MMscf/yr [b,2] | 272 | scf/MMscf[b] | 20,111.0 |
| ***Condensate Tank Vents*** | | | | | |
| Condensate Tanks without Control Devices | 12.5 | MMbbl/yr [h,1] | 21.87 | scf/bbl[i,ff] | 5,265.2 |
| Condensate Tanks with Control Devices | 12.5 | MMbbl/yr [h,1] | 4.37 | scf/bbl[i,ff] | 1,053.0 |
| ***Compressor Exhaust Vented*** | | | | | |
| Gas Engines | 16,094 | MMHPhr [b,2] | 0.24 | scf/HPhr[b] | 73,325.5 |
| ***Well Workovers*** | | | | | |
| Workovers without Hydraulic Fracturing | 1,000 | workovers/yr [a,2] | 2,368 | scf/workover [b] | 45.6 |
| Refractures | 609 | refractures/yr [a,2] | 7,691,035 | scf/refracture [e] | 90,281.9 |
| ***Liquids Unloading*** | | wells [a,j,2] | | scfy/well[j,gg] | |
| Liquids Unloading (with plunger lifts) | 10,807 | | 119,840 | | 24,943.8 |
| Liquids Unloading (without plunger lifts) | 1,275 | wells [a,j,2] | 2,003,373 | scfy/well[j,gg] | 49,195.8 |
| ***Blowdowns*** | | | | | |
| Vessel Blowdown | 91,858 | vessels [b,2] | 76.88 | scfy/vessel[b] | 136.0 |
| Pipeline Blowdown | 108,372 | miles (gathering) [c,2] | 305 | scfy/mile[b] | 635.7 |
| Compressor Blowdown | 9,317 | compressors [b,2] | 3,720 | scfy/compressor[b] | 667.5 |
| Compressor Starts | 9,317 | compressors [b,2] | 8,322 | scfy/compressor[b] | 1,493.2 |
| ***Upsets*** | | | | | |
| Pressure Relief Valves | 198,612 | PRV [b,2] | 33.51 | scfy/PRV[b] | 128.2 |
| Mishaps | 27,093 | miles [c,2] | 659 | scf/mile[b] | 344.1 |
| ***Produced Water from Coal Bed Methane Wells*** | | | | | |
| Powder River | 20,602,02 2,700 | gallons produced water [k,1] | 2.23E-09 | Gg/gallon water drainage [k] | 45,849.8 |
| ***South West*** | | | | | |
| ***Gas Wells*** | | | | | |
| SW - Associated Gas Wells[cc,dd] | 36,576 | wells [a,1] | NA | | NA |
| SW - Non-associated Gas Wells (less wells with hydraulic fracturing) | 21,821 | wells [a,1] | 37.24 | scfd/well[b] | 5,712.4 |
| SW - Gas Wells with Hydraulic Fracturing | 19,712 | wells [a,1] | 37.24 | scfd/well[b] | 5,160.3 |
| ***Field Separation Equipment*** | | | | | |
| Heaters | 11,255 | heaters [b,2] | 58.97 | scfd/heater[b] | 4,666.3 |
| Separators | 23,342 | separators [b,2] | 125 | scfd/separator[b] | 20,458.1 |

| Activity | Activity Data | | Emission Factor (Potential)[aa] | | Calculated Potential (Mg)[bb] |
|---|---|---|---|---|---|
| Dehydrators | 5,790 | dehydrators [b,2] | 93.12 | scfd/dehydrator[b] | 3,790.4 |
| Meters/Piping | 49,583 | meters [c,2] | 54.06 | scfd/meter[b] | 18,842.6 |
| ***Gathering Compressors*** | | | | | |
| Small Reciprocating Compressors | 5,648 | compressors [b,2] | 274 | scfd/compressor[b] | 10,863.7 |
| Large Reciprocating Compressors | 16 | compressors [b,2] | 15,537 | scfd/compressor[b] | 1,747.5 |
| Large Reciprocating Stations | 2 | stations [b,2] | 8,426 | scfd/station[b] | 118.5 |
| Pipeline Leaks | 60,884 | miles [c,2] | 54.31 | scfd/mile[b] | 23,245.4 |
| ***Drilling and Well Completion*** | | | | | |
| Gas Well Completions without Hydraulic Fracturing[ee] | 74 | completions/yr [d,2] | 749 | scf/completion[b] | 1.1 |
| Gas Well Completions with Hydraulic Fracturing | 603 | completions/yr [a,1] | 7,246,631 | scf/completion[e] | 84,160.8 |
| Well Drilling | 1,382 | wells [f,1] | 2,598 | scf/well[g] | 69.2 |
| ***Normal Operations*** | | | | | |
| Pneumatic Device Vents | 55,156 | controllers [b,2] | 353 | scfd/device[b] | 136,686.9 |
| Chemical Injection Pumps | 2,534 | active pumps [b,2] | 253 | scfd/pump[b] | 4,513.3 |
| Kimray Pumps | 1,694,834 | MMscf/yr [b,2] | 1,014 | scf/MMscf[b] | 33,087.4 |
| Dehydrator Vents | 1,902,171 | MMscf/yr [b,2] | 282 | scf/MMscf[b] | 10,317.0 |
| ***Condensate Tank Vents*** | | | | | |
| Condensate Tanks without Control Devices | 25.5 | MMbbl/yr [h,1] | 303 | scf/bbl[i,ff] | 148,691.8 |
| Condensate Tanks with Control Devices | 25.5 | MMbbl/yr [h,1] | 60.55 | scf/bbl[i,ff] | 29,738.4 |
| ***Compressor Exhaust Vented*** | | | | | |
| Gas Engines | 7,964 | MMHPhr [b,2] | 0.25 | scf/HPhr[b] | 37,616.1 |
| ***Well Workovers*** | | | | | |
| Workovers without Hydraulic Fracturing | 949 | workovers/yr [a,2] | 2,508 | scf/workover[b] | 45.8 |
| Refractures | 197 | refractures/yr [a,2] | 7,246,631 | scf/refracture [e] | 27,512.1 |
| ***Liquids Unloading*** | | | | | |
| Liquids Unloading (with plunger lifts) | 1,380 | wells [a,j,2] | 2,856 | scfy/well[j,gg] | 75.9 |
| Liquids Unloading (without plunger lifts) | 8,087 | wells [a,j,2] | 77,900 | scfy/well[j,gg] | 12,133.3 |
| ***Blowdowns*** | | | | | |
| Vessel Blowdown | 40,387 | vessels [b,2] | 79.70 | scfy/vessel[b] | 62.0 |
| Pipeline Blowdown | 60,884 | miles (gathering) [c,2] | 316 | scfy/mile[b] | 370.2 |
| Compressor Blowdown | 5,648 | compressors [b,2] | 3,856 | scfy/compressor[b] | 419.5 |
| Compressor Starts | 5,648 | compressors [b,2] | 8,627 | scfy/compressor[b] | 938.5 |
| ***Upsets*** | | | | | |
| Pressure Relief Valves | 98,280 | PRV [b,2] | 34.74 | scfy/PRV[b] | 65.8 |
| Mishaps | 15,221 | miles [c,2] | 684 | scf/mile[b] | 200.4 |
| ***West Coast*** | | | | | |
| ***Gas Wells*** | | | | | |
| WC - Associated Gas Wells[cc,dd] | 29,315 | wells [a,1] | NA | | NA |
| WC - Non-associated Gas Wells (less wells with hydraulic fracturing) | 2,115 | wells [a,1] | 42.49 | scfd/well[b] | 631.8 |
| WC - Gas Wells with Hydraulic Fracturing | - | wells [a,1] | 42.49 | scfd/well[b] | - |
| ***Field Separation Equipment*** | | | | | |
| Heaters | 2,115 | heaters [b,2] | 67.29 | scfd/heater[b] | 1,000.5 |
| Separators | 1,544 | separators [b,2] | 142 | scfd/separator[b] | 1,544.1 |
| Dehydrators | 295 | dehydrators [b,2] | 106 | scfd/dehydrator[b] | 220.3 |
| Meters/Piping | 3,996 | meters [c,2] | 61.68 | scfd/meter[b] | 1,733.0 |
| ***Gathering Compressors*** | | | | | |
| Small Reciprocating Compressors | 2,456 | compressors [b,2] | 312 | scfd/compressor[b] | 5,389.0 |
| Large Reciprocating Compressors | 8 | compressors [b,2] | 17,728 | scfd/compressor[b] | 997.0 |
| Large Reciprocating Stations | 1 | stations [b,2] | 9,615 | scfd/station[b] | 67.6 |
| Pipeline Leaks | 16,735 | miles [c,2] | 61.97 | scfd/mile[b] | 7,290.8 |
| ***Drilling and Well Completion*** | | | | | |
| Gas Well Completions without Hydraulic Fracturing[ee] | 4 | completions/yr [d,2] | 855 | scf/completion[b] | 0.1 |
| Gas Well Completions with Hydraulic Fracturing | - | completions/yr [a,1] | 8,268,969 | scf/completion[e] | - |
| Well Drilling | 70 | wells [f,1] | 2,965 | scf/well[g] | 4.0 |

| Activity | Activity Data | | Emission Factor (Potential)[aa] | | Calculated Potential (Mg)[bb] |
|---|---|---|---|---|---|
| ***Normal Operations*** | | | | | |
| Pneumatic Device Vents | 2,119 | controllers [b,2] | 402 | scfd/device[b] | 5,992.8 |
| Chemical Injection Pumps | 1,436 | active pumps [b,2] | 289 | scfd/pump[b] | 2,919.2 |
| Kimray Pumps | 86,307 | MMscf/yr [b,2] | 1,157 | scf/MMscf[b] | 1,922.6 |
| Dehydrator Vents | 96,865 | MMscf/yr [b,2] | 321 | scf/MMscf[b] | 599.5 |
| ***Condensate Tank Vents*** | | | | | |
| Condensate Tanks without Control Devices | - | MMbbl/yr [h,1] | 21.87 | scf/bbl[i,ff] | - |
| Condensate Tanks with Control Devices | - | MMbbl/yr [h,1] | 4.37 | scf/bbl[i,ff] | - |
| ***Compressor Exhaust Vented*** | | | | | |
| Gas Engines | 406 | MMHPhr [b,2] | 0.28 | scf/HPhr[b] | 2,185.8 |
| ***Well Workovers*** | | | | | |
| Workovers without Hydraulic Fracturing | 92 | workovers/yr [a,2] | 2,861 | scf/workover[b] | 5.1 |
| Refractures | | | | | |
| ***Liquids Unloading*** | - | refracture/yr [a,2] | 8,268,969 | scf/refracture [e] | - |
| | | wells [a,j,2] | | scfy/well[j,gg] | |
| Liquids Unloading (with plunger lifts) | 161 | | 317,292 | | 983.9 |
| Liquids Unloading (without plunger lifts) | 144 | wells [a,j,2] | 279,351 | scfy/well[j,gg] | 774.8 |
| ***Blowdowns*** | | | | | |
| Vessel Blowdown | 3,954 | vessels [b,2] | 90.94 | scfy/vessel[b] | 6.9 |
| Pipeline Blowdown | 16,735 | miles (gathering) [c,2] | 360 | scfy/mile[b] | 116.1 |
| Compressor Blowdown | 2,456 | compressors [b,2] | 4,400 | scfy/compressor[b] | 208.1 |
| Compressor Starts | 2,456 | compressors [b,2] | 9,844 | scfy/compressor[b] | 465.6 |
| ***Upsets*** | | | | | |
| Pressure Relief Valves | 5,005 | PRV [b,2] | 39.64 | scfy/PRV[b] | 3.8 |
| Mishaps | 4,184 | miles [c,2] | 780 | scf/mile[b] | 62.9 |
| ***Gulf Coast*** | | | | | |
| ***Gas Wells*** | | | | | |
| GC - Associated Gas Wells[cc,dd] | 14,782 | wells [a,1] | NA | | NA |
| GC - Non-associated Gas Wells (less wells with hydraulic fracturing) | 37,586 | wells [a,1] | 7.99 | scfd/well[b] | 2,111.9 |
| GC - Gas Wells with Hydraulic Fracturing | 38,743 | wells [a,1] | 7.99 | scfd/well[b] | 2,177.0 |
| ***Field Separation Equipment*** | | | | | |
| Heaters | 17,098 | heaters [b,2] | 64.89 | scfd/heater[b] | 7,799.3 |
| Separators | 50,224 | separators [b,2] | 137.18 | scfd/separator[b] | 48,435.4 |
| Dehydrators | 10,642 | dehydrators [b,2] | 102.46 | scfd/dehydrator[b] | 7,664.7 |
| Meters/Piping | 88,313 | meters [c,2] | 59.48 | scfd/meter[b] | 36,927.0 |
| ***Gathering Compressors*** | | | | | |
| Small Reciprocating Compressors | 6,183 | compressors [b,2] | 301 | scfd/compressor[b] | 13,083.8 |
| Large Reciprocating Compressors | 32 | compressors [b,2] | 17,095 | scfd/compressor[b] | 3,845.6 |
| Large Reciprocating Stations | 4 | stations [b,2] | 9,272 | scfd/station[b] | 260.7 |
| Pipeline Leaks | 99,855 | miles [c,2] | 59.76 | scfd/mile[b] | 41,948.4 |
| ***Drilling and Well Completion*** | | | | | |
| Gas Well Completions without Hydraulic Fracturing[ee] | 136 | completions/yr [d,2] | 824 | scf/completion[b] | 2.2 |
| Gas Well Completions with Hydraulic Fracturing | 2,913 | completions/yr [a,1] | 7,973,495 | scf/completion[e] | 447,348.0 |
| Well Drilling | 2,541 | wells [f,1] | 2,859 | scf/well[g] | 139.9 |
| ***Normal Operations*** | | | | | |
| Pneumatic Device Vents | 53,049 | controllers [b,2] | 388 | scfd/device[b] | 144,651.4 |
| Chemical Injection Pumps | 2,519 | active pumps [b,2] | 279 | scfd/pump[b] | 4,937.2 |
| Kimray Pumps | 3,114,752 | MMscf/yr [b,2] | 1,115 | scf/MMscf[b] | 66,907.0 |
| Dehydrator Vents | 3,495,794 | MMscf/yr [b,2] | 310 | scf/MMscf[b] | 20,862.3 |
| ***Condensate Tank Vents*** | | | | | |
| Condensate Tanks without Control Devices | 31.5 | MMbbl/yr [h,1] | 21.87 | scf/bbl[i,ff] | 13,268.3 |
| Condensate Tanks with Control Devices | 31.5 | MMbbl/yr [h,1] | 4.37 | scf/bbl[i,ff] | 2,653.7 |
| ***Compressor Exhaust Vented*** | | | | | |
| Gas Engines | 14,636 | MMHPhr [b,2] | 0.27 | scf/HPhr[b] | 76,064.6 |
| ***Well Workovers*** | | | | | |
| Workovers without Hydraulic Fracturing | 1,635 | workovers/yr [a,2] | 2,759 | scf/workover[b] | 86.9 |
| Refractures | 387 | refractures/yr [a,2] | 7,973,495 | scf/refracture [e] | 59,497.4 |
| ***Liquids Unloading*** | | | | | |
| Liquids Unloading (with plunger lifts) | 1,771 | | 62,035 | | 2,116.0 |

| Activity | Activity Data | | Emission Factor (Potential)[aa] | | Calculated Potential (Mg)[bb] |
|---|---|---|---|---|---|
| | | wells [a,j,2] | | scfy/well[j,gg] | |
| Liquids Unloading (without plunger lifts) | 5,406 | wells [a,j,2] | 266,308 | scfy/well[j,gg] | 27,727.8 |
| ***Blowdowns*** | | | | | |
| Vessel Blowdown | 77,964 | vessels [b,2] | 87.69 | scfy/vessel[b] | 131.7 |
| Pipeline Blowdown | 99,855 | miles (gathering) [c,2] | 347 | scfy/mile[b] | 668.1 |
| Compressor Blowdown | 6,183 | compressors [b,2] | 4,243 | scfy/compressor[b] | 505.3 |
| Compressor Starts | 6,183 | compressors [b,2] | 9,492 | scfy/compressor[b] | 1,130.3 |
| ***Upsets*** | | | | | |
| Pressure Relief Valves | 180,619 | PRV [b,2] | 38.23 | scfy/PRV[b] | 133.0 |
| Mishaps | 24,964 | miles [c,2] | 752 | scf/mile[b] | 361.6 |
| ***Produced Water from Coal Bed Methane Wells*** | | | | | |
| Black Warrior | 5,462 | wells [l,1] | 2.33E-03 | Gg/well [1] | 12,707.5 |
| ***Offshore Platforms*** | | | | | |
| Shallow water Gas Platforms (GoM and Pacific) | 1,973 | shallow water gas platforms [m,3] | 19,178 | scfd/platform [n] | 266,066.5 |
| Deepwater Gas Platforms (GoM and Pacific) | 41 | deepwater gas platforms [m,3] | 79,452 | scfd/platform [n] | 22,950.4 |
| **Regulatory Reductions (Gg)** | | | | | **(333.6)** |
| **Voluntary Reductions (Gg)** | | | | | **(2,317.5)** |
| **Total Reductions (Gg)** | | | | | **(2,651.1)** |
| **Total Potential Emissions (Gg)** | | | | | **4,949.1** |
| **Total Net Emissions (Gg)** | | | | | **2,298.0** |

[a] DI Desktop (2012)
[b].EPA/GRI (1996), Methane Emissions from the Natural Gas Industry
[c] ICF (1996), Estimation of Activity Factors for the Natural Gas Exploration and Production Industry in the U.S.
[d] API/ICF memo (1997)
[e] EPA NSPS Technical Support Document (2012)
[f] EIA Monthly Energy Review
[g] Radian (1992), Global Emissions of Methane Sources
[h] EIA US Crude Oil, Natural Gas, and Natural Gas Liquids Reserves Annual Report
[i] EP&P/API Tank Calc runs
[j] API/ANGA (2012), Characterizing Pivotal Sources of Methane Emissions from Natural Gas Production – Summary and Analysis of API and ANGA Survey Responses
[k] Wyoming Oil and Gas Conservation Commission (2012)
[l] Alabama State Oil and Gas Board (2012)
[m] Bureau of Ocean Energy Management, Regulation and Enforcement (2012)
[n] MMS (2000), 2000 Gulfwide Offshore Activity Data System
[aa] Emission factors listed in this table are for potential emissions (unless otherwise indicated in a footnote). For many of these sources, emission reductions are subtracted from potential emissions to calculate net emissions. For this reason, emission factors presented in these tables cannot be used to directly estimate net emissions from these sources. See detailed explanation of methodology above.
[bb] Totals may not sum due to independent rounding.
[cc] Emissions from oil wells that produce associated gas are estimated in the Petroleum Systems model. In the Natural Gas Systems mode, the oil wells counts are used as a driver only.
[dd] NA = not applicable (i.e., this data is not applicable for the Natural Gas Systems model).
[ff] Emission factors for condensate tanks represent actual emissions and can be used to calculate emissions directly.
[gg] Emission factors for liquids unloading represent actual emissions and can be used to calculate emissions directly.
[1] Activity data for 2011 available from source.
[2] Ratios relating other factors for which activity data are available.
[3] 2010 activity data are used to determine some or all of the 2011 activity.

Table A-125: 2011 Data and $CH_4$ Emissions (Mg) for the Natural Gas Processing Stage

| | *2011 EPA Inventory Values* | | |
|---|---|---|---|
| **Activity** | **Activity Data** | **Emission Factor (Potential)[aa]** | **Calculated Potential Emissions (Mg)** |

| Activity | 2011 EPA Inventory Values | | | | |
|---|---|---|---|---|---|
| | Activity Data | | Emission Factor (Potential)[aa] | | Calculated Potential Emissions (Mg) |
| *Normal Fugitives* | | | | | |
| Plants | 585 | plants[a,1] | 7,906 | scfd/plant[b] | 32,513.4 |
| Reciprocating Compressors | 5,369 | compressors[c,2] | 11,196 | scfd/compressor[b] | 422,546.6 |
| Centrifugal Compressors (wet seals) | 654 | compressors[d,2] | 51,370 | scfd/compressor[d] | 236,238.7 |
| Centrifugal Compressors (dry seals) | 211 | compressors[d,2] | 25,189 | scfd/compressor[d] | 37,381.3 |
| *Compressor Exhaust* | | | | | |
| Gas Engines | 38,570 | MMHPhr[c,2] | 0.24 | scf/HPhr[b] | 178,285.2 |
| Gas Turbines | 45,733 | MMHPhr[c,2] | 0.01 | scf/HPhr[b] | 5,020.6 |
| AGR Vents | 296 | AGR units[b,2] | 6,083 | scfd/AGR[b] | 12,679.0 |
| Kimray Pumps | 1,397,253 | MMscf/yr[c,2] | 178 | scf/MMscf[b] | 4,783.4 |
| Dehydrator Vents | 12,587,864 | MMscf/yr[c,2] | 122 | scf/MMscf[b] | 29,468.9 |
| Pneumatic Devices | 585 | gas plants[a,1] | 164,721 | scfy/plant[b] | 1,855.9 |
| *Compressor Exhaust* | | | | | |
| Blowdowns/Venting | 585 | gas plants[a,1] | 4,060 | Mscfy/plant[b] | 45,744.4 |
| **Regulatory Reductions (Gg)** | | | | | (15.6) |
| **Voluntary Reductions (Gg)** | | | | | (58.9) |
| **Total Reductions (Gg)** | | | | | **(74.5)** |
| **Total Potential Emissions (Gg)** | | | | | **1,006.5** |
| **Total Net Emissions (Gg)** | | | | | **932.0** |

[a] Oil and Gas Journal
[b] EPA/GRI (1996), Methane Emissions from the Natural Gas Industry
[c] ICF (2008), Natural Gas Model Activity Factor Basis Change
[d] ICF (2010), Emissions from Centrifugal Compressors
[aa] Emission factors listed in this table are for potential emissions (unless otherwise indicated in a footnote). For many of these sources, emission reductions are subtracted from potential emissions to calculate net emissions. For this reason, emission factors presented in these tables cannot be used to directly estimate net emissions from these sources. See detailed explanation of methodology above.
[1] Activity data for 2011 available from source.
[2] Ratios relating other factors for which activity data are available.

Table A-126: 2011 Data and $CH_4$ Emissions (Mg) for the Natural Gas Transmission Stage

| Activity | 2011 EPA Inventory Values | | | | |
|---|---|---|---|---|---|
| | Activity Data | | Emission Factor (Potential)[aa] | | Calculated Potential Emissions (Mg) |
| ***Fugitives*** | | | | | |
| Pipeline Leaks | 304,606 | miles[a,1] | 1.55 | Scfd/ mile[b] | 3,327.5 |
| *Compressor Stations (Transmission)* | | | | | |
| Station | 1,808 | stations[c,2] | 8,778 | Scfd/station[b] | 111,579.2 |
| Reciprocating Compressor | 7,270 | compressors[c,2] | 15,205 | Scfd/ compressor[b] | 777,069.9 |

| Activity | 2011 EPA Inventory Values | | | | |
|---|---|---|---|---|---|
| | Activity Data | | Emission Factor (Potential)[aa] | | Calculated Potential Emissions (Mg) |
| Centrifugal Compressor (wet seals) | 664 | compressors [d,2] | 50,222 | Scfd/ compressor[d] | 234,294.8 |
| Centrifugal Compressor (dry seals) | 66 | compressors [d,2] | 32,208 | Scfd/ compressor[d] | 14,831.9 |
| *Compressor Stations (Storage)* | | | | | |
| Station | 389 | stations [e,2] | 21,507 | Scfd/ station[b] | 58,844.6 |
| Reciprocating Compressor | 1,145 | compressors [e,2] | 21,116 | Scfd/ compressor[b] | 169,967.7 |
| Centrifugal Compressor (wet seals) | 83 | compressors [d,2] | 45,441 | Scfd/ compressor[d] | 26,499.5 |
| Centrifugal Compressor (dry seals) | 29 | compressors [d,2] | 31,989 | Scfd/compressor [d] | 6,531.7 |
| Wells (Storage) | 18,148 | wells [b,2] | 115 | Scfd/well[b] | 14,608.1 |
| M&R (Trans. Co. Interconnect) | 2,712 | stations [c,2] | 3,984 | scfd/station[b] | 75,942.5 |
| M& R (Farm Taps + Direct Sales) | 80,400 | stations [c,2] | 31.20 | scfd/station[b] | 17,634.4 |
| ***Vented and Combusted*** | | | | | |
| Dehydrator vents (Transmission) | 1,152,591 | MMscf/year [b,2] | 93.72 | scf/MMscf[b] | 2,080.5 |
| Dehydrator vents (Storage) | 2,016,604 | MMscf/year [b,2] | 117 | scf/MMscf[b] | 4,551.2 |
| *Compressor Exhaust* | | | | | |
| Engines (Transmission) | 48,540 | MMHPhr [b,2] | 0.24 | scf/HPhr[b] | 224,371.7 |
| Turbines (Transmission) | 11,582 | MMHPhr [b,2] | 0.01 | scf/HPhr[b] | 1,271.5 |
| Engines (Storage) | 4,963 | MMHPhr [b,2] | 0.24 | scf/HPhr[b] | 22,940.3 |
| Turbines (Storage) | 1,743 | MMHPhr [b,2] | 0.01 | scf/HPhr[b] | 191.4 |
| Generators (Engines) | 2,375 | MMHPhr [b,2] | 0.24 | scf/HPhr[b] | 10,979.7 |
| Generators (Turbines) | 28 | MMHPhr [b,2] | 0.01 | scf/HPhr[b] | 3.1 |
| *Pneumatic Devices Transmission + Storage* | | | | | |
| Pneumatic Devices Transmission | 71,173 | devices [f,2] | 162,197 | Scfy/device[b] | 222,337.2 |
| Pneumatic Devices Storage | 15,320 | devices [e,2] | 162,197 | Scfy/device[b] | 47,858.4 |
| ***Routine Maintenance/Upsets*** | | | | | |
| Pipeline venting | 304,606 | miles [a,1] | 31.65 | Mscfy/mile[b] | 185,681.4 |
| *Station Venting Transmission + Storage* | | | | | |
| Station Venting Transmission | 1,808 | compressor stations [c,2] | 4,359 | Mscfy/station[b] | 151,803.5 |
| Station Venting Storage | 389 | compressor stations [e,2] | 4,359 | Mscfy/station[b] | 32,675.4 |
| ***LNG Storage*** | | | | | |
| LNG Stations | 70 | stations [f,g,3] | 21,507 | scfd/station[b] | 10,622.8 |
| LNG Reciprocating Compressors | 270 | compressors [f,g,3] | 21,116 | scfd/comp[b] | 40,146.5 |
| LNG Centrifugal Compressors | 64 | compressors [f,g,3] | 30,573 | scfd/comp[b] | 13,766.0 |
| *LNG Compressor Exhaust* | | | | | |
| LNG Engines | 579 | MMHPhr [f,g,3] | 0.24 | scf/HPhr[b] | 2,677.7 |

| Activity | 2011 EPA Inventory Values | | | | |
|---|---|---|---|---|---|
| | Activity Data | | Emission Factor (Potential)[aa] | | Calculated Potential Emissions (Mg) |
| LNG Turbines | 113 | MMHPhr [f,g,3] | 0.01 | scf/HPhr[b] | 12.4 |
| LNG Station Venting | 70 | stations [f,g,3] | 4,359 | Mscfy/station[b] | 5,898.6 |
| ***LNG Import Terminals*** | | | | | |
| LNG Stations | 8 | stations [f,g,3] | 21,507 | scfd/station[b] | 1,164.2 |
| LNG Reciprocating Compressors | 37 | compressors [f,g,3] | 21,116 | scfd/compressor [b] | 5,551.8 |
| LNG Centrifugal Compressors | 7 | compressors [f,g,3] | 30,573 | scfd/compressor [b] | 1,418.5 |
| *LNG Compressor Exhaust* | | | | | |
| LNG Engines | 1,819 | MMHPhr [f,g,3] | 0.24 | scf/HPhr[b] | 8,407.5 |
| LNG Turbines | 439 | MMHPhr [f,g,3] | 0.01 | scf/HPhr[b] | 48.2 |
| LNG Station Venting | 8 | stations [f,g,3] | 4,359 | Mscfy/station[b] | 646.4 |
| **Regulatory Reductions (Gg)** | | | | | (0.0) |
| **Voluntary Reductions (Gg)** | | | | | (421.4) |
| **Total Reductions (Gg)** | | | | | **(421.4)** |
| **Total Potential Emissions (Gg)** | | | | | **2,508.2** |
| **Total Net Emissions (Gg)** | | | | | **2,086.8** |

[a] Pipeline and Hazardous Materials Safety Administration (PHMSA), Office of Pipeline Safety (OPS) (2012)
[b] EPA/GRI (1996), Methane Emissions from the Natural Gas Industry
[c] ICF (2008), Natural Gas Model Activity Factor Basis Change
[d] ICF (2010), Emissions from Centrifugal Compressors
[e] ICF (1997), Additional Changes to Activity Factors for Portions of the Gas Industry
[f] ICF (1996), Estimation of Activity Factors for the Natural Gas Exploration and Production Industry in the U.S.
[g] EIA (2004), US LNG Markets and Uses
[1] Activity data for 2011 available from source.
[2] Ratios relating other factors for which activity data are available.
[3] 2010 activity data are used to determine some or all of the 2011 activity (to be updated).
[aa] Emission factors listed in this table are for potential emissions (unless otherwise indicated in a footnote). For many of these sources, emission reductions are subtracted from potential emissions to calculate net emissions. For this reason, emission factors presented in these tables cannot be used to directly estimate net emissions from these sources. See detailed explanation of methodology above.

Table A-127: 2011 Data and $CH_4$ Emissions (Mg) for the Natural Gas Distribution Stage

| Activity | 2011 EPA Inventory Values | | | | |
|---|---|---|---|---|---|
| | Activity Data | | Emission Factor (Potential)[aa] | | Calculated Potential Emissions (Mg) |
| *Pipeline Leaks* | | | | | |
| Mains—Cast Iron | 33,586 | miles [a,1] | 239 | Mscf/mile-yr[b] | 154,407.0 |
| Mains—Unprotected steel | 64,092 | miles [a,1] | 110 | Mscf/mile-yr[b] | 136,019.7 |
| Mains—Protected steel | 488,265 | miles [a,1] | 3.07 | Mscf/mile-yr[b] | 28,841.1 |
| Mains—Plastic | 645,102 | miles [a,1] | 9.91 | Mscf/mile-yr[c] | 123,128.4 |
| Services—Unprotected steel | 4,140,616 | services [a,1] | 1.70 | Mscf/service[b] | |

| Activity | 2011 EPA Inventory Values | | | | |
|---|---|---|---|---|---|
| | Activity Data | | Emission Factor (Potential)[aa] | | Calculated Potential Emissions (Mg) |
| | | | | | 135,633.3 |
| Services Protected steel | 15,267,357 | services [a,1] | 0.18 | Mscf/service[b] | 51,898.5 |
| Services—Plastic | 44,269,061 | services [a,1] | 0.01 | Mscf/service[b] | 7,927.8 |
| Services—Copper | 1,054,804 | services [a,1] | 0.25 | Mscf/service[b] | 5,166.8 |
| *Meter/Regulator (City Gates)* | | | | | |
| M&R >300 | 3,920 | stations [d,2] | 180 | scfh/station[b] | 118,905.2 |
| M&R 100-300 | 14,304 | stations [d,2] | 95.60 | scfh/station[b] | 230,720.3 |
| M&R <100 | 7,646 | stations [d,2] | 4.31 | scfh/station[b] | 5,559.7 |
| Reg >300 | 4,285 | stations [d,2] | 162 | scfh/station[b] | 117,057.8 |
| R-Vault >300 | 2,517 | stations [d,2] | 1.30 | scfh/station[b] | 552.0 |
| Reg 100-300 | 12,964 | stations [d,2] | 40.50 | scfh/station[b] | 88,584.9 |
| R-Vault 100-300 | 5,824 | stations [d,2] | 0.18 | scfh/station[b] | 176.9 |
| Reg 40-100 | 38,904 | stations [d,2] | 1.04 | scfh/station[b] | 6,826.3 |
| R-Vault 40-100 | 34,500 | stations [d,2] | 0.09 | scfh/station[b] | 503.5 |
| Reg <40 | 16,496 | stations [d,2] | 0.13 | scfh/station[b] | 370.2 |
| *Customer Meters* | | | | | |
| Residential | 40,381,779 | outdoor meters [b,2] | 143 | scfy/meter[b] | 111,429.3 |
| Commercial/Industry | 4,409,628 | meters [b,2] | 47.90 | scfy/meter[b] | 4,068.1 |
| Routine Maintenance | | | | | |
| Pressure Relief Valve Releases | 1,231,045 | mile main [a,1] | 0.05 | Mscf/mile[b] | 1,185.5 |
| Pipeline Blowdown | 1,308,341 | miles [b,2] | 0.10 | Mscfy/mile[b] | 2,570.3 |
| *Upsets* | | | | | |
| | | | 1.59 | | 40,065.8 |
| Mishaps (Dig-ins) | 1,308,341 | miles [b,2] | | Mscfy/mile[b] | |
| **Regulatory Reductions (Gg)** | | | | | (0.0) |
| **Voluntary Reductions (Gg)** | | | | | (42.5) |
| **Total Reductions (Gg)** | | | | | **(42.5)** |
| **Total Potential Emissions (Gg)** | | | | | **1,371.6** |
| **Total Net Emissions (Gg)** | | | | | **1,329.1** |

[a] Pipeline and Hazardous Materials Safety Administration (PHMSA), Office of Pipeline Safety (OPS) (2012)
[b] EPA/GRI (1996), Methane Emissions from the Natural Gas Industry
[c] ICF (2005), Plastic Pipe Emission Factors
[d] ICF (2008), Natural Gas Model Activity Factor Basis Change
[aa] Emission factors listed in this table are for potential emissions (unless otherwise indicated in a footnote). For many of these sources, emission reductions are subtracted from potential emissions to calculate net emissions. For this reason, emission factors presented in these tables cannot be used to directly estimate net emissions from these sources. See detailed explanation of methodology above.
[1] Activity data for 2011 available from source.
[2] Ratios relating other factors for which activity data are available.

1 Table A-128: Key Activity Data Drivers

| Variable | Units | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|
| **Transmission Pipelines Length** | **miles** | 291,925 | 296,947 | 298,957 | 300,468 | 304,667 | 304,606 |
| **Wells** | | | | | | | |
| NE—Associated Gas Wells[a,1] | # wells | 25,839 | 23,540 | 24,701 | 29,679 | 36,589 | 36,102 |
| NE—Non-associated Gas Wells [a,1] | # wells | 63,375 | 89,354 | 102,766 | 128,847 | 155,811 | 152,544 |
| MC—Associated Gas Wells [a,1] | # wells | 19,479 | 15,698 | 12,776 | 12,269 | 12,146 | 11,535 |
| MC—Non-associated Gas Wells [a,1] | # wells | 54,511 | 57,639 | 62,415 | 75,506 | 89,980 | 90,291 |
| RM—Associated Gas Wells [a,1] | # wells | 18,880 | 20,100 | 19,619 | 21,421 | 27,155 | 29,566 |
| RM—Non-associated Gas Wells [a,1] | # wells | 26,005 | 31,569 | 42,285 | 66,838 | 83,711 | 83,933 |
| SW—Associated Gas Wells [a,1] | # wells | 48,438 | 37,685 | 33,023 | 31,625 | 34,417 | 36,576 |
| SW—Non-associated Gas Wells [a,1] | # wells | 21,075 | 22,831 | 25,789 | 33,984 | 41,377 | 41,533 |
| WC—Associated Gas Wells [a,1] | # wells | 17,147 | 14,029 | 15,754 | 18,750 | 28,854 | 29,315 |
| WC—Non-associated Gas Wells [a,1] | # wells | 2,029 | 1,913 | 2,004 | 1,991 | 2,117 | 2,115 |
| GC—Associated Gas Wells [a,1] | # wells | 32,645 | 22,968 | 17,310 | 14,775 | 14,368 | 14,782 |
| GC—Non-associated Gas Wells [a,1] | # wells | 36,339 | 38,083 | 43,496 | 57,265 | 74,964 | 76,329 |
| **Platforms[aa]** | | | | | | | |
| Gulf of Mexico and Pacific OCS Off-shore Platforms [b,2] | # platforms | 3,941 | 3,978 | 4,016 | 3,909 | 3,432 | 3,432 |
| GoM and Pacific OCS Deep Water Platforms [b,2] | # platforms | 17 | 23 | 38 | 59 | 70 | 70 |
| **Gas Plants[c,1]** | **# gas plants** | 761 | 675 | 585 | 566 | 580 | 585 |
| **Distribution Services** | **# of services** | 47,883,083 | 54,644,033 | 56,761,042 | 61,832,574 | 64,055,780 | 64,731,838 |
| Steel—Unprotected [d,1] | # of services | 7,633,526 | 6,151,653 | 5,675,520 | 5,507,356 | 4,223,830 | 4,140,616 |
| Steel—Protected [d,1] | # of services | 19,781,581 | 21,002,455 | 17,855,560 | 16,529,118 | 15,317,995 | 15,267,357 |
| Plastic [d,1] | # of services | 18,879,865 | 26,044,545 | 31,795,871 | 38,549,089 | 43,435,563 | 44,269,061 |
| Copper [d,1] | # of services | 1,588,111 | 1,445,380 | 1,434,091 | 1,247,011 | 1,078,392 | 1,054,804 |
| **Distribution Mains** | **miles** | 944,157 | 1,001,706 | 1,048,485 | 1,162,560 | 1,223,455 | 1,231,045 |
| Cast Iron [d,1] | miles | 58,292 | 50,625 | 44,750 | 39,645 | 34,604 | 33,586 |
| Steel—Unprotected [d,1] | miles | 108,941 | 94,058 | 82,800 | 72,458 | 66,593 | 64,092 |
| Steel—Protected [d,1] | miles | 465,538 | 503,288 | 471,510 | 490,156 | 489,207 | 488,265 |
| Plastic [d,1] | miles | 311,386 | 353,735 | 449,425 | 560,301 | 633,051 | 645,102 |

[aa] Number of platforms include both oil and gas platforms

[a] DI Desktop (2012)

[b] Bureau of Ocean Energy Management, Regulation and Enforcement (2012)

[c] Oil and Gas Journal

[d] Pipeline and Hazardous Materials Safety Administration (PHMSA), Office of Pipeline Safety (OPS) (2012)

[1] Activity data for 2011 available from source.

[2] 2010 activity data are used to determine some or all of the 2011 activity (to be updated).

Table A-129: $CH_4$ Reductions Derived from the Natural Gas STAR Program (Gg)

| Process | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| **Production** | **(8.8)** | **(87.9)** | **(326.6)** | **(1,345.3)** | **(1,941.7)** | **(2,317.5)** |
| Completions with Hydraulic Fracturing and Refractures | 0.0 | (1.0) | (7.5) | (744.0) | (546.6) | (546.6) |
| Pneumatic Device Vents | (5.4) | (25.8) | (118.4) | (222.1) | (701.5) | (778.0) |
| Kimray Pumps | (0.7) | (8.2) | (14.7) | (20.4) | (124.0) | (179.7) |
| Gas Engines | 0.0 | (7.1) | (23.4) | (43.3) | (49.1) | (49.1) |
| Other Production | (2.7) | (45.9) | (162.7) | (315.4) | (520.5) | (764.1) |
| **Processing** | **(1.9)** | **(22.6)** | **(36.1)** | **(132.8)** | **(144.4)** | **(58.9)** |
| Blowdowns/venting | (0.4) | (16.9) | (26.9) | (42.5) | (53.5) | (32.4) |
| Other Processing | (1.5) | (5.7) | (9.1) | (90.3) | (91.0) | (26.5) |
| **Transmission and Storage** | **0.0** | **(123.5)** | **(293.8)** | **(590.9)** | **(528.5)** | **(421.4)** |
| Reciprocating Compressors | 0.0 | (15.9) | (30.1) | (84.9) | (90.2) | (89.5) |
| Pneumatic Devices | 0.0 | (5.4) | (8.9) | (10.5) | (12.3) | (12.4) |
| Pipeline Venting | 0.0 | (36.3) | (33.3) | (124.9) | (123.0) | (53.2) |
| Other Transmission/ Storage | 0.0 | (65.9) | (221.6) | (370.8) | (303.0) | (266.3) |
| **Distribution** | **0.0** | **(18.2)** | **(27.9)** | **(44.1)** | **(43.2)** | **(42.5)** |
| **Total** | **(10.6)** | **(252.2)** | **(684.3)** | **(2,113.1)** | **(2,657.9)** | **(2,840.2)** |

These reductions will not match the Natural Gas STAR program reductions. These numbers are adjusted for reductions prior to the 1992 base year, and do not include a "sunsetting" period. Totals may not sum due to independent rounding.

This table presents aggregate Gas STAR reduction data for each natural gas system stage, and also presents reductions for select technologies for which disaggregated Gas STAR data can be matched to an Inventory source category. In general, the Inventory uses aggregated Gas STAR reductions by natural gas system stage (i.e., production, processing, transmission and storage, and distribution). In some cases, emissions reductions reported to Gas STAR have been matched to potential emissions calculated in the Inventory, to provide a net emissions number for specific emissions sources. This table presents sources for which Gas STAR reductions can be matched to Inventory emissions sources. Net emissions values for these sources are presented in Table A-12. Some reported reduction activities cover multiple Inventory sources. It is not possible to attribute those reductions to specific Inventory source categories, and they will remain included in the "Other" category.

Table A-130: $CH_4$ Reductions Derived from Regulations (Gg)

| Process | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| **Production** | **A** | **A** | **(44.4)** | **(61.4)** | **(345.4)** | **(333.6)** |
| Completions with Hydraulic Fracturing and Refractures(stage regulations) | A | A | - | - | (225.0) | (213.4) |
| Dehydrator vents (NESHAP) | A | A | (22.7) | (29.5) | (36.6) | (36.5) |
| Condensate tanks (NESHAP) | A | A | (21.7) | (31.9) | (83.8) | (83.8) |
| **Processing** | **0.0)** | **0.0)** | **(12.9)** | **(12.1)** | **(14.4)** | **(15.6)** |
| Dehydrator vents (NESHAP) | 0.0) | 0.0) | (12.9) | (12.1) | (14.4) | (15.6) |
| **Transmission and Storage** | | | | | | |

| Process | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| | A | A | A | A | A | A |
| Distribution | A | A | A | A | A | A |
| Total | 0.0) | 0.0) | (57.3) | (73.5) | (359.8) | (349.2) |

NA Not applicable
Note: Totals may not sum due to independent rounding.

Table A-131: $CH_4$ Potential Emission Estimates from the Natural Gas Production Stage, and Reductions from the Natural Gas STAR Program and Regulations (Gg)

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Normal Fugitives | | | | | | |
| Associated Gas Wells | IE | IE | IE | IE | IE | IE |
| Non-Associated Gas Wells (less wells with hydraulic fracturing) | 12.5 | 15.3 | 17.1 | 20.4 | 23.9 | 23.8 |
| Gas Wells with Hydraulic Fracturing | 6.0 | 8.7 | 11.9 | 20.5 | 27.6 | 27.5 |
| Field Separation Equipment | | | | | | |
| Heaters | 12.4 | 15.4 | 18.9 | 26.2 | 32.6 | 32.8 |
| Separators | 40.3 | 50.0 | 60.9 | 84.0 | 105.8 | 106.8 |
| Dehydrators | 13.3 | 16.1 | 18.9 | 24.9 | 31.0 | 31.1 |
| Meters/ Piping | 40.3 | 49.2 | 59.1 | 80.7 | 101.1 | 102.0 |
| Gathering Compressors | | | | | | |
| Small Reciprocating Compressors | 30.6 | 36.4 | 42.4 | 54.9 | 67.3 | 67.7 |
| Large Reciprocating Compressors | 7.3 | 8.9 | 10.0 | 11.7 | 13.5 | 14.5 |
| Large Reciprocating Stations | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 |
| Pipeline Leaks | 86.0 | 102.5 | 115.8 | 142.7 | 169.4 | 169.8 |
| Vented and Combusted | | | | | | |
| Drilling and Well Completion | | | | | | |
| Gas Well Completions without Hydraulic Fracturing | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Gas Well Completions with Hydraulic Fracturing | 489.0 | 401.5 | 772.0 | 1,524.5 | 1,307.7 | 1,221.3 |
| Well Drilling | 0.7 | 0.5 | 1.0 | 1.6 | 1.0 | 0.8 |
| Produced Water from Coal Bed Methane Wells | | | | | | |
| Powder River | 0.0 | 1.5 | 31.4 | 50.0 | 50.4 | 45.8 |
| Black Warrior | 2.7 | 6.3 | 6.8 | 9.9 | 12.3 | 12.7 |
| Normal Operations | | | | | | |
| Pneumatic Device Vents | 484.7 | 593.7 | 696.0 | 916.3 | 1,132.6 | 1,133.7 |
| Chemical Injection Pumps | 27.2 | 32.6 | 38.8 | 51.7 | 63.4 | 63.6 |
| Kimray Pumps | 155.9 | 195.2 | 227.2 | 295.2 | 365.8 | 364.9 |
| Dehydrator Vents | 48.6 | 60.9 | 70.8 | 92.0 | 114.1 | 113.8 |
| Condensate Tank Vents | | | | | | |
| Condensate Tanks without Control Device | 77.7 | 58.1 | 67.5 | 99.3 | 260.7 | 260.7 |

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Condensate Tanks with Control Device | 15.5 | 11.6 | 13.5 | 19.9 | 52.1 | 52.1 |
| Compressor Exhaust Vented | | | | | | |
| Gas Engines | 117.4 | 140.0 | 164.9 | 219.5 | 273.9 | 275.9 |
| Well Workovers | | | | | | |
| Workovers without Hydraulic Fracturing | 0.3 | 0.4 | 0.4 | 0.5 | 0.6 | 0.6 |
| Refractures | 60.6 | 88.9 | 117.3 | 184.9 | 260.8 | 266.2 |
| Liquids Unloading | | | | | | |
| Liquids Unloading (with plunger lifts) | - | 14.9 | 34.5 | 66.5 | 108.9 | 108.4 |
| Liquids Unloading (without plunger lifts) | 870.1 | 893.3 | 817.1 | 668.5 | 148.7 | 148.5 |
| Blowdowns | | | | | | |
| Vessel Blowdown | 0.3 | 0.4 | 0.4 | 0.6 | 0.7 | 0.7 |
| Pipeline Blowdown | 1.4 | 1.6 | 1.8 | 2.3 | 2.7 | 2.7 |
| Compressor Blowdown | 1.2 | 1.4 | 1.6 | 2.1 | 2.6 | 2.6 |
| Compressor Starts | 2.6 | 3.1 | 3.7 | 4.7 | 5.8 | 5.9 |
| Upsets | | | | | | |
| Pressure Relief Valves | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.7 |
| Mishaps | 0.7 | 0.9 | 1.0 | 1.2 | 1.5 | 1.5 |
| Offshore | | | | | | |
| Offshore Water Gas Platforms (Gulf of Mexico & Pacific) | 290.5 | 307.3 | 323.7 | 321.8 | 266.1 | 266.1 |
| Deepwater Gas Platforms (Gulf of Mexico & Pacific) | 5.2 | 7.4 | 12.8 | 20.4 | 23.0 | 23.0 |
| **Regulatory Reductions** | - | - | (44.4) | (61.4) | (345.4) | (333.6) |
| **Voluntary Reductions** | (8.8) | (87.9) | (326.6) | (1,345.3) | (1,941.7) | (2,317.5) |
| **Total Reductions** | **(8.8)** | **(87.9)** | **(371.0)** | **(1,406.7)** | **(2,287.1)** | **(2,651.1)** |
| **Total Potential Emissions** | **2,901.6** | **3,125.1** | **3,760.4** | **5,020.9** | **5,029.1** | **4,949.1** |
| **Total Net Emissions** | **2,892.9** | **3,037.1** | **3,389.3** | **3,614.2** | **2,742.0** | **2,298.0** |

Note 1: Totals may not sum due to independent rounding.
IE: Included Elsewhere. These emissions are included in the Petroleum Systems estimates.

Table A-132: Potential $CH_4$ Emission Estimates from the Natural Gas Processing Plants, and Reductions from the Natural Gas STAR Program and Regulations (Gg)

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Normal Fugitives | | | | | | |
| Plants | 42.3 | 37.5 | 32.5 | 31.5 | 32.2 | 32.5 |

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Reciprocating Compressors | 324.9 | 338.4 | 349.5 | 327.9 | 391.2 | 422.5 |
| Centrifugal Compressors (wet seals) | 240.3 | 248.6 | 251.3 | 229.2 | 233.9 | 236.2 |
| Centrifugal Compressors (dry seals) | - | 0.8 | 3.5 | 6.5 | 27.2 | 37.4 |
| Vented and Combusted | | | | | | |
| Normal Operations | | | | | | |
| Compressor Exhaust | | | | | | |
| Gas Engines | 137.1 | 142.8 | 147.5 | 138.3 | 165.1 | 178.3 |
| Gas Turbines | 3.9 | 4.0 | 4.2 | 3.9 | 4.6 | 5.0 |
| AGR Vents | 16.5 | 14.6 | 12.7 | 12.3 | 12.6 | 12.7 |
| Kimray Pumps | 3.7 | 3.8 | 4.0 | 3.7 | 4.4 | 4.8 |
| Dehydrator Vents | 22.7 | 23.6 | 24.4 | 22.9 | 27.3 | 29.5 |
| Pneumatic Devices | 2.4 | 2.1 | 1.9 | 1.8 | 1.8 | 1.9 |
| Routine Maintenance | | | | | | |
| Blowdowns/Venting | 59.5 | 52.8 | 45.7 | 44.3 | 45.4 | 45.7 |
| **Regulatory Reductions** | - | - | (12.9) | (12.1) | (14.4) | (15.6) |
| **Voluntary Reductions** | (1.9) | (22.6) | (36.1) | (132.8) | (144.4) | (58.9) |
| **Total Reductions** | **(1.9)** | **(22.6)** | **(49.0)** | **(144.9)** | **(158.9)** | **(74.5)** |
| **Total Potential Emissions** | **853.2** | **869.2** | **877.1** | **822.2** | **945.7** | **1,006.5** |
| **Total Net Emissions** | **851.4** | **846.6** | **828.1** | **677.3** | **786.9** | **932.0** |

Note 1: Totals may not sum due to independent rounding.

Table A-133: Potential $CH_4$ Emission Estimates from the Natural Gas Transmission and Storage, and Reductions from the Natural Gas STAR Program and Regulations (Gg)

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| **Fugitives** | | | | | | |
| Pipelines Leaks | 3.2 | 3.2 | 3.3 | 3.3 | 3.3 | 3.3 |
| **Compressor Stations (Transmission)** | | | | | | |
| Station | 106.9 | 108.8 | 109.5 | 110.1 | 111.6 | 111.6 |
| Recip Compressor | 744.7 | 757.5 | 762.7 | 766.5 | 777.2 | 777.1 |
| Centrifugal Compressor (wet seals) | 246.7 | 249.7 | 243.0 | 234.1 | 234.3 | 234.3 |
| Centrifugal Compressor (dry seals) | - | 0.8 | 6.2 | 12.7 | 14.8 | 14.8 |
| **Compressor Stations (Storage)** | | | | | | |
| Station | 54.6 | 60.4 | 62.2 | 60.1 | 59.6 | 58.8 |
| Recip Compressor | 157.8 | 174.3 | 179.6 | 173.5 | 172.0 | 170.0 |

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Centrifugal Compressor (wet seals) | 33.2 | 36.6 | 34.4 | 30.9 | 27.1 | 26.5 |
| Centrifugal Compressor (dry seals) | - | 0.1 | 2.5 | 4.1 | 6.5 | 6.5 |
| Wells (Storage) | 13.6 | 15.0 | 15.4 | 14.9 | 14.8 | 14.6 |
| M&R (Trans. Co. Interconnect) | 72.8 | 74.0 | 74.5 | 74.9 | 76.0 | 75.9 |
| M&R (Farm Taps + Direct Sales) | 16.9 | 17.2 | 17.3 | 17.4 | 17.6 | 17.6 |
| **Vented and Combusted** | | | | | | |
| Normal Operation | | | | | | |
| Dehydrator Vents (Transmission) | 2.0 | 2.0 | 2.0 | 2.1 | 2.1 | 2.1 |
| Dehydrator Vents (Storage) | 4.2 | 4.7 | 4.8 | 4.6 | 4.6 | 4.6 |
| **Compressor Exhaust** | | | | | | |
| Engines (Transmission) | 176.9 | 204.9 | 215.3 | 203.1 | 219.4 | 224.4 |
| Turbines (Transmission) | 1.0 | 1.2 | 1.2 | 1.2 | 1.2 | 1.3 |
| Engines (Storage) | 21.3 | 23.5 | 24.2 | 23.4 | 23.2 | 22.9 |
| Turbines (Storage) | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Generators (Engines) | 8.7 | 10.0 | 10.5 | 9.9 | 10.7 | 11.0 |
| Generators (Turbines) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Pneumatic Devices** | | | | | | |
| **Transmission + Storage** | | | | | | |
| Pneumatic Devices Trans | 213.1 | 216.7 | 218.2 | 219.3 | 222.4 | 222.3 |
| Pneumatic Devices Storage | 44.4 | 49.1 | 50.6 | 48.8 | 48.4 | 47.9 |
| **Routine Maintenance/Upsets** | | | | | | |
| Pipeline Venting | 178.0 | 181.0 | 182.2 | 183.2 | 185.7 | 185.7 |
| **Station venting** | | | | | | |
| **Transmission + Storage** | | | | | | |
| Station Venting Transmission | 145.5 | 148.0 | 149.0 | 149.7 | 151.8 | 151.8 |
| Station Venting Storage | 30.3 | 33.5 | 34.5 | 33.4 | 33.1 | 32.7 |
| **LNG Storage** | | | | | | |
| LNG Stations | 9.2 | 9.8 | 10.3 | 10.6 | 10.6 | 10.6 |
| LNG Reciprocating Compressors | 34.5 | 36.7 | 38.8 | 40.1 | 40.1 | 40.1 |
| LNG Centrifugal Compressors | 11.8 | 12.5 | 13.3 | 13.8 | 13.8 | 13.8 |
| **LNG Compressor Exhaust** | | | | | | |
| LNG Engines | 2.6 | 2.6 | 2.7 | 2.7 | 2.7 | 2.7 |
| LNG Turbines | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| LNG Station Venting | 5.1 | 5.4 | 5.7 | 5.9 | 5.9 | 5.9 |

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| **LNG Import Terminals** | | | | | | |
| LNG Stations | 0.2 | 0.2 | 0.2 | 0.4 | 1.2 | 1.2 |
| LNG Reciprocating Compressors | 1.0 | 1.0 | 1.0 | 2.0 | 5.6 | 5.6 |
| LNG Centrifugal Compressors | 0.3 | 0.3 | 0.3 | 0.5 | 1.4 | 1.4 |
| **LNG Compressor Exhaust** | | | | | | |
| LNG Engines | 1.7 | 0.5 | 4.4 | 12.2 | 8.4 | 8.4 |
| LNG Turbines | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 |
| LNG Station Venting | 0.1 | 0.1 | 0.1 | 0.2 | 0.6 | 0.6 |
| **Regulatory Reductions** | - | - | - | - | - | - |
| **Voluntary Reductions** | - | (123.5) | (293.8) | (590.9) | (528.5) | (421.4) |
| **Total Reductions** | - | **(123.5)** | **(293.8)** | **(590.9)** | **(528.5)** | **(421.4)** |
| **Total Potential Emissions** | **2,342.6** | **2,441.6** | **2,480.4** | **2,470.0** | **2,508.3** | **2,508.2** |
| **Total Net Emissions** | **2,342.6** | **2,318.1** | **2,186.6** | **1,879.0** | **1,979.7** | **2,086.8** |

Note: Totals may not sum due to independent rounding.

Table A-134: Potential $CH_4$ Emission Estimates from the Natural Gas Distribution Stage, and Reductions from the Natural Gas STAR Program, and Regulations (Gg)

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| **Pipeline Leaks** | | | | | | |
| Mains—Cast Iron | 268.0 | 232.7 | 205.7 | 182.3 | 159.1 | 154.4 |
| Mains—Unprotected steel | 231.2 | 199.6 | 175.7 | 153.8 | 141.3 | 136.0 |
| Mains—Protected steel | 27.5 | 29.7 | 27.9 | 29.0 | 28.9 | 28.8 |
| Mains—Plastic | 59.4 | 67.5 | 85.8 | 106.9 | 120.8 | 123.1 |
| Services—Unprotected steel | 250.0 | 201.5 | 185.9 | 180.4 | 138.4 | 135.6 |
| Services Protected steel | 67.2 | 71.4 | 60.7 | 56.2 | 52.1 | 51.9 |
| Services—Plastic | 3.4 | 4.7 | 5.7 | 6.9 | 7.8 | 7.9 |
| Services—Copper | 7.8 | 7.1 | 7.0 | 6.1 | 5.3 | 5.2 |
| **Meter/Regulator (City Gates)** | | | | | | |
| M&R >300 | 110.4 | 122.0 | 125.6 | 121.4 | 120.4 | 118.9 |
| M&R 100-300 | 214.2 | 236.6 | 243.8 | 235.5 | 233.6 | 230.7 |
| M&R <100 | 5.2 | 5.7 | 5.9 | 5.7 | 5.6 | 5.6 |
| Reg >300 | 108.7 | 120.1 | 123.7 | 119.5 | 118.5 | 117.1 |
| R-Vault >300 | 0.5 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| Reg 100-300 | 82.3 | 90.9 | 93.6 | 90.4 | 89.7 | 88.6 |
| R-Vault 100-300 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Reg 40-100 | 6.3 | 7.0 | 7.2 | 7.0 | 6.9 | 6.8 |
| R-Vault 40-100 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Reg <40 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| **Customer Meters** | | | | | | |
| Residential | 103.5 | 114.3 | 117.7 | 113.7 | 112.8 | 111.4 |
| Commercial/Industry | 4.0 | 4.8 | 4.7 | 3.9 | 4.0 | 4.1 |
| **Routine Maintenance** | | | | | | |
| Pressure Relief Valve Releases | 0.9 | 1.0 | 1.0 | 1.1 | 1.2 | 1.2 |
| Pipeline Blowdown | 2.4 | 2.6 | 2.7 | 2.6 | 2.6 | 2.6 |
| **Upsets** | | | | | | |
| Mishaps (Dig-ins) | 37.2 | 41.1 | 42.3 | 40.9 | 40.6 | 40.1 |
| **Regulatory Reductions** | - | - | - | - | - | - |
| **Voluntary Reductions** | - | (18.2) | (27.9) | (44.1) | (43.2) | (42.5) |
| **Total Reductions** | **-** | **(18.2)** | **(27.9)** | **(44.1)** | **(43.2)** | **(42.5)** |
| **Total Potential Emissions** | **1,591.1** | **1,561.9** | **1,524.3** | **1,464.9** | **1,391.0** | **1,371.6** |
| **Total Net Emissions** | **1,591.1** | **1,543.7** | **1,496.4** | **1,420.8** | **1,347.7** | **1,329.1** |

Note: Totals may not sum due to independent rounding.

Table A-135: Net emissions for select sources (Gg)

| Stage/Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| **Production** | **2,892.9** | **3,037.1** | **3,389.3** | **3,614.2** | **2,742.0** | **2,298.0** |
| Completions with Hydraulic Fracturing and Refractures | 549.5 | 489.3 | 881.8 | 965.4 | 797.0 | 727.5 |
| Pneumatic Device Vents | 479.3 | 568.0 | 577.6 | 694.2 | 431.0 | 355.7 |
| Kimray Pumps | 155.2 | 187.0 | 212.5 | 274.8 | 241.8 | 185.2 |
| Gas Engines | 117.4 | 132.9 | 141.5 | 176.2 | 224.7 | 226.8 |
| Other Production | 1,591.5 | 1,660.0 | 1,575.9 | 1,503.7 | 1,047.4 | 802.8 |
| **Processing** | **851.4** | **846.6** | **828.1** | **677.3** | **786.9** | **932.0** |
| Blowdowns/venting | 59.1 | 35.9 | 18.8 | 1.7 | (8.1) | 13.4 |
| Other Processing | 792.3 | 810.7 | 809.3 | 675.5 | 795.0 | 918.6 |
| **Transmission and Storage** | **2,342.6** | **2,318.1** | **2,186.6** | **1,879.0** | **1,979.7** | **2,086.8** |
| Reciprocating Compressors | 744.7 | 741.6 | 732.6 | 681.6 | 687.0 | 687.6 |
| Pneumatic Devices | 213.1 | 211.4 | 209.3 | 208.9 | 210.1 | 210.0 |
| Pipeline Venting | 178.0 | 144.7 | 149.0 | 58.3 | 62.7 | 132.4 |
| Other Transmission/ Storage | 1,206.9 | 1,220.4 | 1,095.7 | 930.2 | 1,019.9 | 1,056.9 |

| Stage/Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Distribution | 1,591.1 | 1,543.7 | 1,496.4 | 1,420.8 | 1,347.7 | 1,329.1 |
| Total | 7,678.0 | 7,745.5 | 7,900.4 | 7,591.3 | 6,856.3 | 6,646.0 |

Note: This table presents net emissions for each natural gas system stage, and also presents net emissions for select emissions sources for which disaggregated Gas STAR data and/or regulation reduction data can be matched to an Inventory source category. In general, the Inventory uses aggregated Gas STAR reductions by natural gas system stage (i.e., production, processing, transmission and storage, and distribution). In some cases, emissions reductions reported to Gas STAR have been matched to potential emissions calculated in the Inventory, to provide a net emissions number for specific emissions sources. This table presents sources for which Gas STAR reductions and/or regulatory reductions can be matched to Inventory emissions sources. Net emissions values presented here were calculated by deducting the voluntary reductions (Table A-6) and the regulatory reductions (Table A-7) from the potential emissions values in Tables A-1 through A-4. Some reported reduction activities cover multiple Inventory sources. It is not possible to attribute those reductions to specific Inventory source categories, and they will remain included in the "Other" category.

Table A-13: U.S. Production Sector $CO_2$ Content in Natural Gas by NEMS Region and Formation Type for all years

| | U.S. Region | | | | | | |
|---|---|---|---|---|---|---|---|
| Formation Types | North East | Midcontinent | Gulf Coast | South West | Rocky Mountain | West Coast | Lower-48 States |
| Conventional | **0.92%** | 0.79% | 2.17% | 3.81% | 7.95% | 0.16% | 3.41% |
| Non-conventional* | **7.42%** | 0.31% | 0.23% | NA | 0.64% | NA | 4.83% |
| All types | **3.04%** | 0.79% | 2.17% | 3.81% | 7.58% | 0.16% | 3.45% |

Source: GRI-01/0136 GTI's Gas Resource Database: Unconventional Natural Gas and Gas Composition Databases. Second Edition. August, 2001
*In GTI, this refers to shale, coal bed methane, and tight geologic formations.

Table A-14: $CO_2$ Emission Estimates from the Natural Gas Production Stage (Gg)

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| **Normal Fugitives** | | | | | | |
| Gas Wells | | | | | | |
| Non-Associated Gas Wells | 1.4 | 1.6 | 1.8 | 2.2 | 2.7 | 2.7 |
| Gas Wells with Hydraulic Fracturing | 0.3 | 0.4 | 0.5 | 0.7 | 0.8 | 0.8 |
| Field Separation Equipment | | | | | | |
| Heaters | 1.9 | 2.2 | 2.8 | 4.2 | 5.2 | 5.2 |
| Separators | 5.8 | 6.6 | 8.2 | 12.0 | 15.1 | 15.2 |
| Dehydrators | 1.4 | 1.6 | 1.9 | 2.8 | 3.5 | 3.5 |
| Meter/ Piping | 5.6 | 6.4 | 7.9 | 11.5 | 14.4 | 14.5 |
| Gathering Compressors | | | | | | |
| Small Reciprocating Compressors | 2.9 | 3.3 | 4.0 | 5.9 | 7.3 | 7.4 |
| Large Reciprocating Compressors | 0.8 | 0.9 | 1.0 | 1.3 | 1.6 | 1.7 |
| Large Reciprocating Stations | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Pipeline Leaks | 9.6 | 10.8 | 12.6 | 16.6 | 19.9 | 19.9 |
| **Vented and Combusted** | | | | | | |
| Drilling and Well Completion | | | | | | |
| Gas Well Completions without Hydraulic Fracturing[2] | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Gas Well Completions with Hydraulic Fracturing | 75.6 | 64.3 | 175.6 | 242.4 | 174.5 | 147.3 |
| Well Drilling | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 |
| Produced Water from Coal Bed Methane Wells | | | | | | |
| Powder River[1] | NE | NE | NE | NE | NE | NE |
| Black Warrior[1] | NE | NE | NE | NE | NE | NE |
| Normal Operations | | | | | | |
| Pneumatic Device Vents | 50.6 | 60.2 | 74.1 | 106.4 | 132.0 | 132.1 |
| Chemical Injection Pumps | 3.0 | 3.5 | 4.5 | 6.7 | 8.4 | 8.4 |
| Kimray Pumps | 15.8 | 19.4 | 23.3 | 32.3 | 40.0 | 39.9 |
| Dehydrator Vents | 4.9 | 6.0 | 7.3 | 10.1 | 12.5 | 12.4 |
| Condensate Tank Vents | | | | | | |
| Condensate Tanks without Control Device | 10.3 | 8.8 | 9.3 | 10.3 | 15.7 | 15.7 |
| Condensate Tanks with Control Device | 2.1 | 1.8 | 1.9 | 2.1 | 3.1 | 3.1 |
| Compressor Exhaust Vented | | | | | | |
| Gas Engines[1] | NE | NE | NE | NE | NE | NE |
| Well Workovers | | | | | | |
| Workovers without Hydraulic Fracturing | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 |

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Refractures | 12.5 | 16.4 | 22.0 | 34.7 | 44.3 | 44.6 |
| Liquids Unloading | | | | | | |
| Liquids Unloading (with plunger lifts) | - | 1.7 | 4.1 | 8.7 | 14.3 | 14.2 |
| Liquids Unloading (without plunger lifts) | 265.0 | 243.6 | 220.2 | 182.5 | 26.9 | 26.9 |
| Blowdowns | | | | | | |
| Vessel Blowdown | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 |
| Pipeline Blowdown | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 |
| Compressor Blowdown | 0.1 | 0.1 | 0.2 | 0.2 | 0.3 | 0.3 |
| Compressor Starts | 0.2 | 0.3 | 0.3 | 0.5 | 0.6 | 0.6 |
| Upsets | | | | | | |
| Pressure Relief Valves | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 |
| Mishaps | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 |
| Flaring Emissions – Onshore | 9,092.7 | 17,167.8 | 5,525.0 | 7,193.0 | 9,957.9 | 9,895.6 |
| **Offshore** | | | | | | |
| Offshore water Gas Platforms (Gulf of Mexico & Pacific) | 1.5 | 1.6 | 1.6 | 1.6 | 1.4 | 1.4 |
| Deepwater Gas Platforms (Gulf of Mexico & Pacific) | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 |
| Flaring Emissions – Offshore | 230.4 | 197.2 | 204.3 | 180.7 | 359.0 | 359.0 |
| **Total** | **9,794.8** | **17,826.8** | **6,315.2** | **8,070.2** | **10,862.5** | **10,773.6** |

[1] Energy use $CO_2$ emissions not estimated to avoid double counting. NE = not estimated.
[2] Emissions are not actually 0, but too small to show at this level of precision.
Note: Totals may not sum due to independent rounding.

Table A-15: $CO_2$ Emission Estimates from the Natural Gas Processing Stage (Gg)

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| **Normal Fugitives** | | | | | | |
| Plants – Before $CO_2$ removal | 2.6 | 2.3 | 2.0 | 1.9 | 2.0 | 2.0 |
| Plants – After $CO_2$ removal | 0.6 | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 |
| Reciprocating Compressors – Before $CO_2$ removal | 19.7 | 20.5 | 21.2 | 19.8 | 23.7 | 25.6 |
| Reciprocating Compressors – After $CO_2$ removal | 4.4 | 4.5 | 4.7 | 4.4 | 5.3 | 5.7 |
| Centrifugal Compressors (wet seals) – Before $CO_2$ removal | 14.5 | 15.0 | 15.2 | 13.9 | 14.2 | 14.3 |
| Centrifugal Compressors (wet seals) – After $CO_2$ removal | 3.2 | 3.3 | 3.4 | 3.1 | 3.1 | 3.2 |
| Centrifugal Compressors (dry seals) – Before $CO_2$ removal | - | 0.0 | 0.2 | 0.4 | 1.6 | 2.3 |
| Centrifugal Compressors (dry seals) – After $CO_2$ removal | - | 0.0 | 0.0 | 0.1 | 0.4 | 0.5 |
| **Vented and Combusted** | | | | | | |
| Normal Operations | | | | | | |
| Compressor Exhaust | | | | | | |
| Gas Engines[1] | NE | NE | NE | NE | NE | NE |
| Gas Turbines[1] | NE | NE | NE | NE | NE | NE |

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| AGR Vents | 27,708.2 | 24,576.9 | 23,288.2 | 21,694.3 | 21,286.7 | 21,403.6 |
| Kimray Pumps | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 |
| Dehydrator Vents | 2.4 | 2.5 | 2.6 | 2.4 | 2.9 | 3.2 |
| Pneumatic Devices | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.2 |
| **Routine Maintenance** | | | | | | |
| Blowdowns/Venting | 6.4 | 5.6 | 4.9 | 4.7 | 4.9 | 4.9 |
| **Total** | **27,762.6** | **24,629.7** | **23,341.5** | **21,744.2** | **21,343.9** | **21,464.3** |

[1] Energy use $CO_2$ emissions not estimated to avoid double counting. NE = not estimated.
Note: Totals may not sum due to independent rounding.

Table A-16: $CO_2$ Emission Estimates from the Natural Gas Transmission and Storage Stage (Gg)

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| **Fugitives** | | | | | | |
| Pipelines Leaks | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Compressor Stations (Transmission) | | | | | | |
| Station | 3.1 | 3.1 | 3.2 | 3.2 | 3.2 | 3.2 |
| Reciprocating Compressor | 21.5 | 21.9 | 22.0 | 22.1 | 22.4 | 22.4 |
| Centrifugal Compressor (wet seals) | 7.1 | 7.2 | 7.0 | 6.8 | 6.8 | 6.8 |
| Centrifugal Compressor (dry seals) | - | 0.0 | 0.2 | 0.4 | 0.4 | 0.4 |
| Compressor Stations (Storage) | | | | | | |
| Station | 1.6 | 1.7 | 1.8 | 1.7 | 1.7 | 1.7 |
| Reciprocating Compressor | 4.6 | 5.0 | 5.2 | 5.0 | 5.0 | 4.9 |
| Centrifugal Compressor (wet seals) | 1.0 | 1.1 | 1.0 | 0.9 | 0.8 | 0.8 |
| Centrifugal Compressor (dry seals) | - | 0.0 | 0.1 | 0.1 | 0.2 | 0.2 |
| Wells (Storage) | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| M&R (Trans. Co. Interconnect) | 2.1 | 2.1 | 2.1 | 2.2 | 2.2 | 2.2 |
| M&R (Farm Taps + Direct Sales) | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| **Vented and Combusted** | | | | | | |
| Normal Operation | | | | | | |
| Dehydrator Vents (Transmission) | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Dehydrator Vents (Storage) | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Compressor Exhaust | | | | | | |
| Engines (Transmission)[1] | NE | NE | NE | NE | NE | NE |
| Turbines (Transmission)[1] | NE | NE | NE | NE | NE | NE |
| Engines (Storage)[1] | NE | NE | NE | NE | NE | NE |
| Turbines (Storage)[1] | NE | NE | NE | NE | NE | NE |
| Generators (Engines)[1] | NE | NE | NE | NE | NE | NE |

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Generators (Turbines)[1] | NE | NE | NE | NE | NE | NE |
| Pneumatic Devices Transmission + Storage | | | | | | |
| Pneumatic Devices Transmission | 6.1 | 6.3 | 6.3 | 6.3 | 6.4 | 6.4 |
| Pneumatic Devices Storage | 1.3 | 1.4 | 1.5 | 1.4 | 1.4 | 1.4 |
| Routine Maintenance/Upsets | | | | | | |
| Pipeline Venting | 5.1 | 5.2 | 5.3 | 5.3 | 5.4 | 5.4 |
| Station venting Transmission + Storage | | | | | | |
| Station Venting Transmission | 4.2 | 4.3 | 4.3 | 4.3 | 4.4 | 4.4 |
| Station Venting Storage | 0.9 | 1.0 | 1.0 | 1.0 | 1.0 | 0.9 |
| **LNG Storage** | | | | | | |
| LNG Stations | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 |
| LNG Reciprocating Compressors | 1.2 | 1.2 | 1.3 | 1.3 | 1.3 | 1.3 |
| LNG Centrifugal Compressors | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 |
| LNG Compressor Exhaust | | | | | | |
| LNG Engines[1] | NE | NE | NE | NE | NE | NE |
| LNG Turbines[1] | NE | NE | NE | NE | NE | NE |
| LNG Station Venting | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| **LNG Import Terminals** | | | | | | |
| LNG Stations | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| LNG Reciprocating Compressors | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.2 |
| LNG Centrifugal Compressors | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| LNG Compressor Exhaust | | | | | | |
| LNG Engines[1] | NE | NE | NE | NE | NE | NE |
| LNG Turbines[1] | NE | NE | NE | NE | NE | NE |
| LNG Station Venting[2] | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Total** | **61.6** | **63.6** | **64.3** | **64.2** | **65.0** | **64.8** |

[1] Energy use $CO_2$ emissions not estimated to avoid double counting. NE = not estimated.
[2] Emissions are not actually 0, but too small to show at this level of precision.
Note: Totals may not sum due to independent rounding.

Table A-17: $CO_2$ Emission Estimates from the Natural Gas Distribution Stage (Gg)

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| **Pipeline Leaks** | | | | | | |
| Mains—Cast Iron | 7.7 | 6.7 | 5.9 | 5.3 | 4.6 | 4.5 |
| Mains—Unprotected steel | 6.7 | 5.8 | 5.1 | 4.4 | 4.1 | 3.9 |
| Mains—Protected steel | 0.8 | 0.9 | 0.8 | 0.8 | 0.8 | 0.8 |
| Mains—Plastic | 1.7 | 1.9 | 2.5 | 3.1 | 3.5 | 3.6 |
| **Total Pipeline Miles** | | | | | | |

| Activity | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Services—Unprotected steel | 7.2 | 5.8 | 5.4 | 5.2 | 4.0 | 3.9 |
| Services Protected steel | 1.9 | 2.1 | 1.8 | 1.6 | 1.5 | 1.5 |
| Services—Plastic | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 |
| Services—Copper | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 |
| **Meter/Regulator (City Gates)** | | | | | | |
| M&R >300 | 3.2 | 3.5 | 3.6 | 3.5 | 3.5 | 3.4 |
| M&R 100-300 | 6.2 | 6.8 | 7.0 | 6.8 | 6.7 | 6.7 |
| M&R <100 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Reg >300 | 3.1 | 3.5 | 3.6 | 3.4 | 3.4 | 3.4 |
| R-Vault >300 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Reg 100-300 | 2.4 | 2.6 | 2.7 | 2.6 | 2.6 | 2.6 |
| R-Vault 100-300 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Reg 40-100 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| R-Vault 40-100 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Reg <40 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Customer Meters** | | | | | | |
| Residential | 3.0 | 3.3 | 3.4 | 3.3 | 3.3 | 3.2 |
| Commercial/Industry | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Routine Maintenance** | | | | | | |
| Pressure Relief Valve Releases | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Pipeline Blowdown | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Upsets** | | | | | | |
| Mishaps (Dig-ins) | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 |
| **Total** | **45.9** | **45.1** | **44.0** | **42.3** | **40.1** | **39.6** |

Note: Totals may not sum due to independent rounding.

## 3.6. Methodology for Estimating $CH_4$ and $CO_2$ Emissions from Petroleum Systems

The methodology for estimating $CH_4$ and non-combustion $CO_2$ emissions from petroleum systems is based on the 1999 EPA draft report, *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA 1999) and the study, *Methane Emissions from the U.S. Petroleum Industry* (EPA/GRI 1996). Sixty-four activities that emit $CH_4$ and thirty activities that emit non-combustion $CO_2$ from petroleum systems were examined from these reports. Most of the activities analyzed involve crude oil production field operations, which accounted for over 98 percent of total oil industry $CH_4$ emissions. Crude transportation and refining accounted for the remaining $CH_4$ emissions of less than 0.4 and about 1.3 percent, respectively. Non-combustion $CO_2$ emissions were analyzed for production operations and asphalt blowing in refining operations. Non-combustion $CO_2$ emissions from transportation operations are not included because they are negligible. The following steps were taken to estimate $CH_4$ and $CO_2$ emissions from petroleum systems.

#### Step 1: Determine Activity Data for Each Year

Activity levels change from year to year. Some data changes in proportion to crude oil rates: production, transportation, refinery runs. Some change in proportion to the number of facilities: oil wells, petroleum refineries. Some factors change proportional to both the rate and number of facilities.

For most sources, activity data found in the EPA/GRI 1996 for the 1995 base year are extrapolated to other years using publicly-available data sources. For the remaining sources, the activity data are obtained directly from publicly available data.

For both sets of data, a determination was made on a case-by-case basis as to which measure of petroleum industry activity best reflects the change in annual activity. Publicly-reported data from the Bureau of Ocean Energy Management (BOEM), Energy Information Administration (EIA), American Petroleum Institute (API), the Oil & Gas Journal (O&GJ), the Interstate Oil and Gas Compact Commission (IOGCC), and the U.S Army Corps of Engineers (USACE) were used to extrapolate the activity data from the base year to each year between 1990 and 2011. Data used include total domestic crude oil production, number of domestic crude oil wells, total imports and exports of crude oil, total petroleum refinery crude runs, and number of oil-producing offshore platforms. The activity data for the total crude transported in the transportation sector is not available. In this case, all the crude oil that was transported was assumed to go to refineries. Therefore, the activity data for the refining sector was used also for the transportation sector. In the few cases where no data was located, oil industry data based on expert judgment was used. In the case of non-combustion $CO_2$ emission sources, the activity factors are the same as for $CH_4$ emission sources.

#### Step 2: Determine Emission Factors for all Activities

The $CH_4$ emission factors for the majority of the activities for 1995 are taken from the 1999 EPA draft report, which contained the most recent and comprehensive determination of $CH_4$ emission factors for the 64 $CH_4$-emitting activities in the oil industry at that time. Emission factors for pneumatic devices in the production sector were recalculated in 2002 using emissions data in the EPA/GRI 1996c study. The gas engine emission factor is taken from the EPA/GRI 1996b study. The oil tank venting emission factor is taken from the API E&P Tank Calc weighted average for API gravity less than 45 API degrees with the distribution of gravities taken from a sample of production data from the HPDI database. Offshore emissions from shallow water and deep water oil platforms are taken from analysis of the Gulf-wide Offshore Activity Data System (GOADS) report (EPA 2005, BOEMRE 2004). The emission factors determined for 1995 were assumed to be representative of emissions from each source type over the period 1990 through 2011. Therefore, the same emission factors are used for each year throughout this period.

The $CO_2$ emission factors were derived from the corresponding source $CH_4$ emission factors. The amount of $CO_2$ in the crude oil stream changes as it passes through various equipment in petroleum production operations. As a result, four distinct stages/streams with varying $CO_2$ contents exist. The four streams that are used to estimate the emissions factors are the associated gas stream separated from crude oil, hydrocarbons flashed out from crude oil (such as in storage tanks), whole crude oil itself when it leaks downstream, and gas emissions from offshore oil platforms. The standard approach used to estimate $CO_2$ emission factors was to use the existing $CH_4$ emissions factors and multiply them by a conversion factor, which is the ratio of $CO_2$ content to methane content for the particular stream. Ratios of $CO_2$ to $CH_4$ volume in emissions are presented in Table A-140. The two exceptions are the emissions factor for storage tanks, which is estimated using API E&P Tank Calc simulation runs of tank emissions for crude oil of different gravities less than 45 API degrees; and the emissions factor for uncontrolled asphalt blowing, which is estimated using the data and methods provided by API (2009).

**Step 3: Estimate Methane and Carbon Dioxide Emissions for Each Activity for Each Year**

Annual $CH_4$ emissions from each of the 64 petroleum system activities and $CO_2$ emissions from the 30 petroleum system activities were estimated by multiplying the activity data for each year by the corresponding emission factor. These annual emissions for each activity were then summed to estimate the total annual $CH_4$ and $CO_2$ emissions, respectively.

Table A-136, Table A-137, Table A-138, and Table A-141 provide 2011 activity data, emission factors, and emission estimates and Table A-139 and Table A-142 provide a summary of emission estimates for the years 1990, 1995, 2000, and 2005 through 2011. Table A-140provides the $CO_2$ content in natural gas for equipment in different crude streams to estimate $CO_2$ emission factors using $CH_4$ emission factors.

The tables provide references for emission factors and activity data in footnotes (the lettered footnotes). The tables also provide information on which method was used for supplying activity data for 2011 (the numbered footnotes).

Key to table notations on methods for supplying activity data for 2011 for all tables:

1. Ratios relating other factors for which activity data are available. For example, EPA (1996) found that the number of heater treaters (a source of $CH_4$ emissions) is related to both number of producing wells and annual production. To estimate the activity data for heater treaters, reported statistics for wells and production were used, along with the ratios developed for EPA (1996).
2. Activity data for 2011 available from source.
3. Activity data was held constant from 1990 through 2011 based on EPA (1999).
4. 2010 activity data are used to determine some or all of the 2011 activity data.

Table A-136: 2010 $CH_4$ Emissions from Petroleum Production Field Operations

| | *2010 EPA Inventory Values* | | | | | |
|---|---|---|---|---|---|---|
| **Activity/Equipment** | **Emission Factor** | | **Activity Data** | | **Emissions (Bcf/yr)** | **Emissions (Gg/yr)** |
| **Vented Emissions** | | | | | **68.988** | **1,307** |
| Oil Tanks | 7.39 | scf of $CH_4$/bbl crude[a] | 1,557 | MMbbl/yr (non stripper wells)[b,c,d,1,4] | 11.515 | 221.4 |
| Pneumatic Devices, High Bleed | 330 | scfd $CH_4$/device[f] | 142,971 | No. of high-bleed devices[c,e,g,1] | 17.242 | 331.6 |
| Pneumatic Devices, Low Bleed | 52 | scfd $CH_4$/device[f] | 265,518 | No. of low-bleed devices[c,e,g,1] | 5.040 | 96.91 |
| Chemical Injection Pumps | 248 | scfd $CH_4$/pump[h] | 28,702 | No. of pumps[g,i,1] | 2.599 | 49.97 |
| Vessel Blowdowns | 78 | scfy $CH_4$/vessel[h] | 186,638 | No. of vessels[c,g,i,1] | 0.015 | 0.280 |
| Compressor Blowdowns | 3,775 | scf/yr of $CH_4$/compressor[h] | 2,531 | No. of compressors[c,g,i,1] | 0.010 | 0.184 |
| Compressor Starts | 8,443 | scf/yr of $CH_4$/compressor[h] | 2,531 | No. of compressors[c,g,i,1] | 0.021 | 0.411 |
| Stripper wells | 2,345 | scf/yr of $CH_4$/stripper well[f] | 315,213 | No. of stripper wells vented[f,1,4] | 0.739 | 14.21 |
| Well Completion Venting | 733 | scf/completion[h] | 19,468 | Oil well completions[c,2] | 0.014 | 0.274 |
| Well Workovers | 96 | scf $CH_4$/workover[i] | 40,200 | Oil well workovers[g,i,1] | 0.004 | 0.074 |
| Pipeline Pigging | 2.40 | scfd of $CH_4$/pig station[j] | 0 | No. of crude pig stations[e,3] | - | - |
| Offshore Platforms, Shallow water Oil, fugitive, vented and combusted | 54,795 | scfd $CH_4$/platform[k] | 1,447 | No. of shallow water oil platforms[l,4] | 28.930 | 556.4 |
| Offshore Platforms, Deepwater oil, fugitive, vented and combusted | 260,274 | scfd $CH_4$/platform[k] | 29 | No. of deep water oil platforms[l,4] | 2.778 | 53.42 |
| **Fugitive Emissions** | | | | | **2.639** | **50.76** |
| Oil Wellheads (heavy crude) | 0.13 | scfd/well[e,m] | 15,565 | No. of hvy. crude wells[d,g,i,1,4] | 0.001 | 0.014 |
| Oil Wellheads (light crude) | 16.6 | scfd/well[e,m] | 205,222 | No. of lt. crude wells[d,g,i,1,4] | 1.246 | 23.96 |
| Separators (heavy crude) | 0.15 | scfd $CH_4$/separator[e,m] | 10,982 | No. of hvy. crude seps.[c,g,i,1] | 0.001 | 0.012 |
| Separators (light crude) | 14 | scfd $CH_4$/separator[e,m] | 99,944 | No. of lt. crude seps.[c,g,i,1] | 0.505 | 9.728 |
| Heater/Treaters (light crude) | 19 | scfd $CH_4$/heater[e,m] | 75,712 | No. of heater treaters[c,g,i,1] | 0.530 | 10.20 |
| Headers (heavy crude) | 0.08 | scfd $CH_4$/header[e,m] | 13,982 | No. of hvy. crude hdrs.[g,i,1] | 0.000* | 0.008 |

| Activity/Equipment | 2010 EPA Inventory Values | | | | | |
|---|---|---|---|---|---|---|
| | Emission Factor | | Activity Data | | Emissions (Bcf/yr) | Emissions (Gg/yr) |
| Headers (light crude) | 11 | scfd $CH_4$/header[e,m] | 43,344 | No. of lt. crude hdrs.[g,i,1] | 0.172 | 3.303 |
| Floating Roof Tanks | 338,306 | scf $CH_4$/floating roof tank/yr[m,n] | 24 | No. of floating roof tanks[e,3] | 0.008 | 0.159 |
| Compressors | 100 | scfd $CH_4$/compressor[e] | 2,531 | No. of compressors[c,g,i,1] | 0.092 | 1.777 |
| Large Compressors | 16,360 | scfd $CH_4$/compressor[e] | 0 | No. of large comprs.[e,3] | - | - |
| Sales Areas | 41 | scf $CH_4$/loading[e] | 1,720,700 | Loadings/year[c,1] | 0.070 | 1.342 |
| Pipelines | NE | scfd of $CH_4$/mile of pipeline | 12,868 | Miles of gathering line[o,2] | NE | NE |
| Well Drilling | NE | scfd of $CH_4$/oil well drilled | 21,899 | No. of oil wells drilled[c,2] | NE | NE |
| Battery Pumps | 0.24 | scfd of $CH_4$/pump[m] | 160,800 | No. of battery pumps[g,e,1] | 0.014 | 0.271 |
| **Combustion Emissions** | | | | | **4.962** | **95.43** |
| Gas Engines | 0.24 | scf $CH_4$/HP-hr[h] | 15,947 | MMHP-hr[c,g,i,1] | 3.827 | 73.60 |
| Heaters | 0.52 | scf $CH_4$/bbl[n] | 2065.2 | MMbbl/yr[c,2] | 1.076 | 20.70 |
| Well Drilling | 2,453 | scf $CH_4$/well drilled[m] | 21,899 | Oil wells drilled[c,2] | 0.054 | 1.033 |
| Flares | 20 | scf $CH_4$/Mcf flared[j] | 253,334 | Mcf flared/yr[b,c,d,1,4] | 0.005 | 0.097 |
| **Process Upset Emissions** | | | | | **0.188** | **3.624** |
| Pressure Relief Valves | 35 | scf/yr/PR valve | 166,894 | No. of PR valves | 0.006 | 0.111 |
| Well Blowouts Onshore | 2.5 | MMscf/blowout | 69.3 | No. of blowouts/yr | 0.173 | 3.332 |
| **Total** | | | | | **76.70** | **1,475** |

[a] TankCALC
[b] EPA / ICF International (1999)
[c] Energy Information Administration (EIA) Monthly Energy Review
[d] Interstate Oil & Gas Compact Commission (IOGCC) Marginal Wells Report
[e] Consensus of Industrial Review Panel
[f] Expert Judgement
[g] EIA Annual Energy Review
[h] Global Reporting Initiative (GRI) / EPA (1996)
[i] Radian (1996)
[j] Canadian Association of Petroleum Producers (CAPP) (1992)
[k] Adapted from the Minerals Management Service (MMS) Gulfwide Offshore Activities Data System (GOADS) by ICF (2005)
[l] Bureau of Ocean Energy Management (BOEM)
[m] American Petroleum Institute (API) (1996)
[n] EPA, AP 42 Compilation of Air Pollutant Emission Factors
[o] Oil and Gas Journal (OGJ) Petroleum Economics Issue
- Zero Emissions
* Emissions are not actually 0, but too small to show at this level of precision.

Table A-137: 2010 $CH_4$ Emissions from Petroleum Transportation

| Activity/Equipment | Emission Factor | Units | Activity Factor | Units | Emissions (Bcf/yr) | Emissions (Gg/yr) |
|---|---|---|---|---|---|---|
| **Vented Emissions** | | | | | **0.212** | **4.075** |
| Tanks | 0.021 | scf $CH_4$/yr/bbl of crude delivered to refineries[a] | 5,404 | MMbbl crude feed/yr[b,2] | 0.111 | 2.141 |
| Truck Loading | 0.520 | scf $CH_4$/yr/bbl of crude transported by truck[c] | 95.2 | MMbbl crude trans. by truck[d,2] | 0.050 | 0.953 |
| Marine Loading | 2.544 | scf $CH_4$/1000 gal crude marine loadings[c] | 17,550,569 | 1,000 gal/yr loaded[e,1,4] | 0.045 | 0.859 |
| Rail Loading | 0.520 | scf $CH_4$/yr/bbl of crude transported by rail[c] | 6.2 | MMbbl Crude by rail/yr[d,2] | 0.003 | 0.062 |
| Pump Station Maintenance | 36.80 | scf $CH_4$/station/yr[f] | 500 | No. of pump stations[g,1] | 0.000* | 0.000* |
| Pipeline Pigging | 39 | scfd of $CH_4$/pig station[h] | 1,000 | No. of pig stations[g,1] | 0.014 | 0.274 |
| **Fugitive Emissions** | | | | | **0.050** | **0.958** |
| Pump Stations | 25 | scf $CH_4$/mile/yr[f] | 50,004 | No. of miles of crude p/l[g,2] | 0.001 | 0.024 |
| Pipelines | NE | scf $CH_4$/bbl crude transported by pipeline[f] | 7,032 | MMbbl crude piped[g,2] | NE | NE |
| Floating Roof Tanks | 58,965 | scf $CH_4$/floating roof tank/yr[i] | 824 | No. of floating roof tanks[3] | 0.049 | 0.934 |

| Activity/Equipment | Emission Factor | Units | Activity Factor | Units | Emissions (Bcf/yr) | Emissions (Gg/yr) |
|---|---|---|---|---|---|---|
| **Combustion Emissions** | | | | | **NE** | **NE** |
| Pump Engine Drivers | 0.24 | scf $CH_4$/hp-hr[j] | NE | No. of hp-hrs | NE | NE |
| Heaters | 0.521 | scf $CH_4$/bbl burned[k] | NE | No. of bbl Burned | NE | NE |
| **Total** | | | | | **0.273** | **5.247** |

[a] API (1992)
[b] Energy Information Administration (EIA) Petroleum Supply Annual, Volume 1.
[c] EPA, AP 42 Compilation of Air Pollutant Emission Factors
[d] EIA Refinery Capacity Report
[e] EIA Monthly Energy Review
[f] Radian (1996)
[g] OGJ Petroleum Economics Issue
[h] CAPP (1992)
[I] API TANK
[j] GRI / EPA (1996)
[k] EPA / ICF International (1999)
* Emissions are not actually 0, but too small to show at this level of precision.
NE: Not estimated for lack of data

Table A-138: 2010 $CH_4$ Emissions from Petroleum Refining

| Activity/Equipment | 2010 EPA Inventory Values | | | | | |
|---|---|---|---|---|---|---|
| | Emission Factor | | Activity Factor | | Emissions (Bcf/yr) | Emissions (Gg/yr) |
| **Vented Emissions** | | | | | **0.785** | **15.12** |
| Tanks | 20.6 | scf $CH_4$/Mbbl[a] | 1,900 | Mbbl/calendar day heavy crude feed[b,c,1] | 0.014 | 0.275 |
| System Blowdowns | 137 | scf $CH_4$/Mbbl[c] | 14,806 | Mbbl/calendar day refinery feed[b,2] | 0.739 | 14.22 |
| Asphalt Blowing | 2,555 | scf $CH_4$/Mbbl[c] | 37 | Mbbl/calendar day production[b,2] | 0.034 | 0.655 |
| **Fugitive Emissions** | | | | | **0.088** | **1.696** |
| Fuel Gas System | 439 | Mscf $CH_4$/refinery/yr[a] | 148 | Refineries[d,2] | 0.065 | 1.249 |
| Floating Roof Tanks | 587 | scf $CH_4$/floating roof tank/yr[e] | 767 | No. of floating roof tanks[3] | 0.000* | 0.009 |
| Wastewater Treating | 1.88 | scf $CH_4$/Mbbl[c] | 14,806 | Mbbl/calendar day refinery feed[b,2] | 0.010 | 0.196 |
| Cooling Towers | 2.36 | scf $CH_4$/Mbbl[c] | 14,806 | Mbbl/calendar day refinery feed[b,2] | 0.013 | 0.245 |
| **Combustion Emissions** | | | | | **0.093** | **1.79** |
| Atmospheric Distillation | 3.61 | scf $CH_4$/Mbbl[c] | 15,289 | Mbbl/calendar day refinery feed[d,2] | 0.020 | 0.387 |
| Vacuum Distillation | 3.61 | scf $CH_4$/Mbbl[c] | 6,826 | Mbbl/calendar day feed[f,1] | 0.009 | 0.173 |
| Thermal Operations | 6.01 | scf $CH_4$/Mbbl[c] | 2,224 | Mbbl/calendar day feed[f,1] | 0.005 | 0.094 |
| Catalytic Cracking | 5.17 | scf $CH_4$/Mbbl[c] | 4,876 | Mbbl/calendar day feed[f,1] | 0.009 | 0.177 |
| Catalytic Reforming | 7.22 | scf $CH_4$/Mbbl[c] | 3,014 | Mbbl/calendar day feed[f,1] | 0.008 | 0.153 |
| Catalytic Hydrocracking | 7.22 | scf $CH_4$/Mbbl[c] | 1,490 | Mbbl/calendar day feed[f,1] | 0.004 | 0.075 |
| Hydrorefining | 2.17 | scf $CH_4$/Mbbl[c] | 2,172 | Mbbl/calendar day feed[f,1] | 0.002 | 0.033 |
| Hydrotreating | 6.50 | scf $CH_4$/Mbbl[c] | 9,963 | Mbbl/calendar day feed[f,1] | 0.024 | 0.454 |
| Alkylation/Polymerization | 12.6 | scf $CH_4$/Mbbl[c] | 1,050 | Mbbl/calendar day feed[f,1] | 0.005 | 0.093 |
| Aromatics/Isomeration | 1.80 | scf $CH_4$/Mbbl[c] | 987 | Mbbl/calendar day feed[f,1] | 0.001 | 0.012 |
| Lube Oil Processing | 0.00 | scf $CH_4$/Mbbl[c] | 167 | Mbbl/calendar day feed[f,1] | 0.000 | 0.000 |
| Engines | 0.006 | scf $CH_4$/hp-hr[g] | 1,099 | MMhp-hr/yr[f,1] | 0.006 | 0.120 |
| Flares | 0.189 | scf $CH_4$/Mbbl[c,e] | 14,806 | Mbbl/calendar day refinery feed[b,2] | 0.001 | 0.020 |
| **Total** | | | | | **0.969** | **18.64** |

[a] API (1992)
[b] EIA Petroleum Supply Annual, Volume 1.
[c] Radian (1996)
[d] EIA Petroleum Navigator

[e] EPA, AP 42 Compilation of Air Pollutant Emission Factors
[f] OGJ Refinery Worldwide Report
[g] GRI / EPA (1996)
* Emissions are not actually 0, but too small to show at this level of precision.

Table A-139: Summary of $CH_4$ Emissions from Petroleum Systems (Gg)

| Activity | 1990 | 1995 | 2000 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|
| **Production Field Operations** | **1,653** | **1,557** | **1,467** | **1,364** | **1,396** | **1,407** | **1,432** | **1,443** | **1,475** |
| Pneumatic device venting | 489 | 463 | 428 | 396 | 398 | 416 | 419 | 416 | 428 |
| Tank venting | 250 | 226 | 214 | 187 | 193 | 185 | 202 | 211 | 221 |
| Combustion & process upsets | 88 | 82 | 76 | 71 | 72 | 75 | 94 | 95 | 99 |
| Misc. venting & fugitives | 799 | 762 | 726 | 692 | 714 | 706 | 694 | 700 | 702 |
| Wellhead fugitives | 26 | 25 | 22 | 17 | 20 | 24 | 23 | 22 | 24 |
| **Crude Oil Transportation** | **7** | **6** | **5** | **5** | **5** | **5** | **5** | **5** | **5** |
| **Refining** | **18** | **18** | **19** | **19** | **19** | **19** | **18** | **19** | **19** |
| **Total** | **1,677** | **1,581** | **1,492** | **1,388** | **1,421** | **1,431** | **1,455** | **1,467** | **1,499** |

Note: Totals may not sum due to independent rounding.

Table A-140: Ratios of $CO_2$ to $CH_4$ Volume in Emissions from Petroleum Production Field Operations

| | Whole Crude, Post-Separator | Associated Gas | Tank Flash Gas | Offshore |
|---|---|---|---|---|
| **Ratio $\%CO_2$ / $\%CH_4$** | 0.052 | 0.020 | 0.017 | 0.004 |

Table A-141: 2010 $CO_2$ Emissions from Petroleum Production Field Operations and Petroleum Refining

| Activity/Equipment | 2010 EPA Inventory Values: Emission Factor | | Activity Factor | | Emissions (Bcf/yr) | Emissions (Gg/yr) |
|---|---|---|---|---|---|---|
| **Vented Emissions** | | | | | **6.028** | **319.5** |
| Oil Tanks | 3.53 | scf of $CO_2$/bbl crude[a] | 1,557 | MMbbl/yr (non stripper wells)[b,c,d,1,4] | 5.494 | 290.5 |
| Pneumatic Devices, High Bleed | 6.704 | scfd $CO_2$/device[f] | 142,971 | No. of high-bleed devices[c,e,g,1] | 0.350 | 18.50 |
| Pneumatic Devices, Low Bleed | 1.055 | scfd $CO_2$/device[f] | 265,518 | No. of low-bleed devices[c,e,g,1] | 0.102 | 5.408 |
| Chemical Injection Pumps | 5.033 | scfd $CO_2$/pump[h] | 28,702 | No. of pumps[g,i,1] | 0.053 | 2.789 |
| Vessel Blowdowns | 1.583 | scfy $CO_2$/vessel[h] | 186,638 | No. of vessels[c,g,i,1] | 0.000* | 0.016 |
| Compressor Blowdowns | 77 | scf/yr of $CO_2$/compressor[h] | 2,531 | No. of compressors[c,g,i,1] | 0.000* | 0.010 |
| Compressor Starts | 171 | scf/yr of $CO_2$/compressor[h] | 2,531 | No. of compressors[c,g,i,1] | 0.000* | 0.023 |
| Stripper wells | 48 | scf/yr of $CO_2$/stripper well[f] | 315,213 | No. of stripper wells vented[f,1,4] | 0.015 | 0.793 |
| Well Completion Venting | 14.87 | scf/completion[h] | 19,468 | Oil well completions[c,2] | 0.000* | 0.015 |
| Well Workovers | 1.95 | scf $CO_2$/workover[i] | 40,200 | Oil well workovers[g,i,1] | 0.000* | 0.004 |
| Pipeline Pigging | NE | scfd of $CO_2$/pig station | NE | No. of crude pig stations | NE | NE |
| Offshore Platforms, Shallow water Oil, fugitive, vented and combusted | 358 | scfd $CO_2$/platform[k] | 1,447 | No. of shallow water oil platforms[l,4] | 0.189 | 10.00 |
| Offshore Platforms, Deepwater oil, fugitive, vented and combusted | 1,701 | scfd $CO_2$/platform[k] | 29 | No. of deep water oil platforms[l,4] | 0.018 | 0.960 |
| **Fugitive Emissions** | | | | | **0.054** | **2.882** |
| Oil Wellheads (heavy crude) | 0.003 | scfd/well[e,m] | 15,565 | No. of hvy. crude wells[d,g,i,1,4] | 0.000* | 0.001 |
| Oil Wellheads (light crude) | 0.337 | scfd/well[e,m] | 205,222 | No. of lt. crude wells[d,g,i,1,4] | 0.025 | 1.337 |
| Separators (heavy crude) | 0.003 | scfd $CO_2$/separator[e,m] | 10,982 | No. of hvy. crude seps.[c,g,i,1] | 0.000* | 0.001 |
| Separators (light crude) | 0.281 | scfd $CO_2$/separator[e,m] | 99,944 | No. of lt. crude seps.[c,g,i,1] | 0.010 | 0.542 |
| Heater/Treaters (light crude) | 0.319 | scfd $CO_2$/heater[e,m] | 75,712 | No. of heater treaters[c,g,i,1] | 0.009 | 0.466 |
| Headers (heavy crude) | 0.002 | scfd $CO_2$/header[e,m] | 13,982 | No. of hvy. crude hdrs.[g,i,1] | 0.000* | 0.000* |
| Headers (light crude) | 0.220 | scfd $CO_2$/header[e,m] | 43,344 | No. of lt. crude hdrs.[g,i,1] | 0.003 | 0.184 |

| Activity/Equipment | 2010 EPA Inventory Values | | | | | |
|---|---|---|---|---|---|---|
| | Emission Factor | | Activity Factor | | Emissions (Bcf/yr) | Emissions (Gg/yr) |
| Floating Roof Tanks | 17,490 | scf $CO_2$/floating roof tank/yr[m,n] | 24 | No. of floating roof tanks[e,3] | 0.000* | 0.023 |
| Compressors | 2.029 | scfd $CO_2$/compressor[e] | 2,531 | No. of compressors[c,g,i,1] | 0.002 | 0.099 |
| Large Compressors | 332 | scfd $CO_2$/compressor[e] | 0 | No. of large comprs.[e,3] | 0.000 | 0.000 |
| Sales Areas | 2.096 | scf $CO_2$/loading[e] | 1,720,700 | Loadings/year[c,1] | 0.004 | 0.191 |
| Pipelines | NE | scfd of $CO_2$/mile of pipeline | 12,868 | Miles of gathering line[o,2] | NE | NE |
| Well Drilling | NE | scfd of $CO_2$/oil well drilled | 21,899 | No. of oil wells drilled[c,2] | NE | NE |
| Battery Pumps | 0.012 | scfd of $CO_2$/pump[m] | 160,800 | No. of battery pumps[g,e,1] | 0.001 | 0.039 |
| **Process Upset Emissions** | | | | | **0.004** | **0.212** |
| Pressure Relief Valves | 1.794 | scf/yr/PR valve[h] | 172,504 | No. of PR valves[c,e,1] | 0.000* | 0.016 |
| Well Blowouts Onshore | 0.051 | MMscf/blowout[e] | 73.0 | No. of blowouts/yr[c,e,1] | 0.004 | 0.196 |
| **Refining Emissions** | | | | | **0.276** | **14.62** |
| Asphalt Blowing† | 20,736 | scf $CO_2$/Mbbl[m] | 37 | Mbbl/calendar day production[p,2] | 0.276 | 14.62 |
| **Total** | | | | | **6.557** | **346.8** |

[a] TankCALC
[b] EPA / ICF International (1999)
[c] EIA Monthly Energy Review
[d] IOGCC Marginal Wells Report
[e] Consensus of Industrial Review Panel
[f] Expert Judgement
[g] EIA Annual Energy Review
[h] GRI / EPA (1996)
[i] Radian (1996)
[j] CAPP (1992)
[k] Adapted from the MMS GOADS by ICF (2005)
[l] BOEM
[m] API (1996)
[n] EPA, AP 42 Compilation of Air Pollutant Emission Factors
[o] OGJ Petroleum Economics Issue
[p] EIA Petroleum Supply Annual, Volume 1
* Emissions are not actually 0, but too small to show at this level of precision.
† Asphalt Blowing emissions are the only significant vented emissions from the refining sector; other sources are too small to show at this level of precision.
NE: Not estimated for lack of data
Energy use $CO_2$ emissions not estimated to avoid double counting with fossil fuel combustion

Table A-142: Summary of $CO_2$ Emissions from Petroleum Systems (Gg)

| Activity | 1990 | 1995 | 2000 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|
| **Production Field Operations** | **376** | **341** | **323** | **284** | **293** | **284** | **306** | **317** | **332** |
| Pneumatic device venting | 27 | 26 | 24 | 22 | 22 | 23 | 23 | 23 | 24 |
| Tank venting | 328 | 296 | 281 | 245 | 253 | 243 | 265 | 276 | 291 |
| Misc. venting & fugitives | 18 | 18 | 17 | 16 | 16 | 16 | 16 | 16 | 16 |
| Wellhead fugitives | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Refining** | **18** | **19** | **21** | **20** | **18** | **16** | **14** | **15** | **15** |
| Asphalt Blowing | 18 | 19 | 21 | 20 | 18 | 16 | 14 | 15 | 15 |
| **Total** | **394** | **360** | **344** | **305** | **311** | **300** | **320** | **332** | **347** |

## 3.7. Methodology for Estimating $CO_2$, $N_2O$ and $CH_4$ Emissions from the Incineration of Waste

Emissions of $CO_2$ from the incineration of waste include $CO_2$ generated by the incineration of plastics, synthetic rubber and synthetic fibers in municipal solid waste (MSW), and incineration of tires (which are composed in part of synthetic rubber and C black) in a variety of other combustion facilities (e.g., cement kilns). Incineration of waste also results in emissions of $N_2O$ and $CH_4$. The methodology for calculating emissions from each of these waste incineration sources is described in this Annex.

### $CO_2$ from Plastics Incineration

In the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2011b, 2011a), the flows of plastics in the U.S. waste stream are reported for seven resin categories. For 2011, the quantity generated, recovered, and discarded for each resin is shown in Table A-143. The latest MSW Facts and Figures report contains data through 2010, so 2011 data is assumed to be equal to 2010. The data set for 1990 through 2011 is incomplete, and several assumptions were employed to bridge the data gaps. The EPA reports do not provide estimates for individual materials landfilled and incinerated, although they do provide such an estimate for the waste stream as a whole. To estimate the quantity of plastics landfilled and incinerated, total discards were apportioned based on the proportions of landfilling and incineration for the entire U.S. waste stream for each year in the time series according to *Biocycle's State of Garbage in America* (van Haaren et al. 2010). For those years when distribution by resin category was not reported (1990 through 1994), total values were apportioned according to 1995 (the closest year) distribution ratios. Generation and recovery figures for 2002 and 2004 were linearly interpolated between surrounding years' data.

Table A-143: 2011 Plastics in the Municipal Solid Waste Stream by Resin (Gg)

| Waste Pathway | PET | HDPE | PVC | LDPE/ LLDPE | PP | PS | Other | Total |
|---|---|---|---|---|---|---|---|---|
| Generation | 3,611 | 4,944 | 826 | 6,740 | 6,831 | 1,869 | 3,293 | **28,114** |
| Recovery | 508 | 517 | 0 | 381 | 54 | 18 | 662 | **2,141** |
| Discard | 3,103 | 4,427 | 826 | 6,359 | 6,777 | 1,851 | 2,631 | **25,973** |
| Landfill | 2,829 | 4,037 | 753 | 5,799 | 6,179 | 1,688 | 2,399 | **23,683** |
| Combustion | 274 | 390 | 73 | 561 | 597 | 163 | 232 | **2,290** |
| Recovery* | 14% | 10% | 0% | 6% | 1% | 1% | 20% | **8%** |
| Discard* | 86% | 90% | 100% | 94% | 99% | 99% | 80% | **92%** |
| Landfill* | 78% | 82% | 91% | 86% | 90% | 90% | 73% | **84%** |
| Combustion* | 8% | 8% | 9% | 8% | 9% | 9% | 7% | **8%** |

*As a percent of waste generation.
Note: Totals may not sum due to independent rounding. Abbreviations: PET (polyethylene terephthalate), HDPE (high density polyethylene), PVC (polyvinyl chloride), LDPE/LLDPE (linear low density polyethylene), PP (polypropylene), PS (polystyrene).

Fossil fuel-based $CO_2$ emissions were calculated as the product of plastic combusted, C content, and fraction oxidized (see Table A-144). The C content of each of the six types of plastics is listed, with the value for "other plastics" assumed equal to the weighted average of the six categories. The fraction oxidized was assumed to be 98 percent.

Table A-144: 2011 Plastics Incinerated (Gg), Carbon Content (%), Fraction Oxidized (%) and Carbon Incinerated (Gg)

| Factor | PET | HDPE | PVC | LDPE/ LLDPE | PP | PS | Other | Total |
|---|---|---|---|---|---|---|---|---|
| Quantity Combusted | 274 | 390 | 73 | 561 | 597 | 163 | 232 | 2,290 |
| Carbon Content of Resin | 63% | 86% | 38% | 86% | 86% | 92% | 66% | - |
| Fraction Oxidized | 98% | 98% | 98% | 98% | 98% | 98% | 98% | - |
| Carbon in Resin Combusted | 168 | 328 | 27 | 471 | 502 | 148 | 150 | 1,793 |
| **Emissions (Tg $CO_2$ Eq.)** | **0.6** | **1.2** | **0.1** | **1.7** | **1.8** | **0.5** | **0.5** | **6.6** |

[a] Weighted average of other plastics produced.
Note: Totals may not sum due to independent rounding.

### $CO_2$ from Incineration of Synthetic Rubber and Carbon Black in Tires

Emissions from tire incineration require two pieces of information: the amount of tires incinerated and the C content of the tires. "U.S. Scrap Tire Management Summary 2005-2009" (RMA 2011) reports that 2084.8 thousand of the 4,391.1 thousand tons of scrap tires generated in 2009 (approximately 47 percent of generation) were used for fuel

purposes. Using RMA's estimates of average tire composition and weight, the mass of synthetic rubber and C black in scrap tires was determined:

- Synthetic rubber in tires was estimated to be 90 percent C by weight, based on the weighted average C contents of the major elastomers used in new tire consumption.[54] Table A- 145 shows consumption and C content of elastomers used for tires and other products in 2002, the most recent year for which data are available.
- C black is 100 percent C (Aslett Rubber Inc. n.d.).

Multiplying the mass of scrap tires incinerated by the total C content of the synthetic rubber, C black portions of scrap tires, and then by a 98 percent oxidation factor, yielded $CO_2$ emissions, as shown in Table A- 146. The disposal rate of rubber in tires (0.4 Tg C/yr) is smaller than the consumption rate for tires based on summing the elastomers listed in Table A-143 (1.3 Tg/yr); this is due to the fact that much of the rubber is lost through tire wear during the product's lifetime and may also reflect the lag time between consumption and disposal of tires. Tire production and fuel use for 1990 through 2009 were taken from RMA 2006, RMA 2009, RMA 2011; where data were not reported, they were linearly interpolated between bracketing years' data or, for the ends of time series, set equal to the closest year with reported data.

In 2009, RMA changed the reporting of scrap tire data from millions of tires to thousands of short tons of scrap tire. As a result, the average weight and percent of the market of light duty and commercial scrap tires was used to convert the previous years from millions of tires to thousands of short tons (STMC 1990 through 1997; RMA 2002 through 2006, 2012a).

Table A- 145: Elastomers Consumed in 2002 (Gg)

| Elastomer | Consumed | Carbon Content | Carbon Equivalent |
|---|---|---|---|
| **Styrene butadiene rubber solid** | **768** | **91%** | **700** |
| For Tires | 660 | 91% | 602 |
| For Other Products* | 108 | 91% | 98 |
| **Polybutadiene** | **583** | **89%** | **518** |
| For Tires | 408 | 89% | 363 |
| For Other Products | 175 | 89% | 155 |
| **Ethylene Propylene** | **301** | **86%** | **258** |
| For Tires | 6 | 86% | 5 |
| For Other Products | 295 | 86% | 253 |
| **Polychloroprene** | **54** | **59%** | **32** |
| For Tires | 0 | 59% | 0 |
| For Other Products | 54 | 59% | 32 |
| **Nitrile butadiene rubber solid** | **84** | **77%** | **65** |
| For Tires | 1 | 77% | 1 |
| For Other Products | 83 | 77% | 64 |
| **Polyisoprene** | **58** | **88%** | **51** |
| For Tires | 48 | 88% | 42 |
| For Other Products | 10 | 88% | 9 |
| **Others** | **367** | **88%** | **323** |
| For Tires | 184 | 88% | 161 |
| For Other Products | 184 | 88% | 161 |
| **Total** | **2,215** | **-** | **1,950** |
| **For Tires** | **1,307** | **-** | **1,174** |

*Used to calculate C content of non-tire rubber products in municipal solid waste.
- Not applicable
Note: Totals may not sum due to independent rounding.

Table A- 146: Scrap Tire Constituents and $CO_2$ Emissions from Scrap Tire Incineration in 2011

| Material | Weight of Material (Tg) | Fraction Oxidized | Carbon Content | Emissions (Tg $CO_2$ Eq.) |
|---|---|---|---|---|
| Synthetic Rubber | 0.4 | 98% | 90% | 1.6 |
| Carbon Black | 0.5 | 98% | 100% | 1.9 |
| **Total** | **1.0** | **-** | **-** | **3.5** |

- Not applicable

[54] The carbon content of tires (1,174 Gg C) divided by the mass of rubber in tires (1,307 Gg) equals 90 percent.

## $CO_2$ from Incineration of Synthetic Rubber in Municipal Solid Waste

Similar to the methodology for scrap tires, $CO_2$ emissions from synthetic rubber in MSW were estimated by multiplying the amount of rubber incinerated by an average rubber C content. The amount of rubber discarded in the MSW stream was estimated from generation and recycling data[55] provided in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2011b, 2011a) and unpublished backup data (Schneider 2007). The latest MSW Facts and Figures report includes data from 2010, so the discards data for 2011 was assumed to be equal to the discards in 2010. The reports divide rubber found in MSW into three product categories: other durables (not including tires), non-durables (which includes clothing and footwear and other non-durables), and containers and packaging. EPA (2011a) did not report rubber found in the product category "containers and packaging;" however, containers and packaging from miscellaneous material types were reported for 2009, 2010, and 2011. As a result, EPA assumes that rubber containers and packaging are reported under the "miscellaneous" category; and therefore, the quantity reported for 2009, 2010, and 2011 were set equal to the quantity reported for 2008. Since there was negligible recovery for these product types, all the waste generated is considered to be discarded. Similar to the plastics method, discards were apportioned into landfilling and incineration based on their relative proportions, for each year, for the entire U.S. waste stream. The report aggregates rubber and leather in the MSW stream; an assumed synthetic rubber content of 70 percent was assigned to each product type, as shown in Table A-147.[56] A C content of 85 percent was assigned to synthetic rubber for all product types (based on the weighted average C content of rubber consumed for non-tire uses), and a 98 percent fraction oxidized was assumed.

Table A-147: Rubber and Leather in Municipal Solid Waste in 2011

| Product Type | Incinerated (Gg) | Synthetic Rubber (%) | Carbon Content (%) | Fraction Oxidized (%) | Emissions (Tg $CO_2$ Eq.) |
|---|---|---|---|---|---|
| **Durables (not Tires)** | 275 | 70% | 85% | 98% | 0.9 |
| **Non-Durables** | 83 | - | - | - | 0.3 |
| Clothing and Footwear | 63 | 70% | 85% | 98% | 0.2 |
| Other Non-Durables | 20 | 70% | 85% | 98% | 0.1 |
| **Containers and Packaging** | 2 | 70% | 85% | 98% | + |
| **Total** | **361** | **-** | **-** | **-** | **1.1** |

+ Less than 0.05 Tg $CO_2$ Eq.
- Not applicable.

## $CO_2$ from Incineration of Synthetic Fibers

$CO_2$ emissions from synthetic fibers were estimated as the product of the amount of synthetic fiber discarded annually and the average C content of synthetic fiber. Fiber in the MSW stream was estimated from data provided in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2011b, 2011a) for textiles. The latest MSW Facts and Figures report includes data from 2010, so the discards data for 2011 was assumed to be equal to the discards in 2010. Production data for the synthetic fibers was based on data from the American Chemical Society (FEB 2009). The amount of synthetic fiber in MSW was estimated by subtracting (a) the amount recovered from (b) the waste generated (see Table A-148). As with the other materials in the MSW stream, discards were apportioned based on the annually variable proportions of landfilling and incineration for the entire U.S. waste stream, as found in van Haaren et al. (2010). It was assumed that approximately 55 percent of the fiber was synthetic in origin, based on information received from the Fiber Economics Bureau (DeZan 2000). An average C content of 70 percent was assigned to synthetic fiber using the production-weighted average of the C contents of the four major fiber types (polyester, nylon, olefin, and acrylic) produced in 1999 (see Table A-149). The equation relating $CO_2$ emissions to the amount of textiles combusted is shown below.

$$CO_2 \text{ Emissions from the Incineration of Synthetic Fibers} = \text{Annual Textile Incineration (Gg)} \times (\text{Percent of Total Fiber that is Synthetic}) \times (\text{Average C Content of Synthetic Fiber}) \times (44\text{g } CO_2/12 \text{ g C})$$

[55] Discards = Generation minus recycling.

[56] As a sustainably harvested biogenic material, the incineration of leather is assumed to have no net $CO_2$ emissions.

Table A-148: Synthetic Textiles in MSW (Gg)

| Year | Generation | Recovery | Discards | Incineration |
|---|---|---|---|---|
| 1990 | 2,884 | 328 | 2,557 | 332 |
| | | | | |
| 1995 | 3,674 | 447 | 3,227 | 442 |
| 1996 | 3,832 | 472 | 3,361 | 467 |
| 1997 | 4,090 | 526 | 3,564 | 458 |
| 1998 | 4,269 | 556 | 3,713 | 407 |
| 1999 | 4,498 | 611 | 3,887 | 406 |
| 2000 | 4,706 | 655 | 4,051 | 417 |
| 2001 | 4,870 | 715 | 4,155 | 432 |
| 2002 | 5,123 | 750 | 4,373 | 459 |
| 2003 | 5,297 | 774 | 4,522 | 472 |
| 2004 | 5,451 | 884 | 4,567 | 473 |
| 2005 | 5,714 | 913 | 4,800 | 480 |
| 2006 | 5,893 | 933 | 4,959 | 479 |
| 2007 | 6,041 | 953 | 5,088 | 470 |
| 2008 | 6,309 | 948 | 5,361 | 473 |
| 2009 | 6,463 | 948 | 5,515 | 486 |
| 2010 | 6,513 | 978 | 5,535 | 488 |
| 2011 | 6,513 | 978 | 5,535 | 488 |

Table A-149: Synthetic Fiber Production in 1999

| Fiber | Production (Tg) | Carbon Content |
|---|---|---|
| Polyester | 1.8 | 63% |
| Nylon | 1.2 | 64% |
| Olefin | 1.4 | 86% |
| Acrylic | 0.1 | 68% |
| **Total** | **4.5** | **70%** |

## $N_2O$ and $CH_4$ from Incineration of Waste

Estimates of $N_2O$ emissions from the incineration of waste in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emission Factors (EPA 1995) and presented in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2011b, 2011a) and unpublished backup data (Schneider 2007). The latest MSW Facts and Figures report includes data from 2010, so the discards data for 2011 was assumed to be equal to the discards in 2010. According to this methodology, emissions of $N_2O$ from waste incineration are the product of the mass of waste incinerated, an emission factor of $N_2O$ emitted per unit mass of waste incinerated, and an $N_2O$ emissions control removal efficiency. The mass of waste incinerated was derived from the information published in *BioCycle* (van Haaren et al. 2010). For waste incineration in the United States, an emission factor of 50 g $N_2O$/metric ton MSW based on the 2006 IPCC Guidelines and an estimated emissions control removal efficiency of zero percent were used (IPCC 2006). It was assumed that all MSW incinerators in the United States use continuously-fed stoker technology (Bahor 2009, ERC 2009).

Estimates of $CH_4$ emissions from the incineration of waste in the United States are based on the methodology outlined in IPCC's *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). According to this methodology, emissions of $CH_4$ from waste incineration are the product of the mass of waste incinerated and an emission factor of $CH_4$ emitted per unit mass of waste incinerated. Similar to the $N_2O$ emissions methodology, the mass of waste incinerated was derived from the information published in *Biocycle* (van Haaren et al. 2010). For waste incineration in the United States, an emission factor of 0.20 kg $CH_4$/Gg MSW was used based on the 2006 IPCC Guidelines and assuming that all MSW incinerators in the United States use continuously-fed stoker technology (Bahor 2009, ERC 2009). No information was available on the mass of waste incinerated from *Biocycle* in 2009, 2010, or 2011, so these values were assumed to remain constant at the 2008 level.

Despite the differences in methodology and data sources, the two series of references (EPA's and BioCycle's) provide estimates of total solid waste incinerated that are relatively consistent (see Table A-149).

Table A-150: U.S. Municipal Solid Waste Incinerated, as Reported by EPA and BioCycle (Metric Tons)

| Year | EPA | BioCycle |
|---|---|---|
| 1990 | 28,939,680 | 30,632,057 |
| | | |
| 1995 | 32,241,888 | 29,639,040 |
| 1996 | 32,740,848 | 29,707,171 |
| 1997 | 33,294,240 | 27,798,368 |
| 1998 | 31,216,752 | 25,489,893 |
| 1999 | 30,881,088 | 24,296,249 |
| 2000 | 30,599,856 | 25,974,978 |
| 2001 | 30,481,920 | 25,942,036[a] |
| 2002 | 30,255,120 | 25,802,917 |
| 2003 | 30,028,320 | 25,930,542[b] |
| 2004 | 28,585,872 | 26,037,823 |
| 2005 | 28,685,664 | 25,973,520[c] |
| 2006 | 28,985,040 | 25,853,401 |
| 2007 | 29,003,184 | 24,788,539[d] |
| 2008 | 28,622,160 | 23,674,017 |
| 2009 | 26,317,872 | NA |
| 2010 | 26,544,672 | NA |
| 2011 | 26,544,672 | NA |

NA (Not Available)
[a] Interpolated between 2000 and 2002 values.
[b] Interpolated between 2002 and 2004 values.
[c] Interpolated between 2004 and 2006 values.
[d] Interpolated between 2006 and 2008 values

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16

## 3.8. Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military

Bunker fuel emissions estimates for the Department of Defense (DoD) are developed using data generated by the Defense Energy Support Center (DESC) for aviation and naval fuels. The DESC of the Defense Logistics Agency (DLA) prepared a special report based on data in the Fuels Automated System (FAS), a database that recently replaced the Defense Fuels Automated Management System (DFAMS). Data for intermediate fuel oil, however, currently remains in the original DFAMS database. DFAMS/FAS contains data for 1995 through 2011, but the data set was not complete for years prior to 1995. Fuel quantities for 1990 to 1994 were estimated based on a back-calculation of the 1995 DFAMS values using DLA aviation and marine fuel procurement data. The back-calculation was refined in 1999 to better account for the jet fuel conversion from JP4 to JP8 that occurred within DoD between 1992 and 1995.

#### Step 1: Omit Extra-Territorial Fuel Deliveries

Beginning with the complete FAS data set for each year, the first step in the development of DoD-related emissions from international bunker fuels was to identify data that would be representative of international bunker fuel consumption as that term is defined by decisions of the UNFCCC (i.e., fuel sold to a vessel, aircraft, or installation within the United States or its territories and used in international maritime or aviation transport). Therefore, fuel data were categorized by the location of fuel delivery in order to identify and omit all international fuel transactions/deliveries (i.e., sales abroad).

#### Step 2: Allocate JP-8 between Aviation and Land-based Vehicles

As a result of DoD[57] and NATO[58] policies on implementing the Single Fuel For the Battlefield concept, DoD activities have been increasingly replacing diesel fuel with JP8 (a type of jet fuel) in compression ignition and turbine engines in land-based equipment. Based on this concept and examination of all data describing jet fuel used in land-based vehicles, it was determined that a portion of JP8 consumption should be attributed to ground vehicle use. Based on available Service data and expert judgment, it was determined that a small fraction of the total JP8 use should be reallocated from the aviation subtotal to a new land-based jet fuel category for 1997 and subsequent years. The amount of JP8 reallocated was determined to be between 1.78 and 2.7 times the amount of diesel fuel used, depending on the Service. As a result of this reallocation, the JP8 use reported for aviation will be reduced and the total fuel use for land-based equipment will increase. DoD's total fuel use will not change.

Table A-151 displays DoD's consumption of fuels that remain at the completion of Step 1, summarized by fuel type. Table A-151 reflects the adjustments for jet fuel used in land-based equipment, as described above.

#### Step 3: Omit Land-Based Fuels

Navy and Air Force land-based fuels (i.e., fuel not used by ships or aircraft) were also omitted for the purpose of calculating international bunker fuels. The remaining fuels, listed below, were considered potential DoD international bunker fuels.

- Marine: naval distillate fuel (F76), marine gas oil (MGO), and intermediate fuel oil (IFO).
- Aviation: jet fuels (JP8, JP5, JP4, JAA, JA1, and JAB).

#### Step 4: Omit Fuel Transactions Received by Military Services that are not Considered to be International Bunker Fuels

Next, the records were sorted by Military Service. The following assumptions were used regarding bunker fuel use by Service, leaving only the Navy and Air Force as users of military international bunker fuels.

- Only fuel delivered to a ship, aircraft, or installation in the United States was considered a potential international bunker fuel. Fuel consumed in international aviation or marine transport was included in the

[57] DoD Directive 4140.43, Fuel Standardization, 1998; DoD Directive 4140.25, DoD Management Policy for Energy Commodities and Related Services, 1999.

[58] NATO Standard Agreement NATO STANAG 4362, Fuels for Future Ground Equipments Using Compression Ignition or Turbine Engines, 1987.

bunker fuel estimate of the country where the ship or aircraft was fueled. Fuel consumed entirely within a country's borders was not considered a bunker fuel.

- Based on discussions with the Army staff, only an extremely small percentage of Army aviation emissions, and none of its watercraft emissions, qualified as bunker fuel emissions. The magnitude of these emissions was judged to be insignificant when compared to Air Force and Navy emissions. Based on this, Army bunker fuel emissions were assumed to be zero.
- Marine Corps aircraft operating while embarked consumed fuel reported as delivered to the Navy. Bunker fuel emissions from embarked Marine Corps aircraft were reported in the Navy bunker fuel estimates. Bunker fuel emissions from other Marine Corps operations and training were assumed to be zero.
- Bunker fuel emissions from other DoD and non-DoD activities (i.e., other federal agencies) that purchased fuel from DLA Energy were assumed to be zero.

#### Step 5: Determine Bunker Fuel Percentages

Next it was necessary to determine what percent of the marine and aviation fuels were used as international bunker fuels. Military aviation bunkers include international operations (i.e., sorties that originate in the United States and end in a foreign country), operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea (e.g., anti-submarine warfare flights). For the Air Force, a bunker fuel weighted average was calculated based on flying hours by major command. International flights were weighted by an adjustment factor to reflect the fact that they typically last longer than domestic flights. In addition, a fuel use correction factor was used to account for the fact that transport aircraft burn more fuel per hour of flight than most tactical aircraft. The Air Force bunker fuel percentage was determined to be 13.2 percent. This percentage was multiplied by total annual Air Force aviation fuel delivered for U.S. activities, producing an estimate for international bunker fuel consumed by the Air Force. The Naval Aviation bunker fuel percentage of total fuel was calculated using flying hour data from Chief of Naval Operations Flying Hour Projection System Budget for fiscal year 1998, and estimates of bunker fuel percent of flights provided by the fleet. The Naval Aviation bunker fuel percentage, determined to be 40.4 percent, was multiplied by total annual Navy aviation fuel delivered for U.S. activities, yielding total Navy aviation bunker fuel consumed.

For marine bunkers, fuels consumed while ships were underway were assumed to be bunker fuels. In 2000, the Navy reported that 79 percent of vessel operations were underway, while the remaining 21 percent of operations occurred in port (i.e., pierside). Therefore, the Navy maritime bunker fuel percentage was determined to be 79 percent. The percentage of time underway may vary from year-to-year. For example, for years prior to 2000, the bunker fuel percentage was 87 percent. Table A-152 and Table A-153 display DoD bunker fuel use totals for the Navy and Air Force.

#### Step 6: Calculate Emissions from International Bunker Fuels

Bunker fuel totals were multiplied by appropriate emission factors to determine GHG emissions. $CO_2$ emissions from Aviation Bunkers and distillate Marine Bunkers are the total of military aviation and marine bunker fuels, respectively.

The rows labeled "U.S. Military" and "U.S. Military Naval Fuels" in the tables in the International Bunker Fuels section of the Energy Chapter were based on the totals provided in Table A-152 and Table A-153, below. $CO_2$ emissions from aviation bunkers and distillate marine bunkers presented in Table A-156, and are based on emissions from fuels tallied in Table A-152 and Table A-153.

Table A-151: Transportation Fuels from Domestic Fuel Deliveries[a] (Million Gallons)

| Vehicle Type/Fuel | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Aviation** | **4,598.4** | **3,099.9** | **2,941.9** | **2,685.6** | **2,741.4** | **2,635.2** | **2,664.4** | **2,900.6** | **2,609.8** | **2,615.0** | **2,703.1** | **2,338.1** | **2,092.0** | **2,081.0** | **2,067.8** | **1,814.5** | **1,663.9** | **1,504.8** |
| **Total Jet Fuels** | **4,598.4** | **3,099.9** | **2,941.9** | **2,685.6** | **2,741.4** | **2,635.2** | **2,664.4** | **2,900.6** | **2,609.6** | **2,614.9** | **2,703.1** | **2,338.0** | **2,091.9** | **2,080.9** | **2,067.7** | **1,814.3** | **1,663.7** | **1,504.6** |
| *JP8* | 285.7 | 2,182.8 | 2,253.1 | 2,072.0 | 2,122.5 | 2,066.5 | 2,122.7 | 2,326.2 | 2,091.4 | 2,094.3 | 2,126.2 | 1,838.8 | 1,709.3 | 1,618.5 | 1,616.2 | 1,358.2 | 1,100.1 | 1,006.9 |
| *JP5* | 1,025.4 | 691.2 | 615.8 | 552.8 | 515.6 | 505.5 | 472.1 | 503.2 | 442.2 | 409.1 | 433.7 | 421.6 | 325.5 | 376.1 | 362.2 | 361.2 | 399.3 | 339.1 |
| *Other Jet Fuels* | 3,287.3 | 225.9 | 72.9 | 60.9 | 103.3 | 63.3 | 69.6 | 71.2 | 76.1 | 111.4 | 143.2 | 77.6 | 57.0 | 86.3 | 89.2 | 94.8 | 164.3 | 158.5 |
| Aviation Gasoline | + | + | + | + | + | + | + | + | 0.1 | 0.1 | + | 0.1 | 0.1 | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 |
| **Marine** | **686.8** | **438.9** | **493.3** | **639.8** | **674.2** | **598.9** | **454.4** | **418.4** | **455.8** | **609.1** | **704.5** | **604.9** | **531.6** | **572.8** | **563.4** | **485.8** | **578.8** | **443.2** |
| Middle Distillate (MGO) | + | + | 38.5 | 47.5 | 51.1 | 49.2 | 48.3 | 33.0 | 41.2 | 88.1 | 71.2 | 54.0 | 45.8 | 45.7 | 55.2 | 56.8 | 48.4 | 47.8 |
| Naval Distillate (F76) | 686.8 | 438.9 | 449.0 | 583.4 | 608.4 | 542.9 | 398.0 | 369.1 | 395.1 | 460.9 | 583.5 | 525.9 | 453.6 | 516.0 | 483.4 | 399.0 | 513.7 | 385.2 |
| Intermediate Fuel Oil (IFO)[b] | + | + | 5.9 | 9.0 | 14.7 | 6.7 | 8.1 | 16.3 | 19.5 | 60.2 | 49.9 | 25.0 | 32.2 | 11.1 | 24.9 | 30.0 | 16.7 | 10.2 |
| **Other[c]** | **717.1** | **310.9** | **276.9** | **263.3** | **256.8** | **256.0** | **248.2** | **109.8** | **211.1** | **221.2** | **170.9** | **205.6** | **107.3** | **169.0** | **173.6** | **206.8** | **224.0** | **235.1** |
| Diesel | 93.0 | 119.9 | 126.1 | 132.6 | 139.5 | 146.8 | 126.6 | 26.6 | 57.7 | 60.8 | 46.4 | 56.8 | 30.6 | 47.3 | 49.1 | 58.3 | 64.1 | 68.3 |
| Gasoline | 624.1 | 191.1 | 150.8 | 119.0 | 93.9 | 74.1 | 74.8 | 24.7 | 27.5 | 26.5 | 19.4 | 24.3 | 11.7 | 19.2 | 19.7 | 25.2 | 25.5 | 24.5 |
| Jet Fuel[d] | + | + | + | 11.7 | 23.4 | 35.0 | 46.7 | 58.4 | 125.9 | 133.9 | 105.1 | 124.4 | 65.0 | 102.6 | 104.8 | 123.3 | 134.4 | 142.3 |
| **Total (Including Bunkers)** | **6,002.4** | **3,849.8** | **3,712.1** | **3,588.8** | **3,672.4** | **3,490.1** | **3,367.0** | **3,428.8** | **3,276.7** | **3,445.3** | **3,578.5** | **3,148.6** | **2,730.9** | **2,822.8** | **2,804.9** | **2,507.1** | **2,466.7** | **2,183.2** |

Note: Totals may not sum due to independent rounding.

[a] Includes fuel consumption in the United States and U.S. Territories.

[b] Intermediate fuel oil (IFO 180 and IFO 380) is a blend of distillate and residual fuels. IFO is used by the Military Sealift Command.

[c] Prior to 2001, gasoline and diesel fuel totals were estimated using data provided by the military Services for 1990 and 1996. The 1991 through 1995 data points were interpolated from the Service inventory data. The 1997 through 1999 gasoline and diesel fuel data were initially extrapolated from the 1996 inventory data. Growth factors used for other diesel and gasoline were 5.2 and -21.1 percent, respectively. However, prior diesel fuel estimates from 1997 through 2000 were reduced according to the estimated consumption of jet fuel that is assumed to have replaced the diesel fuel consumption in land-based vehicles. Data sets for other diesel and gasoline consumed by the military in 2000 were estimated based on ground fuels consumption trends. This method produced a result that was more consistent with expected consumption for 2000. In 2001, other gasoline and diesel fuel totals were generated by DESC.

[d] The fraction of jet fuel consumed in land-based vehicles was estimated using Service data, DESC data, and expert judgment.

+ Does not exceed 0.05 million gallons.

Table A-152: Total U.S. Military Aviation Bunker Fuel (Million Gallons)

| Fuel Type/Service | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **JP8** | **56.7** | **300.4** | **308.8** | **292.0** | **306.4** | **301.4** | **307.6** | **341.2** | **309.5** | **305.1** | **309.8** | **285.6** | **262.5** | **249.1** | **229.4** | **211.4** | **182.5** | **165.4** |
| Navy | 56.7 | 38.3 | 39.8 | 46.9 | 53.8 | 55.5 | 53.4 | 73.8 | 86.6 | 76.3 | 79.2 | 70.9 | 64.7 | 62.7 | 59.2 | 55.4 | 60.8 | 54.8 |
| Air Force | + | 262.2 | 269.0 | 245.1 | 252.6 | 245.9 | 254.2 | 267.4 | 222.9 | 228.7 | 230.6 | 214.7 | 197.8 | 186.5 | 170.3 | 156.0 | 121.7 | 110.5 |
| **JP5** | **370.5** | **249.8** | **219.4** | **194.2** | **184.4** | **175.4** | **160.3** | **169.7** | **158.3** | **146.1** | **157.9** | **160.6** | **125.0** | **144.5** | **139.2** | **137.0** | **152.5** | **128.4** |
| Navy | 365.3 | 246.3 | 216.1 | 191.2 | 181.4 | 170.6 | 155.6 | 163.7 | 153.0 | 141.3 | 153.8 | 156.9 | 122.8 | 141.8 | 136.5 | 133.5 | 149.7 | 125.0 |
| Air Force | 5.3 | 3.5 | 3.3 | 3.0 | 3.0 | 4.8 | 4.7 | 6.1 | 5.3 | 4.9 | 4.1 | 3.7 | 2.3 | 2.7 | 2.6 | 3.5 | 2.8 | 3.4 |
| **JP4** | **420.8** | **21.5** | **1.1** | **0.1** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **0.1** | **+** |
| Navy | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Air Force | 420.8 | 21.5 | 1.1 | 0.1 | + | + | + | + | + | + | + | + | + | + | + | + | 0.1 | + |
| **JAA** | **13.7** | **9.2** | **10.3** | **9.4** | **10.8** | **10.8** | **12.5** | **12.6** | **13.7** | **21.7** | **30.0** | **15.5** | **11.7** | **15.6** | **16.8** | **18.1** | **31.4** | **32.1** |
| Navy | 8.5 | 5.7 | 6.6 | 5.9 | 6.6 | 6.3 | 7.9 | 8.0 | 9.8 | 15.5 | 21.5 | 11.6 | 9.1 | 11.7 | 12.5 | 12.3 | 13.7 | 15.0 |
| Air Force | 5.3 | 3.5 | 3.7 | 3.5 | 4.2 | 4.5 | 4.5 | 4.6 | 3.8 | 6.2 | 8.6 | 3.9 | 2.6 | 3.9 | 4.3 | 5.9 | 17.7 | 17.0 |
| **JA1** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **0.1** | **0.6** | **0.2** | **0.5** | **0.5** | **0.4** | **1.1** | **1.0** | **0.6** | **0.3** | **0.1** |
| Navy | + | + | + | + | + | + | + | + | + | + | + | + | + | 0.1 | 0.1 | 0.1 | 0.1 | + |
| Air Force | + | + | + | + | + | + | + | 0.1 | 0.6 | 0.2 | 0.5 | 0.5 | 0.4 | 1.0 | 0.8 | 0.5 | 0.1 | + |
| **JAB** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** | **+** |
| Navy | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Air Force | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| **Navy Subtotal** | **430.5** | **290.2** | **262.5** | **244.0** | **241.8** | **232.4** | **216.9** | **245.5** | **249.4** | **233.1** | **254.4** | **239.4** | **196.6** | **216.3** | **208.3** | **201.3** | **224.4** | **194.9** |
| **Air Force Subtotal** | **431.3** | **290.7** | **277.0** | **251.7** | **259.9** | **255.2** | **263.5** | **278.1** | **232.7** | **239.9** | **243.7** | **222.9** | **203.1** | **194.0** | **178.1** | **165.9** | **142.4** | **131.0** |
| **Total** | **861.8** | **580.9** | **539.5** | **495.6** | **501.7** | **487.5** | **480.4** | **523.6** | **482.1** | **473.0** | **498.1** | **462.3** | **399.7** | **410.3** | **386.3** | **367.2** | **366.7** | **325.9** |

+ Does not exceed 0.05 million gallons.
Note: Totals may not sum due to independent rounding.

Table A-153: Total U.S. DoD Maritime Bunker Fuel (Million Gallons)

| Marine Distillates | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Navy—MGO | + | + | 30.3 | 35.6 | 31.9 | 39.7 | 23.8 | 22.5 | 27.1 | 63.7 | 56.2 | 38.0 | 33.0 | 31.6 | 40.9 | 39.9 | 32.9 | 33.0 |
| Navy—F76 | 522.4 | 333.8 | 331.9 | 441.7 | 474.2 | 466.0 | 298.6 | 282.6 | 305.6 | 347.8 | 434.4 | 413.1 | 355.9 | 404.1 | 376.9 | 311.4 | 402.2 | 300.8 |
| Navy—IFO | + | + | 4.6 | 7.1 | 11.6 | 5.3 | 6.4 | 12.9 | 15.4 | 47.5 | 39.4 | 19.7 | 25.4 | 8.8 | 19.0 | 23.1 | 12.9 | 7.7 |
| **Total** | **522.4** | **333.8** | **366.8** | **484.3** | **517.7** | **511.0** | **328.8** | **318.0** | **348.2** | **459.0** | **530.0** | **470.7** | **414.3** | **444.4** | **436.7** | **374.4** | **448.0** | **341.5** |

+ Does not exceed 0.005 million gallons.
Note: Totals may not sum due to independent rounding.

Table A-154: Aviation and Marine Carbon Contents (Tg Carbon/QBtu) and Fraction Oxidized

| Mode (Fuel) | Carbon Content Coefficient | Fraction Oxidized |
|---|---|---|
| Aviation (Jet Fuel) | Variable | 1.00 |
| Marine (Distillate) | 20.17 | 1.00 |
| Marine (Residual) | 20.48 | 1.00 |

Source: EPA (2010) and IPCC (2006)

Table A-155: Annual Variable Carbon Content Coefficient for Jet Fuel (Tg Carbon/QBtu)

| Fuel | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jet Fuel | 19.40 | 19.34 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 | 19.70 |

Source: EPA (2010)

Table A-156: Total U.S. DoD $CO_2$ Emissions from Bunker Fuels (Tg $CO_2$ Eq.)

| Mode | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aviation | 8.1 | 5.5 | 5.2 | 4.8 | 4.9 | 4.7 | 4.7 | 5.1 | 4.7 | 4.6 | 4.8 | 4.5 | 3.9 | 4.0 | 3.8 | 3.6 | 3.6 | 3.2 |
| Marine | 5.4 | 3.4 | 3.8 | 5.0 | 5.3 | 5.2 | 3.4 | 3.3 | 3.6 | 4.7 | 5.4 | 4.8 | 4.2 | 4.6 | 4.5 | 3.8 | 4.6 | 3.5 |
| **Total** | **13.4** | **9.0** | **9.0** | **9.8** | **10.2** | **10.0** | **8.0** | **8.3** | **8.3** | **9.3** | **10.3** | **9.3** | **8.1** | **8.5** | **8.2** | **7.4** | **8.2** | **6.7** |

Note: Totals may not sum due to independent rounding.

## 3.9. Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances

Emissions of HFCs and PFCs from the substitution of ozone depleting substances (ODS) are developed using a country-specific modeling approach. The Vintaging Model was developed as a tool for estimating the annual chemical emissions from industrial sectors that have historically used ODS in their products. Under the terms of the Montreal Protocol and the United States' Clean Air Act Amendments of 1990, the domestic U.S. consumption of ODS—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—has been drastically reduced, forcing these industrial sectors to transition to more ozone friendly chemicals. As these industries have moved toward ODS alternatives such as hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), the Vintaging Model has evolved into a tool for estimating the rise in consumption and emissions of these alternatives, and the decline of ODS consumption and emissions.

The Vintaging Model estimates emissions from five ODS substitute end-use sectors: air-conditioning and refrigeration, foams, aerosols, solvents, and fire-extinguishing. Within these sectors, there are 60 independently modeled end-uses. The model requires information on the market growth for each of the end-uses, a history of the market transition from ODS to alternatives, and the characteristics of each end-use such as market size or charge sizes and loss rates. As ODS are phased out, a percentage of the market share originally filled by the ODS is allocated to each of its substitutes.

The model, named for its method of tracking the emissions of annual "vintages" of new equipment that enter into service, is a "bottom-up" model. It models the consumption of chemicals based on estimates of the quantity of equipment or products sold, serviced, and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment. The Vintaging Model makes use of this market information to build an inventory of the in-use stocks of the equipment and ODS and ODS substitute in each of the end-uses. The simulation is considered to be a "business-as-usual" baseline case, and does not incorporate measures to reduce or eliminate the emissions of these gases other than those regulated by U.S. law or otherwise common in the industry. Emissions are estimated by applying annual leak rates, service emission rates, and disposal emission rates to each population of equipment. By aggregating the emission and consumption output from the different end-uses, the model produces estimates of total annual use and emissions of each chemical.

The Vintaging Model synthesizes data from a variety of sources, including data from the ODS Tracking System maintained by the Stratospheric Protection Division and information from submissions to EPA under the Significant New Alternatives Policy (SNAP) program. Published sources include documents prepared by the United Nations Environment Programme (UNEP) Technical Options Committees, reports from the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), and conference proceedings from the International Conferences on Ozone Protection Technologies and Earth Technologies Forums. EPA also coordinates extensively with numerous trade associations and individual companies. For example, the Alliance for Responsible Atmospheric Policy; the Air-Conditioning, Heating and Refrigeration Institute; the Association of Home Appliance Manufacturers; the American Automobile Manufacturers Association; and many of their member companies have provided valuable information over the years. In some instances the unpublished information that the EPA uses in the model is classified as Confidential Business Information (CBI). The annual emissions inventories of chemicals are aggregated in such a way that CBI cannot be inferred. Full public disclosure of the inputs to the Vintaging Model would jeopardize the security of the CBI that has been entrusted to the EPA.

The following sections discuss the emission equations used in the Vintaging Model for each broad end-use category. These equations are applied separately for each chemical used within each of the different end-uses. In the majority of these end-uses, more than one ODS substitute chemical is used.

In general, the modeled emissions are a function of the amount of chemical consumed in each end-use market. Estimates of the consumption of ODS alternatives can be inferred by determining the transition path of each regulated ODS used in the early 1990s. Using data gleaned from a variety of sources, assessments are made regarding which alternatives have been used, and what fraction of the ODS market in each end-use has been captured by a given alternative. By combining this with estimates of the total end-use market growth, a consumption value can be estimated for each chemical used within each end-use.

### Methodology

The Vintaging Model estimates the use and emissions of ODS alternatives by taking the following steps:

1. *Gather historical data*. The Vintaging Model is populated with information on each end-use, taken from published sources and industry experts.

2. *Simulate the implementation of new, non-ODS technologies*. The Vintaging Model uses detailed characterizations of the existing uses of the ODS, as well as data on how the substitutes are replacing the ODS, to simulate the implementation of new technologies that enter the market in compliance with ODS phase-out policies. As part of this simulation, the ODS substitutes are introduced in each of the end-uses over time as seen historically and as needed to comply with the ODS phase-out.

3. *Estimate emissions of the ODS substitutes*. The chemical use is estimated from the amount of substitutes that are required each year for the manufacture, installation, use, or servicing of products. The emissions are estimated from the emission profile for each vintage of equipment or product in each end-use. By aggregating the emissions from each vintage, a time profile of emissions from each end-use is developed.

Each set of end-uses is discussed in more detail in the following sections.

## Refrigeration and Air-Conditioning

For refrigeration and air conditioning products, emission calculations are split into two categories: emissions during equipment lifetime, which arise from annual leakage and service losses, and disposal emissions, which occur at the time of discard. Two separate steps are required to calculate the lifetime emissions from leakage and service, and the emissions resulting from disposal of the equipment. For any given year, these lifetime emissions (for existing equipment) and disposal emissions (from discarded equipment) are summed to calculate the total emissions from refrigeration and air-conditioning. As new technologies replace older ones, it is generally assumed that there are improvements in their leak, service, and disposal emission rates.

### Step 1: Calculate lifetime emissions

Emissions from any piece of equipment include both the amount of chemical leaked during equipment operation and the amount emitted during service. Emissions from leakage and servicing can be expressed as follows:

$$Es_j = (l_a + l_s) \times \sum Qc_{j-i+1} \quad for\ i = 1 \rightarrow k$$

Where:

$Es$ = Emissions from Equipment Serviced. Emissions in year $j$ from normal leakage and servicing (including recharging) of equipment.

$l_a$ = Annual Leak Rate. Average annual leak rate during normal equipment operation (expressed as a percentage of total chemical charge).

$l_s$ = Service Leak Rate. Average leakage during equipment servicing (expressed as a percentage of total chemical charge).

$Qc$ = Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in a given year by weight.

$i$ = Counter, runs from 1 to lifetime (k).

$j$ = Year of emission.

$k$ = Lifetime. The average lifetime of the equipment.

### Step 2: Calculate disposal emissions

The disposal emission equations assume that a certain percentage of the chemical charge will be emitted to the atmosphere when that vintage is discarded. Disposal emissions are thus a function of the quantity of chemical contained in the retiring equipment fleet and the proportion of chemical released at disposal:

$$Ed_j = Qc_{j-k+1} \times [1 - (rm \times rc)]$$

Where:

$Ed$ = Emissions from Equipment Disposed. Emissions in year $j$ from the disposal of equipment.

$Qc$ = Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in year $j-k+1$, by weight.

$rm$ = Chemical Remaining. Amount of chemical remaining in equipment at the time of disposal (expressed as a percentage of total chemical charge).

*rc* = Chemical Recovery Rate. Amount of chemical that is recovered just prior to disposal (expressed as a percentage of chemical remaining at disposal *(rm)*).

*j* = Year of emission.

*k* = Lifetime. The average lifetime of the equipment.

**Step 3: Calculate total emissions**

Finally, lifetime and disposal emissions are summed to provide an estimate of total emissions.

$$E_j = Es_j + Ed_j$$

Where:

*E* = Total Emissions. Emissions from refrigeration and air conditioning equipment in year *j*.

*Es* = Emissions from Equipment Serviced. Emissions in year *j* from leakage and servicing (including recharging) of equipment.

*Ed* = Emissions from Equipment Disposed. Emissions in year *j* from the disposal of equipment.

*j* = Year of emission.

**Assumptions**

The assumptions used by the Vintaging Model to trace the transition of each type of equipment away from ODS are presented in Table A- 157, below. As new technologies replace older ones, it is generally assumed that there are improvements in their leak, service, and disposal emission rates. Additionally, the market for each equipment type is assumed to grow independently, according to annual growth rates.

Table A-157: Refrigeration and Air-Conditioning Market Transition Assumptions

| Initial Market Segment | Primary Substitute | | | | Secondary Substitute | | | | Tertiary Substitute | | | | Growth Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | |
| **Centrifugal Chillers** | | | | | | | | | | | | | |
| CFC-11 | HCFC-123 | 1993 | 1993 | 45% | Unknown | | | | | | | | 0.5% |
| | HCFC-22 | 1991 | 1993 | 16% | HFC-134a | 2000 | 2010 | 100% | None | | | | |
| | HFC-134a | 1992 | 1993 | 39% | None | | | | | | | | |
| CFC-12 | HFC-134a | 1992 | 1994 | 53% | None | | | | | | | | 0.5% |
| | HCFC-22 | 1991 | 1994 | 16% | HFC-134a | 2000 | 2010 | 100% | None | | | | |
| | HCFC-123 | 1993 | 1994 | 31% | Unknown | | | | | | | | |
| R-500 | HFC-134a | 1992 | 1994 | 53% | None | | | | | | | | 0.5% |
| | HCFC-22 | 1991 | 1994 | 16% | HFC-134a | 2000 | 2010 | 100% | None | | | | |
| | HCFC-123 | 1993 | 1994 | 31% | Unknown | | | | | | | | |
| CFC-114 | HFC-236fa | 1993 | 1996 | 100% | HFC-134a | 1998 | 2009 | 100% | None | | | | 0.2% |
| **Cold Storage** | | | | | | | | | | | | | |
| CFC-12 | HCFC-22 | 1990 | 1993 | 65% | R-404A | 1996 | 2010 | 75% | None | | | | 2.5% |
| | | | | | R-507 | 1996 | 2010 | 25% | None | | | | |
| | R-404A | 1994 | 1996 | 26% | None | | | | | | | | |
| | R-507 | 1994 | 1996 | 9% | None | | | | | | | | |
| HCFC-22 | HCFC-22 | 1992 | 1993 | 100% | R-404A | 1996 | 2009 | 8% | None | | | | 2.5% |
| | | | | | R-507 | 1996 | 2009 | 3% | None | | | | |
| | | | | | R-404A | 2009 | 2010 | 68% | None | | | | |
| | | | | | R-507 | 2009 | 2010 | 23% | None | | | | |
| R-502 | HCFC-22 | 1990 | 1993 | 40% | R-404A | 1996 | 2010 | 38% | None | | | | 2.5% |
| | | | | | R-507 | 1996 | 2010 | 12% | None | | | | |
| | | | | | Non-ODP/GWP | 1996 | 2010 | 50% | None | | | | |
| | R-404A | 1993 | 1996 | 45% | None | | | | | | | | |
| | R-507 | 1994 | 1996 | 15% | None | | | | | | | | |
| **Commercial Unitary Air Conditioners (Large)** | | | | | | | | | | | | | |
| HCFC-22 | HCFC-22 | 1992 | 1993 | 100% | R-410A | 2001 | 2005 | 5% | None | | | | 0.8% |
| | | | | | R-407C | 2006 | 2009 | 1% | None | | | | |
| | | | | | R-410A | 2006 | 2009 | 9% | None | | | | |
| | | | | | R-407C | 2009 | 2010 | 5% | None | | | | |
| | | | | | R-410A | 2009 | 2010 | 81% | None | | | | |
| **Commercial Unitary Air Conditioners (Small)** | | | | | | | | | | | | | |
| HCFC-22 | HCFC-22 | 1992 | 1993 | 100% | R-410A | 1996 | 2000 | 3% | None | | | | 0.8% |
| | | | | | R-410A | 2001 | 2005 | 18% | None | | | | |
| | | | | | R-410A | 2006 | 2009 | 8% | None | | | | |
| | | | | | R-410A | 2009 | 2010 | 71% | None | | | | |
| **Dehumidifiers** | | | | | | | | | | | | | |
| HCFC-22 | HFC-134a | 1997 | 1997 | 89% | None | | | | | | | | 0.2% |
| | R-410A | 2007 | 2010 | 11% | None | | | | | | | | |

| Initial Market Segment | Primary Substitute | | | | Secondary Substitute | | | | Tertiary Substitute | | | | Growth Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | |
| **Ice Makers** | | | | | | | | | | | | | |
| CFC-12 | HFC-134a | 1993 | 1995 | 100% | None | | | | | | | | 2.5% |
| **Industrial Process Refrigeration** | | | | | | | | | | | | | |
| CFC-11 | HCFC-123 | 1992 | 1994 | 70% | Unknown | | | | | | | | 2.5% |
| | HFC-134a | 1992 | 1994 | 15% | None | | | | | | | | |
| | HCFC-22 | 1991 | 1994 | 15% | HFC-134a | 1995 | 2010 | 100% | None | | | | |
| CFC-12 | HCFC-22 | 1991 | 1994 | 10% | HFC-134a | 1995 | 2010 | 15% | None | | | | 2.5% |
| | | | | | R-404A | 1995 | 2010 | 50% | None | | | | |
| | | | | | R-410A | 1999 | 2010 | 20% | None | | | | |
| | | | | | R-507 | 1995 | 2010 | 15% | None | | | | |
| | HCFC-123 | 1992 | 1994 | 35% | Unknown | | | | | | | | |
| | HFC-134a | 1992 | 1994 | 50% | None | | | | | | | | |
| | R-401A | 1995 | 1996 | 5% | HFC-134a | 1997 | 2000 | 100% | None | | | | |
| HCFC-22 | HFC-134a | 1995 | 2009 | 2% | None | | | | | | | | 2.5% |
| | R-404A | 1995 | 2009 | 5% | None | | | | | | | | |
| | R-410A | 1999 | 2009 | 2% | None | | | | | | | | |
| | R-507 | 1995 | 2009 | 2% | None | | | | | | | | |
| | HFC-134a | 2009 | 2010 | 14% | None | | | | | | | | |
| | R-404A | 2009 | 2010 | 45% | None | | | | | | | | |
| | R-410A | 2009 | 2010 | 18% | None | | | | | | | | |
| | R-507 | 2009 | 2010 | 14% | None | | | | | | | | |
| **Mobile Air Conditioners (Passenger Cars)** | | | | | | | | | | | | | |
| CFC-12 | HFC-134a | 1992 | 1994 | 100% | None | | | | | | | | 1.9% |
| **Mobile Air Conditioners (Light Duty Trucks)** | | | | | | | | | | | | | |
| CFC-12 | HFC-134a | 1993 | 1994 | 100% | None | | | | | | | | -0.4% |
| **Mobile Air Conditioners (School and Tour Buses)** | | | | | | | | | | | | | |
| CFC-12 | HCFC-22 | 1994 | 1995 | 0.5% | HFC-134a | 2006 | 2007 | 100% | None | | | | 2.6% |
| | HFC-134a | 1994 | 1997 | 99.5% | None | | | | | | | | |
| **Mobile Air Conditioners (Transit Buses)** | | | | | | | | | | | | | |
| HCFC-22 | HFC-134a | 1995 | 2009 | 100% | None | | | | | | | | 2.6% |
| **Mobile Air Conditioners (Trains)** | | | | | | | | | | | | | |
| HCFC-22 | HFC-134a | 2002 | 2009 | 50% | None | | | | | | | | 2.6% |
| | R-407C | 2002 | 2009 | 50% | None | | | | | | | | |
| **Packaged Terminal Air Conditioners and Heat Pumps** | | | | | | | | | | | | | |
| HCFC-22 | R-410A | 2006 | 2009 | 10% | None | | | | | | | | 0.8% |
| | R-410A | 2009 | 2010 | 90% | None | | | | | | | | |
| **Positive Displacement Chillers** | | | | | | | | | | | | | |
| HCFC-22 | HFC-134a | 2000 | 2009 | 9% | R-407C | 2010 | 2020 | 60% | None | | | | 0.5% |
| | | | | | R-410A | 2010 | 2020 | 40% | None | | | | |
| | R-407C | 2000 | 2009 | 1% | None | | | | | | | | |
| | HFC-134a | 2009 | 2010 | 81% | R-407C | 2010 | 2020 | 60% | None | | | | |

| Initial Market Segment | Primary Substitute | | | | Secondary Substitute | | | | Tertiary Substitute | | | | Growth Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | |
| | | | | | | | | | R-410A | 2010 | 2020 | 40% | |
| | | | | | R-407C | 2009 | 2010 | 9% | None | | | | |
| CFC-12 | HCFC-22 | 1993 | 1993 | 100% | HFC-134a | 2000 | 2009 | 9% | R-407C | 2010 | 2020 | 60% | 0.2% |
| | | | | | | | | | R-410A | 2010 | 2020 | 40% | |
| | | | | | R-407C | 2000 | 2009 | 1% | None | | | | |
| | | | | | HFC-134a | 2009 | 2010 | 81% | R-407C | 2010 | 2020 | 60% | |
| | | | | | | | | | R-410A | 2010 | 2020 | 40% | |
| | | | | | R-407C | 2009 | 2010 | 9% | None | | | | |
| **Refrigerated Appliances** | | | | | | | | | | | | | |
| CFC-12 | HFC-134a | 1994 | 1995 | 100% | None | | | | | | | | 0.5% |
| **Residential Unitary Air Conditioners** | | | | | | | | | | | | | |
| HCFC-22 | HCFC-22 | 2006 | 2006 | 70% | R-410A | 2007 | 2010 | 29% | None | | | | 0.8% |
| | | | | | R-410A | 2010 | 2010 | 71% | None | | | | |
| | R-410A | 2000 | 2005 | 5% | R-410A | 2006 | 2006 | 100% | None | | | | |
| | R-410A | 2000 | 2006 | 5% | None | | | | | | | | |
| | R-410A | 2006 | 2006 | 20% | None | | | | | | | | |
| **Retail Food (Large)** | | | | | | | | | | | | | |
| CFC-12[59] | R-404A | 1995 | 2000 | 17.5% | R-404A | 2000 | 2000 | 100% | R-404A | 2000 | 2009 | 1.7% | 0.8% |
| | | | | | | | | | R-507 | 2000 | 2009 | 0.3% | |
| | | | | | | | | | R-404A | 2000 | 2009 | 16.2% | |
| | | | | | | | | | R-507 | 2000 | 2009 | 1.4% | |
| | | | | | | | | | R-407A | 2000 | 2009 | 0.4% | |
| | R-507 | 1995 | 2000 | 7.5% | R-507 | 2000 | 2000 | 100% | R-404A | 2000 | 2009 | 1.7% | |
| | | | | | | | | | R-507 | 2000 | 2009 | 0.3% | |
| | | | | | | | | | R-404A | 2000 | 2009 | 16.2% | |
| | | | | | | | | | R-507 | 2000 | 2009 | 1.4% | |
| | | | | | | | | | R-407A | 2000 | 2009 | 0.4% | |
| | HCFC-22 | 2000 | 2000 | 75% | R-404A | 2001 | 2010 | 1.7% | None | | | | |
| | | | | | R-507 | 2001 | 2010 | 0.3% | None | | | | |
| | | | | | R-404A | 2001 | 2010 | 16% | None | | | | |
| | | | | | R-507 | 2001 | 2010 | 1% | None | | | | |
| | | | | | R-407A | 2001 | 2010 | 0% | None | | | | |
| | | | | | R-404A | 2009 | 2010 | 64% | R-404A | 2010 | 2010 | 4.3% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 0.8% | |
| | | | | | | | | | R-404A | 2010 | 2010 | 31.5% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 2.8% | |

[59] The CFC-12 retail food market transitioned to R-502 in 1988 (reaching 100% market penetration in 1990) and subsequently transitioned to HCFC-22 in 1991 (reaching 100% market penetration in 1993). These transitions are not shown in this table in order to provide the HFC transitions in greater detail.

| Initial Market Segment | Primary Substitute | | | | Secondary Substitute | | | | Tertiary Substitute | | | | Growth Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | |
| | | | | | | | | | R-407A | 2010 | 2010 | 0.7% | |
| | | | | | R-507 | 2009 | 2010 | 8% | R-404A | 2010 | 2010 | 4.3% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 0.8% | |
| | | | | | | | | | R-404A | 2010 | 2010 | 31.5% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 2.8% | |
| | | | | | | | | | R-407A | 2010 | 2010 | 0.7% | |
| | | | | | R-407A | 2009 | 2010 | 4% | R-404A | 2010 | 2010 | 4.3% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 0.8% | |
| | | | | | | | | | R-404A | 2010 | 2010 | 31.5% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 2.8% | |
| | | | | | | | | | R-407A | 2010 | 2010 | 0.7% | |
| | | | | | R-404A | 2010 | 2010 | 4% | R-404A | 2010 | 2010 | 4.3% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 0.8% | |
| | | | | | | | | | R-404A | 2010 | 2010 | 31.5% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 2.8% | |
| | | | | | | | | | R-407A | 2010 | 2010 | 0.7% | |
| R-502[60] | HCFC-22 | 1995 | 2000 | 75% | R-404A | 2001 | 2010 | 16.2% | | | | | |
| | | | | | R-507 | 2001 | 2010 | 1.4% | | | | | |
| | | | | | R-407A | 2001 | 2010 | 0.4% | | | | | 0.8% |
| | | | | | R-404A | 2001 | 2010 | 1.7% | | | | | |
| | | | | | R-507 | 2001 | 2010 | 0.3% | | | | | |
| | | | | | R-404A | 2009 | 2010 | 64% | R-404A | 2010 | 2010 | 4.3% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 0.8% | |
| | | | | | | | | | R-404A | 2010 | 2010 | 31.5% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 2.8% | |
| | | | | | | | | | R-407A | 2010 | 2010 | 0.7% | |
| | | | | | R-507 | 2009 | 2010 | 8.0% | R-404A | 2010 | 2010 | 4.3% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 0.8% | |
| | | | | | | | | | R-404A | 2010 | 2010 | 31.5% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 2.8% | |
| | | | | | | | | | R-407A | 2010 | 2010 | 0.7% | |
| | | | | | R-407A | 2009 | 2010 | 4.0% | R-404A | 2010 | 2010 | 4.3% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 0.8% | |
| | | | | | | | | | R-404A | 2010 | 2010 | 31.5% | |

[60] The R-502 retail food market transitioned to HCFC-22 in 1990 (reaching 100% market penetration in 1993). This transition is not shown in this table in order to provide the HFC transitions in greater detail.

| Initial Market Segment | Primary Substitute | | | | Secondary Substitute | | | | Tertiary Substitute | | | | Growth Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | |
| | | | | | | | | | R-507A | 2010 | 2010 | 2.8% | |
| | | | | | | | | | R-407A | 2010 | 2010 | 0.7% | |
| | | | | | R-404A | 2010 | 2010 | 4.0% | R-404A | 2010 | 2010 | 4.3% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 0.8% | |
| | | | | | | | | | R-404A | 2010 | 2010 | 31.5% | |
| | | | | | | | | | R-507A | 2010 | 2010 | 2.8% | |
| | | | | | | | | | R-407A | 2010 | 2010 | 0.7% | |
| | R-404A | 1995 | 2000 | 17.5% | R-404A | 2000 | 2009 | 1.7% | None | | | | |
| | | | | | R-507 | 2000 | 2009 | 0.3% | None | | | | |
| | | | | | R-404A | 2000 | 2009 | 16.2% | None | | | | |
| | | | | | R-507 | 2000 | 2009 | 1.4% | None | | | | |
| | | | | | R-407A | 2000 | 2009 | 0.4% | None | | | | |
| | R-507 | 1995 | 2000 | 7.5% | R-404A | 2000 | 2009 | 1.7% | None | | | | |
| | | | | | R-507 | 2000 | 2009 | 0.3% | None | | | | |
| | | | | | R-404A | 2000 | 2009 | 16.2% | None | | | | |
| | | | | | R-507 | 2000 | 2009 | 1.4% | None | | | | |
| | | | | | R-407A | 2000 | 2009 | 0.4% | None | | | | |
| **Retail Food (Large Condensing Units)** | | | | | | | | | | | | | |
| HCFC-22 | R-402A | 1995 | 2005 | 5% | R-404A | 2006 | 2006 | 100% | None | | | | 0.9% |
| | R-404A | 1995 | 2005 | 25% | None | | | | | | | | |
| | R-507 | 1995 | 2005 | 10% | None | | | | | | | | |
| | R-404A | 2008 | 2010 | 45% | None | | | | | | | | |
| | R-507 | 2008 | 2010 | 15% | None | | | | | | | | |
| **Retail Food (Small Condensing Units)** | | | | | | | | | | | | | |
| HCFC-22 | R-401A | 1995 | 2005 | 6% | HFC-134a | 2006 | 2006 | 100% | None | | | | 0.9% |
| | R-402A | 1995 | 2005 | 4% | HFC-134a | 2006 | 2006 | 100% | None | | | | |
| | HFC-134a | 1993 | 2005 | 30% | | | | | | | | | |
| | R-404A | 1995 | 2005 | 30% | | | | | | | | | |
| | R-404A | 2008 | 2010 | 30% | | | | | | | | | |
| **Retail Food (Small)** | | | | | | | | | | | | | |
| CFC-12 | HCFC-22 | 1990 | 1993 | 90% | HFC-134a | 1993 | 1995 | 90% | $CO_2$ | 2010 | 2010 | 5% | 0.8% |
| | | | | | R-404A | 2000 | 2009 | 7.5% | None | | | | |
| | | | | | R-507 | 2000 | 2009 | 2.5% | None | | | | |
| | R-404A | 1993 | 1996 | 7.5% | None | | | | | | | | |
| | R-507 | 1993 | 1996 | 2.5% | None | | | | | | | | |
| **Transport Refrigeration** | | | | | | | | | | | | | |
| CFC-12 | HFC-134a | 1993 | 1995 | 98% | None | | | | | | | | 2.5% |
| | HCFC-22 | 1993 | 1995 | 2% | HFC-134a | 1995 | 1999 | 100% | None | | | | |
| R-502 | HFC-134a | 1993 | 1995 | 55% | None | | | | | | | | 2.5% |
| | R-404A | 1993 | 1995 | 45% | None | | | | | | | | |
| **Water-Source and Ground-Source Heat Pumps** | | | | | | | | | | | | | |

| Initial Market Segment | Primary Substitute | | | | Secondary Substitute | | | | Tertiary Substitute | | | | Growth Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | |
| HCFC-22 | R-407C | 2000 | 2006 | 5% | | | | | None | | | | 0.8% |
| | R-410A | 2000 | 2006 | 5% | | | | | None | | | | |
| | HFC-134a | 2000 | 2009 | 2% | | | | | None | | | | |
| | R-407C | 2006 | 2009 | 2.5% | | | | | None | | | | |
| | R-410A | 2006 | 2009 | 4.5% | | | | | None | | | | |
| | HFC-134a | 2009 | 2010 | 18% | | | | | None | | | | |
| | R-407C | 2009 | 2010 | 22.5% | | | | | None | | | | |
| | R-410A | 2009 | 2010 | 40.5% | | | | | None | | | | |
| **Window Units** | | | | | | | | | | | | | |
| HCFC-22 | R-410A | 2008 | 2009 | 10% | None | | | | | | | | 5.0% |
| | R-410A | 2009 | 2010 | 90% | None | | | | | | | | |

Table A- 158 presents the average equipment lifetimes and annual HFC emission rates (for servicing and leaks) for each end-use assumed by the Vintaging Model.

Table A- 158. Refrigeration and Air-conditioning Lifetime Assumptions

| End-Use | Lifetime (Years) | HFC Emission Rates (%) |
|---|---|---|
| Centrifugal Chillers | 20 – 27 | 2.0 – 10.9 |
| Cold Storage | 20 – 25 | 15.0 |
| Commercial Unitary A/C | 15 | 7.9 – 8.6 |
| Dehumidifiers | 11 | 0.5 |
| Ice Makers | 20 | 3.0 |
| Industrial Process Refrigeration | 25 | 3.6 – 12.3 |
| Mobile Air Conditioners | 5 –12 | 2.3 – 18.0 |
| Positive Displacement Chillers | 20 | 0.5 – 1.5 |
| PTAC/PTHP | 12 | 3.9 |
| Retail Food | 18 – 20 | 1.0 – 25 |
| Refrigerated Appliances | 14 | 0.6 |
| Residential Unitary A/C | 15 | 11.8 |
| Transport Refrigeration | 12 | 20.6 – 27.9 |
| Water & Ground Source Heat Pumps | 20 | 3.9 |
| Window Units | 12 | 0.6 |

## Aerosols

ODSs, HFCs and many other chemicals are used as propellant aerosols. Pressurized within a container, a nozzle releases the chemical, which allows the product within the can to also be released. Two types of aerosol products are modeled: metered dose inhalers (MDI) and consumer aerosols. In the United States, the use of CFCs in consumer aerosols was banned in 1978, and many products transitioned to hydrocarbons or "not-in-kind" technologies, such as solid deodorants and finger-pump hair sprays. However, MDIs can continue to use CFCs as propellants because their use has been deemed essential. Essential use exemptions granted to the United States under the Montreal Protocol for CFC use in MDIs are limited to the treatment of asthma and chronic obstructive pulmonary disease.

All HFCs and PFCs used in aerosols are assumed to be emitted in the year of manufacture. Since there is currently no aerosol recycling, it is assumed that all of the annual production of aerosol propellants is released to the atmosphere. The following equation describes the emissions from the aerosols sector.

$$E_j = Qc_j$$

Where:

$E$ = Emissions. Total emissions of a specific chemical in year $j$ from use in aerosol products, by weight.

$Qc$ = Quantity of Chemical. Total quantity of a specific chemical contained in aerosol products sold in year $j$, by weight.

$j$ = Year of emission.

### Transition Assumptions

Transition assumptions and growth rates for those items that use ODSs or HFCs as propellants, including vital medical devices and specialty consumer products, are presented in Table A- 159.

Table A- 159. Aerosol Product Transition Assumptions

| Initial Market Segment | Primary Substitute | | | | Secondary Substitute | | | | Growth Rate |
|---|---|---|---|---|---|---|---|---|---|
| | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | |
| **MDIs** | | | | | | | | | |
| CFC Mix* | HFC-134a | 1997 | 1997 | 6% | None | | | | 0.8% |
| | Non-ODP/GWP | 1998 | 2007 | 7% | None | | | | |
| | CFC Mix* | 2000 | 2000 | 87% | HFC-134a | 2002 | 2002 | 34% | |
| | | | | | HFC-134a | 2003 | 2009 | 47% | |
| | | | | | HFC-227ea | 2006 | 2009 | 5% | |
| | | | | | HFC-134a | 2010 | 2011 | 6% | |
| | | | | | HFC-227ea | 2010 | 2011 | 1% | |
| | | | | | HFC-134a | 2011 | 2012 | 3% | |
| | | | | | HFC-227ea | 2011 | 2012 | 0.3% | |
| | | | | | HFC-134a | 2014 | 2014 | 3% | |
| | | | | | HFC-227ea | 2014 | 2014 | 0.3% | |
| **Consumer Aerosols (Non-MDIs)** | | | | | | | | | |
| NA** | HFC-152a | 1990 | 1991 | 50% | None | | | | 2.0% |
| | HFC-134a | 1995 | 1995 | 50% | HFC-152a | 1997 | 1998 | 44% | |
| | | | | | HFC-152a | 2001 | 2005 | 36% | |

*CFC Mix consists of CFC-11, CFC-12 and CFC-114 and represents the weighted average of several CFCs consumed for essential use in MDIs from 1993 to 2008.

**Consumer Aerosols transitioned away from ODS prior to 1985, the year in which the Vintaging Model begins. The portion of the market that is now using HFC propellants is modeled.

## Solvents

ODSs, HFCs, PFCs and other chemicals are used as solvents to clean items. For example, electronics may need to be cleaned after production to remove any manufacturing process oils or residues left. Solvents are applied by moving the item to be cleaned within a bath or stream of the solvent. Generally, most solvents are assumed to remain in the liquid phase and are not emitted as gas. Thus, emissions are considered "incomplete," and are a fixed percentage of the amount of solvent consumed in a year. The remainder of the consumed solvent is assumed to be reused or disposed without being released to the atmosphere. The following equation calculates emissions from solvent applications.

$$E_j = l \times Qc_j$$

Where:

$E$ = Emissions. Total emissions of a specific chemical in year $j$ from use in solvent applications, by weight.

$l$ = Percent Leakage. The percentage of the total chemical that is leaked to the atmosphere, assumed to be 90 percent.

$Qc$ = Quantity of Chemical. Total quantity of a specific chemical sold for use in solvent applications in the year j, by weight.

$j$ = Year of emission.

### Transition Assumptions

The transition assumptions and growth rates used within the Vintaging Model for electronics cleaning, metals cleaning, precision cleaning, and adhesives, coatings and inks, are presented in Table A- 160.

Table A-160. Solvent Market Transition Assumptions

| Initial Market Segment | Primary Substitute | | | | Secondary Substitute | | | | Growth Rate |
|---|---|---|---|---|---|---|---|---|---|
| | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | |
| **Adhesives** | | | | | | | | | |
| $CH_3CCl_3$ | Non-ODP/GWP | 1994 | 1995 | 100% | None | | | | 2.0% |
| **Electronics** | | | | | | | | | |
| CFC-113 | Semi-Aqueous | 1994 | 1995 | 52% | None | | | | 2.0% |
| | HCFC-225ca/cb | 1994 | 1995 | 0.2% | Unknown | | | | |
| | HFC-43-10mee | 1995 | 1996 | 0.7% | None | | | | |
| | HFE-7100 | 1994 | 1995 | 0.7% | None | | | | |
| | nPB | 1992 | 1996 | 5% | None | | | | |
| | Methyl Siloxanes | 1992 | 1996 | 0.8% | None | | | | |
| | No-Clean | 1992 | 1996 | 40% | None | | | | |
| $CH_3CCl_3$ | Non-ODP/GWP | 1996 | 1997 | 99.8% | None | | | | 2.0% |
| | PFC/PFPE | 1996 | 1997 | 0.2% | Non-ODP/GWP | 2000 | 2003 | 90% | |
| | | | | | Non-ODP/GWP | 2005 | 2009 | 10% | |
| **Metals** | | | | | | | | | |
| $CH_3CCl_3$ | Non-ODP/GWP | 1992 | 1996 | 100% | None | | | | 2.0% |
| CFC-113 | Non-ODP/GWP | 1992 | 1996 | 100% | None | | | | 2.0% |
| $CCl_4$ | Non-ODP/GWP | 1992 | 1996 | 100% | None | | | | 2.0% |
| **Precision** | | | | | | | | | |
| $CH_3CCl_3$ | Non-ODP/GWP | 1995 | 1996 | 99.3% | None | | | | 2.0% |
| | HFC-43-10mee | 1995 | 1996 | 0.6% | None | | | | |
| | PFC/PFPE | 1995 | 1996 | 0.1% | Non-ODP/GWP | 2000 | 2003 | 90% | |
| | | | | | Non-ODP/GWP | 2005 | 2009 | 10% | |
| CFC-113 | Non-ODP/GWP | 1995 | 1996 | 96% | None | | | | 2.0% |
| | HCFC-225ca/cb | 1995 | 1996 | 1% | Unknown | | | | |
| | HFE-7100 | 1995 | 1996 | 3% | None | | | | |

Non-ODP/GWP includes chemicals with 0 ODP and low GWP, such as hydrocarbons and ammonia, as well as not-in-kind alternatives such as "no clean" technologies.

## Fire Extinguishing

ODSs, HFCs, PFCs and other chemicals are used as fire-extinguishing agents, in both hand-held "streaming" applications as well as in built-up "flooding" equipment similar to water sprinkler systems. Although these systems are generally built to be leak-tight, some leaks do occur and of course emissions occur when the agent is released. Total emissions from fire extinguishing are assumed, in aggregate, to equal a percentage of the total quantity of chemical in operation at a given time. For modeling purposes, it is assumed that fire extinguishing equipment leaks at a constant rate for an average equipment lifetime, as shown in the equation below. In streaming systems, non-halon emissions are assumed to be 3.5 percent of all chemical in use in each year, while in flooding systems 2.5 percent of the installed base of chemical is assumed to leak annually. Halon systems are assumed to leak at higher rates. The equation is applied for a single year, accounting for all fire protection equipment in operation in that year. Each fire protection agent is modeled separately. In the Vintaging Model, streaming applications have a 12-year lifetime and flooding applications have a 20-year lifetime.

$$E_j = \mathrm{r} \times \sum Qc_{j-i+1} \quad for\ i=1 \rightarrow k$$

Where:

$E$ = Emissions. Total emissions of a specific chemical in year $j$ for streaming fire extinguishing equipment, by weight.

r = Percent Released. The percentage of the total chemical in operation that is released to the atmosphere.

$Qc$ = Quantity of Chemical. Total amount of a specific chemical used in new fire extinguishing equipment in a given year, $j$-$i$+1, by weight.

$i$ = Counter, runs from 1 to lifetime (k).

$j$ = Year of emission.

$k$ = Lifetime. The average lifetime of the equipment.

#### Transition Assumptions

Transition assumptions and growth rates for these two fire extinguishing types are presented in Table A- 161.

Table A- 161. Fire Extinguishing Market Transition Assumptions

| Initial Market Segment | Primary Substitute | | | | Secondary Substitute | | | | Growth Rate |
|---|---|---|---|---|---|---|---|---|---|
| | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | |
| **Flooding Agents** | | | | | | | | | |
| Halon-1301 | Halon-1301* | 1994 | 1994 | 4% | Unknown | | | | 2.2% |
| | HFC-23 | 1994 | 1999 | 0.2% | None | | | | |
| | HFC-227ea | 1994 | 1999 | 18% | FK-5-1-12 | 2003 | 2010 | 10% | |
| | | | | | HFC-125 | 2001 | 2008 | 10% | |
| | Non-ODP/GWP | 1994 | 1994 | 46% | FK-5-1-12 | 2003 | 2010 | 7% | |
| | Non-ODP/GWP | 1995 | 2034 | 10% | None | | | | |
| | Non-ODP/GWP | 1998 | 2027 | 10% | None | | | | |
| | $C_4F_{10}$ | 1994 | 1999 | 1% | FK-5-1-12 | 2003 | 2003 | 100% | |
| | HFC-125 | 1997 | 2006 | 11% | None | | | | |
| **Streaming Agents** | | | | | | | | | |
| Halon-1211 | Halon-1211* | 1992 | 1992 | 5% | Unknown | | | | 3.0% |
| | HFC-236fa | 1997 | 1999 | 3% | None | | | | |
| | Halotron | 1994 | 1997 | 4% | Non-ODP/GWP | 2015 | 2015 | 25% | |
| | | | | | HFC-236fa | 2015 | 2015 | 75% | |
| | Non-ODP/GWP | 1993 | 1994 | 58% | None | | | | |
| | Non-ODP/GWP | 1995 | 2024 | 20% | None | | | | |
| | Non-ODP/GWP | 1999 | 2018 | 10% | None | | | | |

*Despite the 1994 consumption ban, a small percentage of new halon systems are assumed to continue to be built and filled with stockpiled or recovered supplies.

### Foam Blowing

ODSs, HFCs, and other chemicals are used to produce foams, including such items as the foam insulation panels around refrigerators, insulation sprayed on buildings, etc. The chemical is used to create pockets of gas within a substrate, increasing the insulating properties of the item. Foams are given emission profiles depending on the foam type (open cell or closed cell). Open cell foams are assumed to be 100 percent emissive in the year of manufacture. Closed cell foams are assumed to emit a portion of their total HFC content upon manufacture, a portion at a constant rate over the lifetime of the foam, a portion at disposal, and a portion after disposal; these portions vary by end-use.

#### Step 1: Calculate manufacturing emissions (open-cell and closed-cell foams)

Manufacturing emissions occur in the year of foam manufacture, and are calculated as presented in the following equation.

$$Em_j = lm \times Qc_j$$

Where:

$Em_j$ = Emissions from manufacturing. Total emissions of a specific chemical in year $j$ due to manufacturing losses, by weight.

$lm$ = Loss Rate. Percent of original blowing agent emitted during foam manufacture. For open-cell foams, $lm$ is 100%.

$Qc$ = Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.

$j$ = Year of emission.

**Step 2: Calculate lifetime emissions (closed-cell foams)**

Lifetime emissions occur annually from closed-cell foams throughout the lifetime of the foam, as calculated as presented in the following equation.

$$Eu_j = lu \times \sum Qc_{j-i+1} \quad for\ i=1 \rightarrow k$$

Where:

$Eu_j$ = Emissions from Lifetime Losses. Total emissions of a specific chemical in year j due to lifetime losses during use, by weight.

$lu$ = Leak Rate. Percent of original blowing agent emitted each year during lifetime use.

$Qc$ = Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.

$i$ = Counter, runs from 1 to lifetime (k).

$j$ = Year of emission.

$k$ = Lifetime. The average lifetime of foam product.

**Step 3: Calculate disposal emissions (closed-cell foams)**

Disposal emissions occur in the year the foam is disposed, and are calculated as presented in the following equation.

$$Ed_j = ld \times Qc_{j-k}$$

Where:

$Ed_j$ = Emissions from disposal. Total emissions of a specific chemical in year j at disposal, by weight.

$ld$ = Loss Rate. Percent of original blowing agent emitted at disposal.

$Qc$ = Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.

$j$ = Year of emission.

$k$ = Lifetime. The average lifetime of foam product.

**Step 4: Calculate post-disposal emissions (closed-cell foams)**

Post-Disposal emissions occur in the years after the foam is disposed; for example, emissions might occur while the disposed foam is in a landfill. Currently, the only foam type assumed to have post-disposal emissions is polyurethane foam used as domestic refrigerator and freezer insulation, which is expected to continue to emit for 26 years post-disposal, calculated as presented in the following equation.

$$Ep_j = lp \times \sum Qc_{j-m} \quad for\ m=k \rightarrow k + 32$$

Where:

$Ep_j$ = Emissions from post disposal. Total post-disposal emissions of a specific chemical in year j, by weight.

$lp$ = Leak Rate. Percent of original blowing agent emitted post disposal.

$Qc$ = Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.

$k$ = Lifetime. The average lifetime of foam product.

$m$ = Counter. Runs from lifetime (k) to (k+26).

$j$ = Year of emission.

**Step 5: Calculate total emissions (open-cell and closed-cell foams)**

To calculate total emissions from foams in any given year, emissions from all foam stages must be summed, as presented in the following equation.

$$E_j = Em_j + Eu_j + Ed_j + Ep_j$$

Where:

$E_j$ = Total Emissions. Total emissions of a specific chemical in year *j*, by weight.

$Em$ = Emissions from manufacturing. Total emissions of a specific chemical in year *j* due to manufacturing losses, by weight.

$Eu_j$ = Emissions from Lifetime Losses. Total emissions of a specific chemical in year j due to lifetime losses during use, by weight.

$Ed_j$ = Emissions from disposal. Total emissions of a specific chemical in year j at disposal, by weight.

$Ep_j$ = Emissions from post disposal. Total post-disposal emissions of a specific chemical in year j, by weight.

**Assumptions**

The Vintaging Model contains 13 foam types, whose transition assumptions away from ODS and growth rates are presented in Table A- 162. The emission profiles of these 13 foam types are shown in Table A- 163.

Table A-162. Foam Blowing Market Transition Assumptions

| Initial Market Segment | Primary Substitute | | | | Secondary Substitute | | | | Tertiary Substitute | | | | Growth Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | |
| **Commercial Refrigeration Foam** | | | | | | | | | | | | | |
| CFC-11 | HCFC-141b | 1989 | 1996 | 40% | HFC-245fa | 2002 | 2003 | 80% | None | | | | 6.0% |
| | | | | | Non-ODP/GWP | 2002 | 2003 | 20% | None | | | | |
| | HCFC-142b | 1989 | 1996 | 8% | Non-ODP/GWP | 2009 | 2010 | 80% | None | | | | |
| | | | | | HFC-245fa | 2009 | 2010 | 20% | None | | | | |
| | HCFC-22 | 1989 | 1996 | 52% | Non-ODP/GWP | 2009 | 2010 | 80% | None | | | | |
| | | | | | HFC-245fa | 2009 | 2010 | 20% | None | | | | |
| **Flexible PU Foam: Integral Skin Foam** | | | | | | | | | | | | | |
| CFC-11 | HCFC-141b | 1989 | 1990 | 100% | HFC-134a | 1993 | 1996 | 25% | None | | | | 2.0% |
| | | | | | HFC-134a | 1994 | 1996 | 25% | None | | | | |
| | | | | | $CO_2$ | 1993 | 1996 | 25% | None | | | | |
| | | | | | $CO_2$ | 1994 | 1996 | 25% | None | | | | |
| **Flexible PU Foam: Slabstock Foam, Moulded Foam** | | | | | | | | | | | | | |
| CFC-11 | Non-ODP/GWP | 1992 | 1992 | 100% | None | | | | | | | | 2.0% |
| **Phenolic Foam** | | | | | | | | | | | | | |
| CFC-11 | HCFC-141b | 1989 | 1990 | 100% | Non-ODP/GWP | 1992 | 1992 | 100% | None | | | | 2.0% |
| **Polyolefin Foam** | | | | | | | | | | | | | |
| CFC-114 | HFC-152a | 1989 | 1993 | 10% | Non-ODP/GWP | 2005 | 2010 | 100% | None | | | | 2.0% |
| | HCFC-142b | 1989 | 1993 | 90% | Non-ODP/GWP | 1994 | 1996 | 100% | None | | | | |
| **PU and PIR Rigid: Boardstock** | | | | | | | | | | | | | |
| CFC-11 | HCFC-141b | 1993 | 1996 | 100% | Non-ODP/GWP | 2000 | 2003 | 95% | None | | | | 6.0% |
| | | | | | HC/HFC-245fa Blend | 2000 | 2003 | 5% | None | | | | |
| **PU Rigid: Domestic Refrigerator and Freezer Insulation** | | | | | | | | | | | | | |
| CFC-11 | HCFC-141b | 1993 | 1995 | 100% | HFC-134a | 1996 | 2001 | 7% | Non-ODP/GWP | 2002 | 2003 | 100% | 0.8% |
| | | | | | HFC-245fa | 2001 | 2003 | 50% | Non-ODP/GWP | 2015 | 2029 | 100% | |
| | | | | | HFC-245fa | 2006 | 2009 | 10% | Non-ODP/GWP | 2015 | 2029 | 100% | |
| | | | | | Non-ODP/GWP | 2002 | 2005 | 10% | None | | | | |
| | | | | | Non-ODP/GWP | 2006 | 2009 | 3% | None | | | | |
| | | | | | Non-ODP/GWP | 2009 | 2014 | 20% | None | | | | |
| **PU Rigid: One Component Foam** | | | | | | | | | | | | | |
| CFC-12 | HCFC-142b/22 Blend | 1989 | 1996 | 70% | Non-ODP/GWP | 2009 | 2010 | 80% | None | | | | 4.0% |
| | | | | | HFC-134a | 2009 | 2010 | 10% | None | | | | |
| | | | | | HFC-152a | 2009 | 2010 | 10% | None | | | | |
| | HCFC-22 | 1989 | 1996 | 30% | Non-ODP/GWP | 2009 | 2010 | 80% | None | | | | |
| | | | | | HFC-134a | 2009 | 2010 | 10% | None | | | | |
| | | | | | HFC-152a | 2009 | 2010 | 10% | None | | | | |

| Initial Market Segment | Primary Substitute | | | | Secondary Substitute | | | | Tertiary Substitute | | | | Growth Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | |
| **PU Rigid: Other: Slabstock Foam** | | | | | | | | | | | | | |
| CFC-11 | HCFC-141b | 1989 | 1996 | 100% | $CO_2$ | 1999 | 2003 | 45% | None | | | | 2.0% |
| | | | | | Non-ODP/GWP | 2001 | 2003 | 45% | None | | | | |
| | | | | | HCFC-22 | 2003 | 2003 | 10% | Non-ODP/GWP | 2009 | 2010 | 100% | |
| **PU Rigid: Sandwich Panels: Continuous and Discontinuous** | | | | | | | | | | | | | |
| CFC-11 | HCFC-141b | 1989 | 1996 | 82% | HCFC-22/Water Blend | 2001 | 2003 | 20% | HFC-245fa/$CO_2$ Blend | 2009 | 2010 | 50% | 6.0% |
| | | | | | | | | | Non-ODP/GWP | 2009 | 2010 | 50% | |
| | | | | | HFC-245fa/$CO_2$ Blend | 2002 | 2004 | 20% | None | | | | |
| | | | | | Non-ODP/GWP | 2001 | 2004 | 40% | None | | | | |
| | | | | | HFC-134a | 2002 | 2004 | 20% | None | | | | |
| | HCFC-22 | 1989 | 1996 | 18% | HFC-245fa/$CO_2$ Blend | 2009 | 2010 | 40% | None | | | | |
| | | | | | Non-ODP/GWP | 2009 | 2010 | 20% | None | | | | |
| | | | | | $CO_2$ | 2009 | 2010 | 20% | None | | | | |
| | | | | | HFC-134a | 2009 | 2010 | 20% | None | | | | |
| **PU Rigid: Spray Foam** | | | | | | | | | | | | | |
| CFC-11 | HCFC-141b | 1989 | 1996 | 100% | HFC-245fa | 2002 | 2003 | 30% | None | | | | 6.0% |
| | | | | | HFC-245fa/$CO_2$ Blend | 2002 | 2003 | 60% | None | | | | |
| | | | | | Non-ODP/GWP | 2001 | 2003 | 10% | None | | | | |
| **XPS: Boardstock Foam** | | | | | | | | | | | | | |
| CFC-12 | HCFC-142b/22 Blend | 1989 | 1994 | 10% | HFC-134a | 2009 | 2010 | 70% | None | | | | 2.5% |
| | | | | | HFC-152a | 2009 | 2010 | 10% | None | | | | |
| | | | | | $CO_2$ | 2009 | 2010 | 10% | None | | | | |
| | | | | | Non-ODP/GWP | 2009 | 2010 | 10% | None | | | | |
| | HCFC-142b | 1989 | 1994 | 90% | HFC-134a | 2009 | 2010 | 70% | None | | | | |
| | | | | | HFC-152a | 2009 | 2010 | 10% | None | | | | |
| | | | | | $CO_2$ | 2009 | 2010 | 10% | None | | | | |
| | | | | | Non-ODP/GWP | 2009 | 2010 | 10% | None | | | | |
| **XPS: Sheet Foam** | | | | | | | | | | | | | |
| CFC-12 | $CO_2$ | 1989 | 1994 | 1% | None | | | | | | | | 2.0% |
| | Non-ODP/GWP | 1989 | 1994 | 99% | $CO_2$ | 1995 | 1999 | 9% | None | | | | |
| | | | | | HFC-152a | 1995 | 1999 | 10% | None | | | | |

1

Table A- 163. Emission profile for the foam end-uses

| Foam End-Use | Loss at Manufacturing (%) | Annual Leakage Rate (%) | Leakage Lifetime (years) | Loss at Disposal (%) | Total* (%) |
|---|---|---|---|---|---|
| Flexible PU Foam: Slabstock Foam, Moulded Foam | 100 | 0 | 1 | 0 | 100 |
| Commercial Refrigeration | 6 | 0.25 | 15 | 90.25 | 100 |
| Rigid PU: Spray Foam | 15 | 1.5 | 56 | 1 | 100 |
| Rigid PU: Slabstock and Other | 37.5 | 0.75 | 15 | 51.25 | 100 |
| Phenolic Foam | 23 | 0.875 | 32 | 49 | 100 |
| Polyolefin Foam | 95 | 2.5 | 2 | 0 | 100 |
| Rigid PU: One Component Foam | 100 | 0 | 1 | 0 | 100 |
| XPS: Sheet Foam* | 40 | 2 | 25 | 0 | 90 |
| XPS: Boardstock Foam | 25 | 0.75 | 50 | 37.5 | 100 |
| Flexible PU Foam: Integral Skin Foam | 95 | 2.5 | 2 | 0 | 100 |
| Rigid PU: Domestic Refrigerator and Freezer Insulation* | 4 | 0.25 | 14 | 40.0 | 47.5 |
| PU and PIR Rigid: Boardstock | 6 | 1 | 50 | 44 | 100 |
| PU Sandwich Panels: Continuous and Discontinuous | 5.5 | 0.5 | 50 | 69.5 | 100 |

PIR (Polyisicyanurate)
PU (Polyurethane)
XPS (Extruded Polystyrene)
*In general, total emissions from foam end-uses are assumed to be 100 percent, although work is underway to investigate that assumption. In the XPS Sheet/Insulation Board end-use, the source of emission rates and lifetimes did not yield 100 percent emission; it is unclear at this time whether that was intentional. In the Rigid PU Appliance Foam end-use, the source of emission rates and lifetimes did not yield 100 percent emission; the remainder is anticipated to be emitted at a rate of 2.0%/year post-disposal for the next 26 years.

## Sterilization

Sterilants kill microorganisms on medical equipment and devices. The principal ODS used in this sector was a blend of 12% ethylene oxide (EtO) and 88% CFC-12, known as "12/88." In that blend, ethylene oxide sterilizes the equipment and CFC-12 is a dilutent solvent to form a non-flammable blend. The sterilization sector is modeled as a single end-use. For sterilization applications, all chemicals that are used in the equipment in any given year are assumed to be emitted in that year, as shown in the following equation.

$$E_j = Qc_j$$

Where:

$E$ = Emissions. Total emissions of a specific chemical in year $j$ from use in sterilization equipment, by weight.

$Qc$ = Quantity of Chemical. Total quantity of a specific chemical used in sterilization equipment in year $j$, by weight.

$j$ = Year of emission.

### Assumptions

The Vintaging Model contains 1 sterilization end-use, whose transition assumptions away from ODS and growth rates are presented in Table A- 164.

Table A-164. Sterilization Market Transition Assumptions

| Initial Market Segment | Primary Substitute | | | | Secondary Substitute | | | | Tertiary Substitute | | | | Growth Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | Name of Substitute | Start Date | Date of Full Penetration in New Equipment | Maximum Market Penetration | |
| **Commercial Refrigeration Foam** | | | | | | | | | | | | | |
| 12/88 | EtO | 1994 | 1995 | 95% | None | | | | | | | | 2.0% |
| | Non-ODP/GWP | 1994 | 1995 | 1% | None | | | | | | | | |
| | HCFC/EtO Blends | 1993 | 1994 | 4% | Non-ODP/GWP | 2010 | 2010 | 100% | None | | | | |

## Model Output

By repeating these calculations for each year, the Vintaging Model creates annual profiles of use and emissions for ODS and ODS substitutes. The results can be shown for each year in two ways: 1) on a chemical-by-chemical basis, summed across the end-uses, or 2) on an end-use or sector basis. Values for use and emissions are calculated both in metric tons and in teragrams of $CO_2$ equivalents (Tg $CO_2$ Eq.). The conversion of metric tons of chemical to Tg $CO_2$ Eq. is accomplished through a linear scaling of tonnage by the global warming potential (GWP) of each chemical.

Throughout its development, the Vintaging Model has undergone annual modifications. As new or more accurate information becomes available, the model is adjusted in such a way that both past and future emission estimates are often altered.

### Bank of ODS and ODS Substitutes

The bank of an ODS or an ODS substitute is "the cumulative difference between the chemical that has been consumed in an application or sub-application and that which has already been released" (IPCC 2006). For any given year, the bank is equal to the previous year's bank, less the chemical in equipment disposed of during the year, plus chemical in new equipment entering the market during that year, less the amount emitted but not replaced, plus the amount added to replace chemical emitted prior to the given year, as shown in the following equation:

$$Bc_j = Bc_{j-1} - Qd_j + Qp_j + E_e - Q_r$$

Where:

$Bc_j$ = Bank of Chemical. Total bank of a specific chemical in year *j*, by weight.

$Qd_j$ = Quantity of Chemical in Equipment Disposed. Total quantity of a specific chemical in equipment disposed of in year *j*, by weight.

$Qp_j$ = Quantity of Chemical Penetrating the Market. Total quantity of a specific chemical that is entering the market in year *j*, by weight.

$E_e$ = Emissions of Chemical Not Replaced. Total quantity of a specific chemical that is emitted during year j but is not replaced in that year. The Vintaging Model assumes all chemical emitted from refrigeration, air conditioning and fire extinguishing equipment is replaced in the year it is emitted, hence this term is zero for all sectors except foam blowing.

$Q_r$ = Chemical Replacing Previous Year's Emissions. Total quantity of a specific chemical that is used to replace emissions that occurred prior to year j. The Vintaging Model assumes all chemical emitted from refrigeration, air conditioning and fire extinguishing equipment is replaced in the year it is emitted, hence this term is zero for all sectors.

$j$ = Year of emission.

Table A- 165 provides the bank for ODS and ODS substitutes by chemical grouping in metric tons (MT) for 1990-2010.

Table A- 165. Banks of ODS and ODS Substitutes, 1990-2010 (MT)

| | CFC | HCFC | HFC |
|---|---|---|---|
| **1990** | 669,869 | 283,288 | 868 |
| | | | |
| **1995** | 764,257 | 497,567 | 52,559 |
| | | | |
| **2000** | 629,594 | 922,760 | 183,071 |
| **2001** | 604,142 | 991,621 | 210,409 |
| **2002** | 580,462 | 1,044,581 | 240,774 |
| **2003** | 557,254 | 1,080,071 | 277,173 |
| **2004** | 535,367 | 1,117,629 | 313,636 |
| **2005** | 517,882 | 1,159,409 | 347,363 |
| **2006** | 503,839 | 1,196,960 | 381,821 |
| **2007** | 491,705 | 1,226,674 | 416,534 |
| **2008** | 483,578 | 1,246,132 | 448,792 |
| **2009** | 480,177 | 1,241,545 | 491,133 |
| **2010** | 466,203 | 1,206,136 | 559,470 |
| **2011** | 452,162 | 1,161,241 | 625,511 |

## References

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

## 3.10. Methodology for Estimating $CH_4$ Emissions from Enteric Fermentation

Methane emissions from enteric fermentation were estimated for seven livestock categories: cattle, horses, sheep, swine, goats, American bison, and the non-horse equids (mules, burros, and donkeys). Emissions from cattle represent the majority of U.S. emissions from enteric fermentation; consequently, the more detailed IPCC Tier 2 methodology was used to estimate emissions from cattle. The IPCC Tier 1 methodology was used to estimate emissions for the other types of livestock, including horses, goats, sheep, swine, American bison, mules, burros, and donkeys.

### Estimate Methane Emissions from Cattle

This section describes the process used to estimate $CH_4$ emissions from enteric fermentation from cattle using the Cattle Enteric Fermentation Model (CEFM).[61] The CEFM was developed based on recommendations provided in IPCC/UNEP/OECD/IEA (1997), IPCC (2000) and IPCC (2006), and uses information on population, energy requirements, digestible energy, and $CH_4$ conversion rates to estimate $CH_4$ emissions.[62] The emission methodology consists of the following three steps: (1) characterize the cattle population to account for animal population categories with different emission profiles; (2) characterize cattle diets to generate information needed to estimate emission factors; and (3) estimate emissions using these data and the IPCC Tier 2 equations.

#### Step 1: Characterize U.S. Cattle Population

The state-level cattle population estimates are based on data obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service Quick Stats database (USDA 2012). A summary of the annual average populations upon which all livestock-related emissions are based is provided in Table A-166. Cattle populations used in the Enteric Fermentation source category were estimated using the cattle transition matrix in the CEFM, which uses January 1 USDA population estimates and weight data to simulate the population of U.S. cattle from birth to slaughter, and results in an estimate of the number of animals in a particular cattle grouping while taking into account the monthly rate of weight gain, the average weight of the animals, and the death and calving rates. The use of supplemental USDA data and the cattle transition matrix in the CEFM results in cattle population estimates for this sector differing slightly from the January 1 or July 1 USDA point estimates and the cattle population data obtained from the Food and Agriculture Organization of the United Nations (FAO).

Table A-166: Cattle Population Estimates from the CEFM Transition Matrix for 1990-2011 (1,000 head)

| Livestock Type | 1990 | 1995 | 2000 | 2005 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|
| Calves 0-6 months | 22,561 | 23,499 | 22,569 | 21,678 | 21,155 | 21,001 | 20,861 | 20,648 |
| **Dairy** | | | | | | | | |
| Dairy Cows | 10,015 | 9,482 | 9,183 | 9,004 | 9,257 | 9,333 | 9,086 | 9,150 |
| Dairy Replacements 7-11 months | 1,214 | 1,216 | 1,196 | 1,257 | 1,304 | 1,327 | 1,347 | 1,341 |
| Dairy Replacements 12-23 months | 2,915 | 2,892 | 2,812 | 2,905 | 3,097 | 3,101 | 3,179 | 3,200 |
| **Beef** | | | | | | | | |
| Bulls | 2,160 | 2,385 | 2,293 | 2,214 | 2,207 | 2,184 | 2,190 | 2,155 |
| Beef Cows | 32,455 | 35,190 | 33,575 | 32,674 | 32,435 | 31,712 | 31,371 | 30,850 |
| Beef Replacements 7-11 months | 1,269 | 1,493 | 1,313 | 1,363 | 1,312 | 1,290 | 1,239 | 1,222 |
| Beef Replacements 12-23 months | 2,967 | 3,637 | 3,097 | 3,171 | 3,169 | 3,098 | 3,055 | 2,888 |
| Steer Stockers | 10,321 | 11,716 | 8,724 | 8,185 | 8,233 | 8,515 | 8,223 | 7,641 |
| Heifer Stockers | 5,946 | 6,699 | 5,371 | 5,015 | 4,868 | 5,059 | 5,054 | 4,786 |
| Feedlot Cattle | 9,549 | 11,064 | 13,006 | 12,652 | 13,070 | 12,953 | 13,191 | 13,548 |

The population transition matrix in the CEFM simulates the U.S. cattle population over time and provides an estimate of the population age and weight structure by cattle type on a monthly basis.[63] Since cattle often do not remain in a single population type for an entire year (e.g., calves become stockers, stockers become feedlot animals), and emission profiles vary both between and within each cattle type, these monthly age groups are tracked in the enteric fermentation model to obtain more accurate emission estimates than would be available from annual point estimates of population (such as available from USDA statistics) and weight for each cattle type.

[61] The IPCC recommends the use of a methane conversion factor of zero for calves, because they consume mainly milk; therefore, this results in no methane emissions from calves through 6 months.

[62] Additional information on the Cattle Enteric Fermentation Model can be found in ICF (2006).

[63] Mature animal populations are not assumed to have significant monthly fluctuations, and therefore the populations utilized are the January estimates downloaded from USDA (2012).

The transition matrix tracks both dairy and beef populations, and divides the populations into males and females, and subdivides the population further into specific cattle groupings for calves, replacements, stocker, feedlot, and mature animals. The matrix is based primarily on two types of data: population statistics and weight statistics (including target weights, slaughter weights, and weight gain). Using the weight data, the transition matrix simulates the growth of animals over time by month. The matrix also relies on supplementary data, such as feedlot placement statistics, slaughter statistics, death rates, and calving rates.

The basic method for tracking population of animals per category is based on the number of births (or graduates) into the monthly age group minus those animals that die or are slaughtered and those that graduate to the next category (such as stockers to feedlot placements).

Each stage in the cattle lifecycle was modeled to simulate the cattle population from birth to slaughter. This level of detail accounts for the variability in $CH_4$ emissions associated with each life stage. Given that a stage can last less than one year (e.g., calves are weaned after 6 months), each is modeled on a per-month basis. The type of cattle also impacts $CH_4$ emissions (e.g., beef versus dairy). Consequently, there is an independent transition matrix for each of three separate lifecycle phases, 1) calves, 2) replacements and stockers, and 3) feedlot animals. In addition, the number of mature cows and bulls are tabulated for both dairy and beef stock. Each lifecycle is discussed separately below, and the categories tracked are listed in Table A-167.

Table A-167: Cattle Population Categories Used for Estimating $CH_4$ Emissions

| Dairy Cattle | Beef Cattle |
|---|---|
| Calves | Calves |
| Heifer Replacements | Heifer Replacements |
| Cows | Heifer and Steer Stockers |
| | Animals in Feedlots (Heifers & Steer) |
| | Cows |
| | Bulls* |

* Bulls (beef and dairy) are accounted for in a single category.

The key variables tracked for each of these cattle population categories are as follows:

**Calves**. The number of animals born on a monthly basis was used to initiate monthly cohorts and to determine population age structure. The number of calves born each month was obtained by multiplying annual births by the percentage of births per month. Annual birth information for each year was taken from USDA (2012). For dairy cows, the number of births is assumed to be distributed equally throughout the year (approximately 8.3 percent per month), beef births are distributed according to Table A-168, based on estimates from the National Animal Health Monitoring System (NAHMS) (USDA/APHIS/VS 1998, 1994, 1993). To determine whether calves were born to dairy or beef cows, the dairy cow calving rate (USDA/APHIS/VS 2002, USDA/APHIS/VS 1996) was multiplied by the total dairy cow population to determine the number of births attributable to dairy cows, with the remainder assumed to be attributable to beef cows. Total annual calf births are obtained from USDA, and distributed into monthly cohorts by cattle type (beef or dairy). Calf growth is modeled by month, based on estimated monthly weight gain for each cohort (approximately 61 pounds per month). The total calf population is modified through time to account for veal calf slaughter at 4 months and a calf death loss of 0.35 percent annually (distributed across age cohorts up to six months of age). An example of a transition matrix for calves is shown in Table A-169. Note that calves age one through six months available in January have been tracked through the model based on births and death loss from the previous year.

Table A-168: Estimated Beef Cow Births by Month

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7% | 15% | 28% | 22% | 9% | 3% | 2% | 2% | 3% | 4% | 3% | 3% |

Table A-169: Example of Monthly Average Populations from Calf Transition Matrix (1,000 head)

| Age (month) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 1,177 | 1,169 | 1,365 | 1,616 | 1,546 | 1,540 | 2,483 | 4,680 | 8,174 | 6,612 | 3,052 | 1,500 |
| 5 | 1,170 | 1,367 | 1,616 | 1,547 | 1,540 | 2,484 | 4,681 | 8,177 | 6,615 | 3,054 | 1,501 | 1,104 |
| 4 | 1,449 | 1,691 | 1,626 | 1,609 | 2,544 | 4,750 | 8,254 | 6,692 | 3,126 | 1,572 | 1,176 | 1,167 |
| 3 | 1,692 | 1,627 | 1,609 | 2,545 | 4,752 | 8,257 | 6,695 | 3,127 | 1,573 | 1,177 | 1,168 | 1,443 |
| 2 | 1,629 | 1,610 | 2,546 | 4,754 | 8,260 | 6,697 | 3,128 | 1,573 | 1,178 | 1,168 | 1,444 | 1,682 |
| 1 | 1,612 | 2,548 | 4,756 | 8,263 | 6,699 | 3,129 | 1,574 | 1,178 | 1,169 | 1,445 | 1,684 | 1,619 |
| 0 | 2,550 | 4,760 | 8,267 | 6,702 | 3,130 | 1,574 | 1,179 | 1,169 | 1,446 | 1,685 | 1,621 | 1,602 |

**Replacements and Stockers.** At seven months of age, calves "graduate" and are separated into the applicable cattle types. First the number of replacements required for beef and dairy cattle are calculated based on estimated death losses and population changes between beginning and end of year population estimates. All steer, and remaining heifers (after subtracting required replacements), are considered "stockers," that is backgrounding animals that are eligible for placement into feedlots as they reach the appropriate weight class. During the stocker phase animals are subtracted out of the transition matrix for placement into feedlots based on feedlot placement statistics from USDA (2012).

The data and calculations that occur for the stocker category include matrices that estimate the population of backgrounding heifers and steer, as well as a matrix for total combined stockers. The matrices start with the beginning of year populations in January and model the progression of each cohort. The age structure of the January population is based on estimated births by month from the previous two years, although in order to balance the population properly, an adjustment is added that slightly reduces population percentages in the older populations. The populations are modified through addition of graduating calves (added in month 7, bottom row of Table A-170) and subtraction through death loss and animals placed in feedlots. Eventually, an entire cohort population of stockers may reach zero, indicating that the complete cohort has been transitioned into feedlots. An example of the transition matrix for stockers is shown in Table A-170.

Table A-170: Example of Monthly Average Populations from Stocker Transition Matrix (1,000 head)

| Age (month) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23 | 202 | 214 | 126 | 47 | 20 | 12 | 10 | 11 | 9 | 7 | 5 | 51 |
| 22 | 353 | 174 | 59 | 23 | 15 | 12 | 13 | 13 | 9 | 7 | 103 | 311 |
| 21 | 286 | 81 | 29 | 17 | 15 | 15 | 15 | 12 | 9 | 153 | 421 | 559 |
| 20 | 133 | 40 | 22 | 17 | 18 | 18 | 14 | 12 | 197 | 526 | 765 | 457 |
| 19 | 66 | 30 | 22 | 21 | 21 | 17 | 14 | 273 | 620 | 965 | 629 | 212 |
| 18 | 49 | 30 | 27 | 25 | 20 | 17 | 321 | 779 | 1,141 | 795 | 291 | 305 |
| 17 | 49 | 37 | 31 | 24 | 20 | 379 | 882 | 1,442 | 942 | 368 | 546 | 49 |
| 16 | 60 | 43 | 30 | 24 | 453 | 1,004 | 1,636 | 1,193 | 435 | 779 | 49 | 49 |
| 15 | 71 | 41 | 30 | 531 | 1,160 | 1,867 | 1,355 | 551 | 985 | 49 | 49 | 61 |
| 14 | 68 | 41 | 669 | 1,324 | 2,162 | 1,547 | 625 | 1,337 | 49 | 49 | 61 | 71 |
| 13 | 67 | 918 | 1,607 | 2,471 | 1,796 | 716 | 1,669 | 49 | 49 | 61 | 71 | 68 |
| 12 | 1,076 | 1,774 | 2,813 | 2,017 | 857 | 2,242 | 282 | 49 | 61 | 71 | 68 | 67 |
| 11 | 2,027 | 3,105 | 2,297 | 962 | 2,765 | 365 | 179 | 82 | 91 | 76 | 72 | 1,094 |
| 10 | 3,532 | 2,542 | 1,082 | 3,229 | 507 | 253 | 209 | 261 | 213 | 128 | 1,151 | 2,683 |
| 9 | 2,860 | 1,204 | 3,588 | 607 | 451 | 425 | 504 | 464 | 429 | 1,353 | 2,916 | 6,195 |
| 8 | 1,328 | 4,083 | 770 | 617 | 664 | 915 | 782 | 831 | 1,682 | 3,596 | 6,832 | 5,605 |
| 7 | 4,450 | 878 | 871 | 1,060 | 1,295 | 1,232 | 1,230 | 2,114 | 4,188 | 7,484 | 6,012 | 2,665 |

In order to ensure a balanced population of both stockers and placements, additional data tables are utilized in the stocker matrix calculations. The tables summarize the placement data by weight class and month, and is based on the total number of animals within the population that are available to be placed in feedlots and the actual feedlot placement statistics provided by USDA (2012). In cases where there are discrepancies between the USDA estimated placements by weight class and the calculated animals available by weight, the model pulls available stockers from one higher weight category if available. If there are still not enough animals to fulfill requirements the model pulls animals from one lower weight category. In the current time series, this method was able to ensure that total placement data matched USDA estimates, and no shortfalls have occurred.

In addition, average weights were tracked for each monthly age group using starting weight and monthly weight gain estimates. Weight gain (i.e., pounds per month) was estimated based on weight gain needed to reach a set target weight, divided by the number of months remaining before target weight was achieved. Birth weight was assumed to be 88 pounds for both beef and dairy animals. Weaning weights were estimated at 515 lbs. Other reported target weights were available for 12, 15, 24, and 36 month-old animals, depending on the animal type. Beef cow mature weight was taken from measurements provided by a major British Bos taurus breed (Enns 2008) and increased during the time series through 2007. Bull mature weight was calculated as 1.5 times the beef cow mature weight (Doren et al. 1989). Beef replacement weight was calculated as 70 percent of mature weight at 15 months and 85 percent of mature weight at 24 months. As dairy weights are not a trait that is typically tracked, mature weight for dairy cows was estimated at 1,500 for all years, based on a personal communication with Kris Johnson (2010) and an estimate from Holstein Association USA (2010). Dairy replacement weight at 15 months was assumed to be 875 lbs and 1,300 lbs at 24. Live slaughter weights were estimated from dressed slaughter weight (USDA 2012) divided by 0.63. This ratio represents the dressed weight

(i.e., weight of the carcass after removal of the internal organs), to the live weight (i.e., weight taken immediately before slaughter). The annual typical animal mass for each livestock type are presented in Table A-171.

Weight gain for stocker animals was based on monthly gain estimates from Johnson (1999) for 1989, and from average daily estimates from Lippke et al. (2000), Pinchack et al. (2004), Platter et al. (2003), and Skogerboe et al. (2000) for 2000 through 2011. Interim years were calculated linearly, as shown in Table A-172, and weight gain was held constant starting in 2000. Table A-172 provides weight gains that vary by year in the CEFM.

Table A-171: Typical Animal Mass (lbs)

| Year/Cattle Type | Dairy Cows[a] | Dairy Replacements[b] | Beef Cows[a] | Bulls[a] | Beef Replacements[b] | Steer Stockers[b] | Heifer Stockers[b] | Steer Feedlot[b] | Heifer Feedlot[b] |
|---|---|---|---|---|---|---|---|---|---|
| 1990 | 1,500 | 900 | 1,221 | 1,832 | 820 | 692 | 652 | 923 | 846 |
| 1991 | 1,500 | 898 | 1,225 | 1,838 | 822 | 695 | 656 | 975 | 867 |
| 1992 | 1,500 | 897 | 1,263 | 1,895 | 841 | 714 | 673 | 984 | 878 |
| 1993 | 1,500 | 899 | 1,280 | 1,920 | 852 | 721 | 683 | 930 | 864 |
| 1994 | 1,500 | 898 | 1,280 | 1,920 | 854 | 721 | 689 | 944 | 876 |
| 1995 | 1,500 | 898 | 1,282 | 1,923 | 858 | 735 | 701 | 947 | 880 |
| 1996 | 1,500 | 898 | 1,285 | 1,928 | 859 | 739 | 707 | 940 | 878 |
| 1997 | 1,500 | 900 | 1,286 | 1,929 | 861 | 737 | 708 | 939 | 877 |
| 1998 | 1,500 | 897 | 1,296 | 1,944 | 866 | 736 | 710 | 957 | 892 |
| 1999 | 1,500 | 899 | 1,292 | 1,938 | 862 | 731 | 709 | 960 | 895 |
| 2000 | 1,500 | 897 | 1,272 | 1,908 | 849 | 720 | 702 | 961 | 899 |
| 2001 | 1,500 | 898 | 1,272 | 1,908 | 850 | 726 | 707 | 963 | 901 |
| 2002 | 1,500 | 897 | 1,276 | 1,914 | 852 | 726 | 708 | 982 | 915 |
| 2003 | 1,500 | 900 | 1,308 | 1,962 | 872 | 719 | 702 | 973 | 905 |
| 2004 | 1,500 | 897 | 1,323 | 1,985 | 878 | 719 | 702 | 967 | 905 |
| 2005 | 1,500 | 895 | 1,327 | 1,991 | 880 | 718 | 706 | 975 | 917 |
| 2006 | 1,500 | 898 | 1,341 | 2,012 | 890 | 725 | 713 | 984 | 925 |
| 2007 | 1,500 | 897 | 1,348 | 2,022 | 895 | 721 | 707 | 992 | 928 |
| 2008 | 1,500 | 898 | 1,348 | 2,022 | 895 | 721 | 705 | 1,000 | 939 |
| 2009 | 1,500 | 897 | 1,348 | 2,022 | 895 | 731 | 715 | 1,007 | 948 |
| 2010 | 1,500 | 898 | 1,348 | 2,022 | 896 | 725 | 712 | 998 | 938 |
| 2011 | 1,500 | 899 | 1,348 | 2,022 | 893 | 723 | 713 | 991 | 933 |

[a] Input into the model.
[b] Annual average calculated in model based on age distribution.

Table A-172: Weight Gains that Vary by Year (lbs)

| Year/Cattle Type | Steer Stockers to 12 months(lbs/day) | Steer Stockers to 24 months (lbs/day) | Heifer Stockers to 12 months(lbs/day) | Heifer Stockers to 24 months(lbs/day) |
|---|---|---|---|---|
| 1990 | 1.53 | 1.23 | 1.23 | 1.08 |
| 1991 | 1.56 | 1.29 | 1.29 | 1.15 |
| 1992 | 1.59 | 1.35 | 1.35 | 1.23 |
| 1993 | 1.62 | 1.41 | 1.41 | 1.30 |
| 1994 | 1.65 | 1.47 | 1.47 | 1.38 |
| 1995 | 1.68 | 1.53 | 1.53 | 1.45 |
| 1996 | 1.71 | 1.59 | 1.59 | 1.53 |
| 1997 | 1.74 | 1.65 | 1.65 | 1.60 |
| 1998 | 1.77 | 1.71 | 1.71 | 1.68 |
| 1999 | 1.80 | 1.77 | 1.77 | 1.75 |
| 2000 onwards | 1.83 | 1.83 | 1.83 | 1.83 |

Sources: Enns (2008), Johnson (1999), Lippke et al. (2000), NRC (1999), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000).

**Feedlot Animals.** Feedlot placement statistics from USDA provide data on the placement of animals from the stocker population into feedlots on a monthly basis by weight class. The model uses these data to shift a sufficient number of animals from the stocker cohorts into the feedlot populations to match the reported placement data. After animals are placed in feedlots they progress through two steps. First, animals spend 25 days on a step-up diet to become acclimated to the new feed type, during this time weight gain is estimated to be 2.7 to 3 pounds per day (Johnson 1999). Animals are then switched to a finishing diet for a period of time before they are slaughtered. Weight gain during finishing diets is estimated to be 2.9 to 3.3 pounds per day (Johnson 1999). The length of time an animal spends in a feedlot depends on the start weight (i.e., placement weight), the rate of weight gain during the start-up and finishing phase of diet, and the target weight (as determined by weights at slaughter). Additionally, animals remaining in feedlots at the end of the year are tracked for inclusion in the following year's emission and population counts. For 1990 to 1995, only the total placement

data were available, therefore placements for each weight category (categories displayed in Table A-173) for those years are based on the average of monthly placements from the 1996 to 1998 reported figures. Placement data is available by weight class for all years from 1996 onward. Table A-173 provides a summary of the reported feedlot placement statistics for 2011.

Table A-173: Feedlot Placements in the United States for 2011 (Number of animals placed in 1,000 Head)

| Weight Placed When: | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| < 600 lbs | 460 | 400 | 380 | 445 | 415 | 460 | 620 | 715 | 685 | 840 | 750 | 550 |
| 600 – 700 lbs | 475 | 365 | 360 | 310 | 355 | 380 | 400 | 365 | 415 | 590 | 500 | 385 |
| 700 – 800 lbs | 544 | 492 | 589 | 485 | 480 | 420 | 495 | 476 | 504 | 487 | 377 | 360 |
| > 800 lbs | 410 | 410 | 585 | 545 | 560 | 435 | 620 | 690 | 865 | 575 | 410 | 378 |
| **Total** | **1,889** | **1,667** | **1,914** | **1,785** | **1,810** | **1,695** | **2,135** | **2,246** | **2,469** | **2,492** | **2,037** | **1,673** |

Source: USDA (2012).
Note: Totals may not sum due to independent rounding.

**Mature Animals.** Energy requirements and hence, composition of diets, level of intake, and emissions for particular animals, are greatly influenced by whether the animal is pregnant or lactating. Information is therefore needed on the percentage of all mature animals that are pregnant each month, as well as milk production, to estimate $CH_4$ emissions. A weighted average percent of pregnant cows each month was estimated using information on births by month and average pregnancy term. For beef cattle, a weighted average total milk production per animal per month was estimated using information on typical lactation cycles and amounts (NRC 1999), and data on births by month. This process results in a range of weighted monthly lactation estimates expressed as lbs/animal/month. The monthly estimates from January to December are 3.3, 5.1, 8.7, 12.0, 13.6, 13.3, 11.7, 9.3, 6.9, 4.4, 3.0, and 2.8 lbs milk/animal/day for beef cows. Annual estimates for dairy cows were taken from USDA milk production statistics. Dairy lactation estimates for 1990 through 2011 are shown in Table A-174. Beef and dairy cow and bull populations are assumed to remain relatively static throughout the year, as large fluctuations in population size are assumed to not occur. These estimates are taken from the USDA beginning and end of year population datasets.

Table A-174: Dairy Lactation Rates by State (lbs/ year/cow)*

| State/Year | 1990 | 1995 | 2000 | 2005 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|
| Alabama | 12,214 | 14,176 | 13,920 | 14,000 | 15,333 | 14,909 | 14,455 | 13,182 |
| Alaska | 13,300 | 17,000 | 14,500 | 12,273 | 12,000 | 10,000 | 11,833 | 13,800 |
| Arizona | 17,500 | 19,735 | 21,820 | 22,679 | 23,382 | 23,028 | 23,441 | 23,468 |
| Arkansas | 11,841 | 12,150 | 12,436 | 13,545 | 12,400 | 12,692 | 12,750 | 11,833 |
| California | 18,456 | 19,573 | 21,130 | 21,404 | 22,344 | 22,000 | 23,025 | 23,438 |
| Colorado | 17,182 | 18,687 | 21,618 | 22,577 | 22,930 | 23,081 | 23,664 | 23,430 |
| Connecticut | 15,606 | 16,438 | 17,778 | 19,200 | 19,158 | 18,579 | 19,158 | 19,000 |
| Delaware | 13,667 | 14,500 | 14,747 | 16,622 | 16,923 | 17,000 | 16,981 | 18,300 |
| Florida | 14,033 | 14,698 | 15,688 | 16,591 | 17,167 | 18,070 | 18,658 | 19,067 |
| Georgia | 12,973 | 15,550 | 16,284 | 17,259 | 17,829 | 18,182 | 17,671 | 18,354 |
| Hawaii | 13,604 | 13,654 | 14,358 | 12,889 | 10,882 | 14,200 | 13,316 | 14,421 |
| Idaho | 16,475 | 18,147 | 20,816 | 22,332 | 22,432 | 22,091 | 22,658 | 22,934 |
| Illinois | 14,707 | 15,887 | 17,450 | 18,827 | 18,569 | 18,873 | 19,170 | 19,357 |
| Indiana | 14,590 | 15,375 | 16,568 | 20,295 | 19,683 | 20,137 | 20,094 | 20,576 |
| Iowa | 15,118 | 16,124 | 18,298 | 20,641 | 19,995 | 20,367 | 20,724 | 21,309 |
| Kansas | 12,576 | 14,390 | 16,923 | 20,505 | 20,641 | 21,085 | 20,975 | 21,057 |
| Kentucky | 10,947 | 12,469 | 12,841 | 12,896 | 13,444 | 14,190 | 14,769 | 14,303 |
| Louisiana | 11,605 | 11,908 | 12,034 | 12,400 | 12,269 | 11,870 | 11,750 | 12,889 |
| Maine | 14,619 | 16,025 | 17,128 | 18,030 | 18,273 | 18,061 | 18,344 | 18,688 |
| Maryland | 13,461 | 14,725 | 16,083 | 16,099 | 18,375 | 18,255 | 18,537 | 18,654 |
| Massachusetts | 14,871 | 16,000 | 17,091 | 17,059 | 16,933 | 17,571 | 17,286 | 16,923 |
| Michigan | 15,394 | 17,071 | 19,017 | 21,635 | 22,180 | 22,445 | 23,277 | 23,164 |
| Minnesota | 14,127 | 15,894 | 17,777 | 18,091 | 18,927 | 19,230 | 19,366 | 18,996 |
| Mississippi | 12,081 | 12,909 | 15,028 | 15,280 | 14,550 | 13,889 | 13,118 | 14,571 |
| Missouri | 13,632 | 14,158 | 14,662 | 16,026 | 14,682 | 14,654 | 14,596 | 14,611 |
| Montana | 13,542 | 15,000 | 17,789 | 19,579 | 18,412 | 19,933 | 20,643 | 20,571 |
| Nebraska | 13,866 | 14,797 | 16,513 | 17,950 | 18,672 | 19,672 | 19,797 | 20,579 |
| Nevada | 16,400 | 18,128 | 19,000 | 21,680 | 20,704 | 21,821 | 23,500 | 22,897 |
| New Hampshire | 15,100 | 16,300 | 17,333 | 18,875 | 19,933 | 19,533 | 19,600 | 20,429 |
| New Jersey | 13,538 | 13,913 | 15,250 | 16,000 | 16,900 | 17,889 | 17,500 | 17,000 |
| New Mexico | 18,815 | 18,969 | 20,944 | 21,192 | 23,269 | 24,320 | 24,551 | 24,854 |
| New York | 14,658 | 16,501 | 17,378 | 18,639 | 19,859 | 20,071 | 20,807 | 21,026 |
| North Carolina | 15,220 | 16,314 | 16,746 | 18,741 | 18,979 | 19,644 | 19,636 | 20,044 |
| North Dakota | 12,624 | 13,094 | 14,292 | 14,182 | 16,077 | 16,739 | 18,286 | 18,105 |
| Ohio | 13,767 | 15,917 | 17,027 | 17,567 | 18,321 | 18,744 | 19,446 | 19,187 |
| Oklahoma | 12,327 | 13,611 | 14,440 | 16,480 | 16,578 | 16,983 | 17,125 | 17,491 |
| Oregon | 16,273 | 17,289 | 18,222 | 18,876 | 19,772 | 19,719 | 20,331 | 20,488 |
| Pennsylvania | 14,726 | 16,492 | 18,081 | 18,722 | 19,262 | 19,360 | 19,847 | 19,601 |
| Rhode Island | 14,250 | 14,773 | 15,667 | 17,000 | 18,091 | 17,818 | 17,727 | 17,909 |
| South Carolina | 12,771 | 14,481 | 16,087 | 16,000 | 17,889 | 19,000 | 17,875 | 17,375 |
| South Dakota | 12,257 | 13,398 | 15,516 | 17,741 | 19,956 | 20,128 | 20,478 | 20,549 |
| Tennessee | 11,825 | 13,740 | 14,789 | 15,743 | 16,068 | 16,232 | 16,346 | 16,200 |
| Texas | 14,350 | 15,244 | 16,503 | 19,646 | 20,134 | 20,898 | 21,375 | 22,232 |
| Utah | 15,838 | 16,739 | 17,573 | 18,875 | 20,894 | 21,036 | 21,400 | 21,068 |
| Vermont | 14,528 | 16,210 | 17,199 | 18,469 | 18,400 | 18,289 | 18,537 | 18,940 |
| Virginia | 14,213 | 15,116 | 15,833 | 16,990 | 17,612 | 18,083 | 18,095 | 17,906 |
| Washington | 18,532 | 20,091 | 22,644 | 23,270 | 23,344 | 23,171 | 23,510 | 23,727 |
| West Virginia | 11,250 | 12,667 | 15,588 | 14,923 | 15,083 | 14,727 | 15,700 | 15,600 |
| Wisconsin | 13,973 | 15,397 | 17,306 | 18,500 | 19,546 | 20,079 | 20,630 | 20,646 |
| Wyoming | 12,337 | 13,197 | 13,571 | 14,878 | 19,386 | 19,036 | 20,067 | 20,517 |

Source: USDA (2012).
* Beef lactation data shown in text above.

**Step 2: Characterize U.S. Cattle Population Diets**

To support development of digestible energy (DE, the percent of gross energy intake digested by the animal) and $CH_4$ conversion rate ($Y_m$, the fraction of gross energy converted to $CH_4$) values for each of the cattle population categories, data were collected on diets considered representative of different regions. For both grazing animals and animals being fed mixed rations, representative regional diets were estimated using information collected from state livestock specialists, the United States Department of Agriculture, expert opinion, and other literature sources. The designated regions for this analysis for dairy cattle for all years and foraging beef cattle from 1990 through 2006 are shown in Table A-175. For

foraging beef cattle from 2007 onwards, the regional designations were revised based on data available from theNAHMS 2007-2008 survey on cow-calf system management practices (USDA 2010) and are shown in and Table A-176. The data for each of the diets (e.g., proportions of different feed constituents, such as hay or grains) were used to determine feed chemical composition for use in estimating DE and $Y_m$ for each animal type.

Table A-175: Regions used for Dairy Cattle (all years) and Foraging Cattle from 1990-2006

| West | California | Northern Great Plains | Midwestern | Northeast | Southcentral | Southeast |
|---|---|---|---|---|---|---|
| Alaska | California | Colorado | Illinois | Connecticut | Arkansas | Alabama |
| Arizona | | Kansas | Indiana | Delaware | Louisiana | Florida |
| Hawaii | | Montana | Iowa | Maine | Oklahoma | Georgia |
| Idaho | | Nebraska | Michigan | Maryland | Texas | Kentucky |
| Nevada | | North Dakota | Minnesota | Massachusetts | | Mississippi |
| New Mexico | | South Dakota | Missouri | New Hampshire | | North Carolina |
| Oregon | | Wyoming | Ohio | New Jersey | | South Carolina |
| Utah | | | Wisconsin | New York | | Tennessee |
| Washington | | | | Pennsylvania | | Virginia |
| | | | | Rhode Island | | |
| | | | | Vermont | | |
| | | | | West Virginia | | |

Source: USDA (1996).

Table A-176: Regions used for Foraging Cattle from 2007-2011

| West | Central | Northeast | Southeast |
|---|---|---|---|
| Alaska | Illinois | Connecticut | Alabama |
| Arizona | Indiana | Delaware | **Arkansas** |
| **California** | Iowa | Maine | Florida |
| **Colorado** | **Kansas** | Maryland | Georgia |
| Hawaii | Michigan | Massachusetts | Kentucky |
| Idaho | Minnesota | New Hampshire | **Louisiana** |
| **Montana** | Missouri | New Jersey | Mississippi |
| Nevada | **Nebraska** | New York | North Carolina |
| New Mexico | **North Dakota** | Pennsylvania | **Oklahoma** |
| Oregon | Ohio | Rhode Island | South Carolina |
| Utah | **South Dakota** | Vermont | Tennessee |
| Washington | Wisconsin | West Virginia | **Texas** |
| **Wyoming** | | | Virginia |

Source: Based on data from USDA (2010).
Note: States in **bold** represent a change in region.

DE and $Y_m$ vary by diet and animal type. The IPCC recommends $Y_m$ values of 3.0±1.0 percent for feedlot cattle and 6.5±1.0 percent for all other cattle (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, DE and $Y_m$ values unique to the United States were developed for dairy and beef cattle. Digestible energy and $Y_m$ values were estimated across the time series for each cattle population category based on physiological modeling, published values, and/or expert opinion.

For dairy cows, ruminant digestion models were used to estimate $Y_m$. The three major categories of input required by the models are animal description (e.g., cattle type, mature weight), animal performance (e.g., initial and final weight, age at start of period), and feed characteristics (e.g., chemical composition, habitat, grain or forage). Data used to simulate ruminant digestion is provided for a particular animal that is then used to represent a group of animals with similar characteristics. The $Y_m$ values were estimated for 1990 using the Donovan and Baldwin model (1999) that represents physiological processes in the ruminant animals and diet characteristics from USDA (1996). The Donovan and Baldwin model accounts for differing diets (i.e., grain-based or forage-based), so that $Y_m$ values for the variable feeding characteristics within the U.S. cattle population can be estimated. Subsequently, a literature review of dairy diets was conducted and nearly 250 diets were analyzed from 1990 through 2009 across 23 states. Kebreab et al. (2008) conducted an evaluation of models and found that the COWPOLL model was the best model for estimating $Y_m$ for dairy. Therefore, the COWPOLL model was used to estimate $Y_m$ values for each of the diets. Due to the high variability associated with cattle diets from the literature, a function based on the national trend observed from the analysis of the dairy diets was used to calculate 1991 and beyond regional values based on the regional 1990 $Y_m$ values from Donovan and Baldwin. The resulting scaling factor is shown below:

$$Y_m = Y_m(1990)\,EXP\left(\frac{1.22}{(1990-1980)}\right)\left(\frac{1.22}{(Year-1980)}\right)$$

DE values for dairy cows were estimated from the literature search based on the annual trends observed in the data collection effort. The regional variability observed in the literature search was not statistically significant, and therefore DE was not varied by region, but did vary over time, and was grouped by the following years 1990-1993, 1994-1998, 1999-2002[64], 2004-2006, 2007, and 2008 onwards.

Considerably less data was available for dairy heifers, so assumptions were based on the relationship of the collected data literature on dairy heifers to the data on dairy cow diets. From this relationship, DE was estimated as the mature cow DE minus three percent, and $Y_m$ was estimated as that of the mature dairy cow plus 0.1 percent.

To calculate the DE values for grazing beef cattle, diet composition assumptions were used to estimate weighted DE values for a combination of forage and supplemental diets. The forage portion makes up an estimated 85 to 95 percent of grazing beef cattle diets, and there is considerable variation of both forage type and quality across the US. Currently there is no comprehensive survey of this data, so for this analysis two regional DE values were developed to account for the generally lower forage quality in the western United States. For all non-western grazing cattle, the forage DE was an average of the estimated seasonal values for grass pasture diets for a calculated DE of 66.4 percent. For foraging cattle in the west, the forage DE was calculated as the seasonal average for grass pasture, meadow and range diets, for a calculated DE of 61.4 percent. The assumed specific components of each of the broad forage types, along with their corresponding DE value and the calculated regional DE values can be found in Table A-177. In addition, it was assumed that each region fed a supplemental diet, and two sets of supplemental diets were developed, one for 1990 through 2006 (Donovan 1999) and one for 2007 onwards (Preston 2010, Archibeque 2011, USDA 2010) as shown in Table A-178 and Table A-179 along with the percent of each total diet that is assumed to be made up of the supplemental portion. By weighting the calculated DE values from the forage and supplemental diets, the DE values for the composite diet were calculated.[65] These values are used for steer and heifer stockers and beef replacements. Finally, for mature beef cows and bulls, the DE value was adjusted downward by two percent to reflect the lower digestibility diets of mature cattle based on Johnson (2002). $Y_m$ values for all grazing beef cattle were set at 6.5 percent based on Johnson (2002). The $Y_m$ values and the resulting final weighted DE values by region for 2007 onwards are shown in Table A-180.

For feedlot animals, DE and $Y_m$ are adjusted over time as diet compositions in actual feedlots are adjusted based on new and improved nutritional information and availability of feed types. Feedlot diets are assumed to not differ significantly by state, and therefore only a single set of national diet values is utilized for each year. The DE and $Y_m$ values for 1990 were estimated by Dr. Don Johnson (1999). In the CEFM, the DE values for 1991 through 1999 were linearly extrapolated based on values for 1990 and 2000. DE and $Y_m$ values from 2000 through the current year were estimated using the MOLLY model as described in Kebreab et al. (2008), based on a series of average diet feed compositions from Galyean and Gleghorn (2001) for 2000 through 2006 and Vasconcelos and Galyean (2007) for 2007 onwards. In addition, feedlot animals are assumed to spend the first 25 days in the feedlot on a "step-up" diet to become accustomed to the higher quality feedlot diets. The step-up DE and $Y_m$ are calculated as the average of all state forage and feedlot diet DE and $Y_m$ values.

Table A-181 shows the regional DE and $Y_m$ for U.S. cattle in each region for 2011.

Table A-177: Feed Components assumed for Forage Diets

| Forage Type | DE, (% of GE) | Grass pasture - Spring | Grass pasture - Summer | Grass pasture - Fall | Range June | Range July | Range August | Range September | Range Winter | Meadow - Spring | Meadow - Fall |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bahiagrass Paspalum notatum, fresh | 61.38 | | | x | | | | | | | |
| Bermudagrass Cynodon dactylon, fresh | 66.29 | | x | | | | | | | | |
| Bremudagrass, Coastal Cynodon dactylon, fresh | 65.53 | | x | | | | | | | | |
| Bluegrass, Canada Poa compressa, fresh, early vegetative | 73.99 | x | | | | | | | | | |

[64] Due to inconsistencies in the 2003 literature values, the 2002 values were extended to include 2003 as well.

[65] For example, the West has a forage DE of 61.4 which makes up 90 percent of the diet and a supplemented diet DE of 67.4 percent was used for 10 percent of the diet, for a total weighted DE of 61.9 percent, as shown in Table A-180.

| Forage Type | DE, (% of GE) | Grass pasture - Spring | Grass pasture - Summer | Grass pasture - Fall | Range June | Range July | Range August | Range September | Range Winter | Meadow - Spring | Meadow - Fall |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Bluegrass, Kentucky Poa pratensis, fresh, early vegetative | 75.62 | x | | | | | | | | | |
| Bluegrass, Kentucky Poa pratensis, fresh, mature | 59.00 | | x | x | | | | | | | |
| Bluestem Andropagon spp, fresh, early vegetative | 73.17 | | | | x | | | | | | |
| Bluestem Andropagon spp, fresh, mature | 56.82 | | | | | x | x | x | x | | x |
| Brome Bromus spp, fresh, early vegetative | 78.57 | x | | | | | | | | | |
| Brome, Smooth Bromus inermis, fresh, early vegetative | 75.71 | x | | | | | | | | | |
| Brome, Smooth Bromus inermis, fresh, mature | 57.58 | | x | x | | | | | x | | |
| Buffalograss, Buchloe dactyloides, fresh | 64.02 | | | | x | x | | | | | |
| Clover, Alsike Trifolium hybridum, fresh, early vegetative | 70.62 | x | | | | | | | | | |
| Clover, Ladino Trifolium repens, fresh, early vegetative | 73.22 | x | | | | | | | | | |
| Clover, Red Trifolium pratense, fresh, early bloom | 71.27 | x | | | | | | | | | |
| Clover, Red Trifolium pratense, fresh, full bloom | 67.44 | | x | | x | | | | | | |
| Corn, Dent Yellow Zea mays indentata, aerial part without ears, without husks, sun-cured, (stover)(straw) | 55.28 | | | x | | | | | | | |
| Dropseed, Sand Sporobolus cryptandrus, fresh, stem cured | 64.69 | | | | x | x | x | | | x | |
| Fescue Festuca spp, hay, sun-cured, early vegetative | 67.39 | x | | | | | | | | | |
| Fescue Festuca spp, hay, sun-cured, early bloom | 53.57 | | | x | | | | | | | |
| Grama Bouteloua spp, fresh, early vegetative | 67.02 | x | | | | | | | | | |
| Grama Bouteloua spp, fresh, mature | 63.38 | | x | x | | | | | | x | |
| Millet, Foxtail Setaria italica, fresh | 68.20 | x | | | x | | | | | | |
| Napiergrass Pennisetum purpureum, fresh, late bloom | 57.24 | | x | x | | | | | | | |
| Needleandthread Stipa comata, fresh, stem cured | 60.36 | | | | | x | x | x | | | |
| Orchardgrass Dactylis glomerata, fresh, early vegetative | 75.54 | x | | | | | | | | | |
| Orchardgrass Dactylis glomerata, fresh, midbloom | 60.13 | | x | | | | | | | | |
| Pearlmillet Pennisetum glaucum, fresh | 68.04 | x | | | | | | | | | |
| Prairie plants, Midwest, hay, sun-cured | 55.53 | | | x | | | | | | | x |
| Rape Brassica napus, fresh, early bloom | 80.88 | x | | | | | | | | | |
| Rye Secale cereale, fresh | 71.83 | x | | | | | | | | | |
| Ryegrass, Perennial Lolium perenne, fresh | 73.68 | x | | | | | | | | | |
| Saltgrass Distichlis spp, fresh, post ripe | 58.06 | | x | x | | | | | | | |
| Sorghum, Sudangrass Sorghum bicolor sudanense, fresh, early vegetative | 73.27 | x | | | | | | | | | |
| Squirreltail Stanion spp, fresh, stem-cured | 62.00 | | x | | | x | | | | | |
| Summercypress, Gray Kochia vestita, fresh, stem-cured | 65.11 | | | x | x | x | | | | | |
| Timothy Phleum pratense, fresh, late vegetative | 73.12 | x | | | | | | | | | |
| Timothy Phleum pratense, fresh, midbloom | 66.87 | | x | | | | | | | | |
| Trefoil, Birdsfoot Lotus corniculatus, fresh | 69.07 | x | | | | | | | | | |
| Vetch Vicia spp, hay, sun-cured | 59.44 | | | x | | | | | | | |
| Wheat Triticum aestivum, straw | 45.77 | | | x | | | | | | | |
| Wheatgrass, Crested Agropyron desertorum, fresh, early vegetative | 79.78 | x | | | | | | | | | |
| Wheatgrass, Crested Agropyron desertorum, fresh, full bloom | 65.89 | | x | | | x | | | | | |
| Wheatgrass, Crested Agropyron desertorum, fresh, post ripe | 52.99 | | | x | | | | | x | | x |
| Winterfat, Common Eurotia lanata, fresh, stem-cured | 40.89 | | | | | | | | x | | |
| **Weighted Average DE** | | **72.99** | **62.45** | **57.26** | **67.11** | **62.70** | **60.62** | **58.59** | **52.07** | **64.03** | **55.11** |
| **Forage Diet for West** | **61.4** | **10%** | **10%** | **10%** | **10%** | **10%** | **10%** | **10%** | **10%** | **10%** | **10%** |
| **Forage Diet for All Other Regions** | **66.4** | **33.3%** | **33.3%** | **33.3%** | **-** | **-** | **-** | **-** | **-** | **-** | **-** |

| Forage Type | DE, (% of GE) | Grass pasture - Spring | Grass pasture - Summer | Grass pasture - Fall | Range June | Range July | Range August | Range September | Range Winter | Meadow - Spring | Meadow - Fall |
|---|---|---|---|---|---|---|---|---|---|---|---|

Sources: Preston (2010) and Archibeque (2011).

Table A-178: DE Values with Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 1990-2006

| Feed | Source of DE (NRC 1984) | Unweighted DE (% of GE) | California* | West | Northern Great Plains | Southcentral | Northeast | Midwest | Southeast |
|---|---|---|---|---|---|---|---|---|---|
| Alfalfa Hay | Table 8, feed #006 | 61.79 | 65% | 30% | 30% | 29% | 12% | 30% | |
| Barley | | 85.08 | 10% | 15% | | | | | |
| Bermuda | Table 8, feed #030 | 66.29 | | | | | | | 35% |
| Bermuda Hay | Table 8, feed #031 | 50.79 | | | | 40% | | | |
| Corn | Table 8, feed #089 | 88.85 | 10% | 10% | 25% | 11% | 13% | 13% | |
| Corn Silage | Table 8, feed #095 | 72.88 | | | 25% | | 20% | 20% | |
| Cotton Seed Meal | | | | | | 7% | | | |
| Grass Hay | Table 8, feed #126, 170, 274 | 58.37 | | 40% | | | | 30% | |
| Orchard | Table 8, feed #147 | 60.13 | | | | | | | 40% |
| Soybean Meal Supplement | | 77.15 | | 5% | 5% | | | | 5% |
| Sorghum | Table 8, feed #211 | 84.23 | | | | | | | 20% |
| Soybean Hulls | | 66.86 | | | | | | 7% | |
| Timothy Hay | Table 8, feed #244 | 60.51 | | | | | 50% | | |
| Whole Cotton Seed | | 75.75 | 5% | | | | 5% | | |
| Wheat Middlings | Table 8, feed #257 | 68.09 | | | 15% | 13% | | | |
| Wheat | Table 8, feed #259 | 87.95 | 10% | | | | | | |
| **Weighted Total DE (%)** | | | **70.1** | **67.4** | **73.0** | **62.0** | **67.6** | **66.9** | **68.0** |
| **Percent of Diet that is Supplement** | | | **5%** | **10%** | **15%** | **10%** | **15%** | **10%** | **5%** |

Source of representative regional diets: Donovan (1999).

* Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above.

Table A-179: DE Values and Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 2007-2011

| Feed | Source of DE (NRC1984) | Unweighted DE (% of GE) | West | Central | Northeast | Southeast |
|---|---|---|---|---|---|---|
| Alfalfa Hay | Table 8, feed #006 | 61.79 | 65% | 30% | 12% | |
| Bermuda | Table 8, feed #030 | 66.29 | | | | 20% |
| Bermuda Hay | Table 8, feed #031 | 50.79 | | | | 20% |
| Corn | Table 8, feed #089 | 88.85 | 10% | 15% | 13% | 10% |
| Corn Silage | Table 8, feed #095 | 72.88 | | 35% | 20% | |
| Grass Hay | Table 8, feed #126, 170, 274 | 58.37 | 10% | | | |
| Orchard | Table 8, feed #147 | 60.13 | | | | 30% |
| Protein supplement (West) | Table 8, feed #082, 134, 225 [b] | 81.01 | 10% | | | |
| Protein Supplement (Central and Northeast) | Table 8, feed #082, 134, 225 [b] | 80.76 | | 10% | 10% | |
| Protein Supplement (Southeast) | Table 8, feed #082, 134, 101 [b] | 77.89 | | | | 10% |
| Sorghum | Table 8, feed #211 | 84.23 | | 5% | | 10% |
| Timothy Hay | Table 8, feed #244 | 60.51 | | | 45% | |
| Wheat Middlings | Table 8, feed #257 | 68.09 | | 5% | | |
| Wheat | Table 8, feed #259 | 87.95 | 5% | | | |
| **Weighted Total DE** | | | **67.4** | **73.1** | **68.9** | **66.6** |
| **Percent of Diet that is Supplement** | | | **10%** | **15%** | **5%** | **15%** |

Sources of representative regional diets: Donovan (1999), Preston (2010), Archibeque (2011), and USDA (2010).

[a] Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above.

[b] Not in equal proportions.

Table A-180: Foraging Animal DE (% of GE) and $Y_m$ Values for Each Region and Animal Type for 2007-2011

| Animal Type | Data | West[c] | Central | Northeast | Southeast |
|---|---|---|---|---|---|
| Beef Repl. Heif. | DE[a] | 61.9 | 65.6 | 64.5 | 64.6 |
| | $Y_m$[b] | 6.5% | 6.5% | 6.5% | 6.5% |
| Steer Stockers | DE | 61.9 | 65.6 | 64.5 | 64.6 |
| | $Y_m$ | 6.5% | 6.5% | 6.5% | 6.5% |
| Heifer Stockers | DE | 61.9 | 65.6 | 64.5 | 64.6 |
| | $Y_m$ | 6.5% | 6.5% | 6.5% | 6.5% |
| Beef Cows | DE | 59.9 | 63.6 | 62.5 | 62.6 |
| | $Y_m$ | 6.5% | 6.5% | 6.5% | 6.5% |
| Bulls | DE | 59.9 | 63.6 | 62.5 | 62.6 |
| | $Y_m$ | 6.5% | 6.5% | 6.5% | 6.5% |

[a] DE is the digestible energy in units of percent of GE (MJ/Day).
[b] $Y_m$ is the methane conversion rate, the fraction of GE in feed converted to methane.
[c] Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above. To see the regional designation per state, please see Table A-176.

Table A-181: Regional DE (% of GE) and $Y_m$ Rates for Non-Foraging Cattle by Animal Type for 2011

| Animal Type | Data | California[c] | West | Northern Great Plains | Southcentral | Northeast | Midwest | Southeast |
|---|---|---|---|---|---|---|---|---|
| DairyRepl. Heif. | DE[a] | 63.7 | 63.7 | 63.7 | 63.7 | 63.7 | 63.7 | 63.7 |
| | Ym[b] | 6.0% | 6.0% | 5.7% | 6.5% | 6.4% | 5.7% | 7.0% |
| Dairy Cows | DE | 66.7 | 66.7 | 66.7 | 66.7 | 66.7 | 66.7 | 66.7 |
| | Ym | 5.9% | 5.9% | 5.6% | 6.4% | 6.3% | 5.6% | 6.9% |
| Steer Feedlot | DE | 82.5 | 82.5 | 82.5 | 82.5 | 82.5 | 82.5 | 82.5 |
| | Ym | 3.9% | 3.9% | 3.9% | 3.9% | 3.9% | 3.9% | 3.9% |
| Heifer Feedlot | DE | 82.5 | 82.5 | 82.5 | 82.5 | 82.5 | 82.5 | 82.5 |
| | Ym | 3.9% | 3.9% | 3.9% | 3.9% | 3.9% | 3.9% | 3.9% |

[a] DE is the digestible energy in units of percent of GE (MJ/Day).
[b] $Y_m$ is the methane conversion rate, the fraction of GE in feed converted to methane.
[c] Note that emissions are currently calculated on a state-by-state basis, but diets are applied Table A-175 by the regions shown in the table above. To see the regional designation for foraging cattle per state, please see Table A-175.

**Step 3: Estimate $CH_4$ Emissions from Cattle**

Emissions by state were estimated in three steps: a) determine gross energy (GE) intake using the Tier 2 IPCC (2006) equations, b) determine an emission factor using the GE values, $Y_m$ and a conversion factor, and c) sum the daily emissions for each animal type. Finally, the state emissions were aggregated to obtain the national emissions estimate. The necessary data values for each state and animal type include:

- Body Weight (kg)
- Weight Gain (kg/day)
- Net Energy for Activity ($C_a$, MJ/day)[66]
- Standard Reference Weight (kg)[67]
- Milk Production (kg/day)
- Milk Fat (percent of fat in milk = 4)
- Pregnancy (percent of population that is pregnant)
- DE (percent of GE intake digestible)
- $Y_m$ (the fraction of GE converted to $CH_4$)
- Population

[66] Zero for feedlot conditions, 0.17 for high quality confined pasture conditions, and 0.36 for extensive open range or hilly terrain grazing conditions. $C_a$ factor for dairy cows is weighted to account for the fraction of the population in the region that grazes during the year (IPCC 2006).

[67] Standard Reference Weight is the mature weight of a female animal of the animal type being estimated, used in the model to account for breed potential.

***Step 3a: Determine Gross Energy, GE***

As shown in the following equation, GE is derived based on the net energy estimates and the feed characteristics. Only variables relevant to each animal category are used (e.g., estimates for feedlot animals do not require the $NE_l$ factor). All net energy equations are provided in IPCC (2006).

$$GE = \left[ \frac{\left( \frac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM} \right) + \left( \frac{NE_g}{REG} \right)}{\frac{DE\%}{100}} \right]$$

Where,

| | |
|---|---|
| GE | = Gross energy (MJ/day) |
| $NE_m$ | = Net energy required by the animal for maintenance (MJ/day) |
| $NE_a$ | = Net energy for animal activity (MJ/day) |
| $NE_l$ | = Net energy for lactation (MJ/day) |
| $NE_{work}$ | = Net energy for work (MJ/day) |
| $NE_p$ | = Net energy required for pregnancy (MJ/day) |
| REM | = Ratio of net energy available in a diet for maintenance to digestible energy consumed |
| $NE_g$ | = Net energy needed for growth (MJ/day) |
| REG | = Ratio of net energy available for growth in a diet to digestible energy consumed |
| DE | = Digestible energy expressed as a percent of gross energy (percent) |

***Step 3b: Determine Emission Factor***

The daily emission factor (DayEmit) was determined using the GE value and the methane conversion factor ($Y_m$) for each category. This relationship is shown in the following equation:

$$DayEmit = \frac{GE \times Y_m}{55.65}$$

Where,

| | |
|---|---|
| DayEmit | = Emission factor (kg $CH_4$/head/day) |
| GE | = Gross energy intake (MJ/head/day) |
| $Y_m$ | = $CH_4$ conversion rate, which is the fraction of GE in feed converted to $CH_4$ (%) |
| 55.65 | = A factor for the energy content of methane (MJ/kg $CH_4$) |

The daily emission factors were estimated for each animal type and state, calculated annual national emission factors are shown by animal type in Table A-182.

Table A-182: Calculated Annual National Emission Factors for Cattle by Animal Type (kg $CH_4$/head/year)

| Cattle Type | 1990 | 1995 | 2000 | 2005 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|
| **Dairy** | | | | | | | | |
| Cows | 124 | 125 | 132 | 133 | 139 | 140 | 142 | 142 |
| Replacements 7-11 months | 48 | 46 | 46 | 45 | 46 | 46 | 46 | 46 |
| Replacements 12-23 months | 73 | 69 | 70 | 67 | 70 | 70 | 69 | 69 |
| **Beef** | | | | | | | | |
| Bulls | 91 | 94 | 94 | 97 | 98 | 98 | 98 | 98 |
| Cows | 89 | 92 | 91 | 94 | 95 | 95 | 95 | 95 |
| Replacements 7-11 months | 54 | 57 | 56 | 59 | 60 | 60 | 60 | 60 |
| Replacements 12-23 months | 63 | 66 | 66 | 68 | 70 | 70 | 70 | 70 |
| Steer Stockers | 55 | 57 | 58 | 58 | 58 | 58 | 58 | 58 |
| Heifer Stockers | 52 | 56 | 60 | 60 | 60 | 60 | 60 | 60 |
| Feedlot Cattle | 39 | 38 | 39 | 39 | 42 | 43 | 42 | 42 |

Note: To convert to a daily emission factor, the yearly emission factor can be divided by 365 (the number of days in a year).

For quality assurance purposes, 2010 U.S. emission factors for each animal type were compared to estimates provided by the other Annex I member countries of the United Nations Framework Convention on Climate Change (UNFCCC). Results, presented in Table A-183 indicate that U.S. emission factors are comparable to those of other Annex I countries.

Table A-183: **Annex I Countries' 2010** Emission Factors for Cattle by Animal Type (kg $CH_4$/head/year)

| Cattle Type | United States | *Median* of Annex I countries (excluding U.S.) | *Mean* of Annex I countries (excluding U.S.) |
|---|---|---|---|
| **Dairy** | 115 | 115 | 111 |
| **Beef** | 56 | 56 | 52 |

***Step 3c: Estimate Total Emissions***

Emissions were summed for each month and for each state population category using the daily emission factor for a representative animal and the number of animals in the category. The following equation was used:

$$\text{Emissions}_{state} = \text{DayEmit}_{state} \times \text{Days/Month} \times \text{SubPop}_{state}$$

Where,

$\text{Emissions}_{state}$ = Emissions for state (kg $CH_4$)
$\text{DayEmit}_{state}$ = Emission factor for the subcategory and state (kg $CH_4$/head/day)
Days/Month = Number of days in the month
$\text{SubPop}_{state}$ = Number of animals in the subcategory and state during the month

This process was repeated for each month, and the totals for each state subcategory were summed to achieve an emission estimate for a state for the entire year and state estimates were summed to obtain the national total. The estimates for each of the 10 subcategories of cattle are listed in Table A-184. The emissions for each subcategory were then aggregated to estimate total emissions from beef cattle and dairy cattle for the entire year.

Table A-184: $CH_4$ Emissions from Cattle (Gg)

| Cattle Type | 1990 | 1995 | 2000 | 2005 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|
| **Dairy** | **1,513** | **1,440** | **1,460** | **1,449** | **1,564** | **1,581** | **1,569** | **1,585** |
| Cows | 1,242 | 1,183 | 1,209 | 1,197 | 1,289 | 1,304 | 1,287 | 1,301 |
| Replacements 7-11 months | 58 | 56 | 55 | 56 | 60 | 61 | 62 | 62 |
| Replacements 12-23 months | 212 | 201 | 196 | 196 | 216 | 216 | 221 | 222 |
| **Beef** | **4,581** | **5,226** | **4,884** | **4,829** | **4,909** | **4,857** | **4,810** | **4,705** |
| Bulls | 196 | 225 | 215 | 214 | 216 | 214 | 214 | 211 |
| Cows | 2,884 | 3,222 | 3,058 | 3,056 | 3,066 | 2,998 | 2,965 | 2,916 |
| Replacements 7-11 months | 69 | 85 | 74 | 80 | 79 | 78 | 75 | 73 |
| Replacements 12-23 months | 188 | 241 | 204 | 217 | 221 | 216 | 213 | 201 |
| Steer Stockers | 563 | 662 | 509 | 473 | 480 | 496 | 480 | 445 |
| Heifer Stockers | 306 | 375 | 323 | 299 | 293 | 304 | 305 | 288 |
| Feedlot Cattle | 375 | 416 | 502 | 488 | 554 | 552 | 559 | 571 |
| **Total** | **6,093** | **6,665** | **6,344** | **6,277** | **6,473** | **6,438** | **6,380** | **6,290** |

Notes: Totals may not sum due to independent rounding. Because calves 6 months and under months consume mainly milk the IPCC recommends the use of methane conversion factor of zero, resulting in no methane emissions from this subcategory of cattle.

## Emission Estimates from Other Livestock

All livestock population data, except for horses and American bison for years prior to 2002, were taken from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) agricultural statistics database (USDA 2012) or earlier census data (USDA 1992, 1997). The Manure Management Annex discusses the methods for obtaining annual average populations and shows the resulting data for horses, sheep, swine, and goats that were used for estimating all livestock-related emissions (See Table A- 189). For each animal category, the USDA publishes monthly, annual, or multi-year livestock population and production estimates. All data were downloaded from the USDA-NASS agricultural database (USDA 2012) or taken from older census reports (USDA 1992, 1997). The Food and Agriculture Organization (FAO) publishes annual horse population data. These data were accessed from the FAOSTAT database (FAO 2012).

The American bison population data was collected and estimated from a variety of sources. Population was collected as part of USDA's Census of Agriculture (USDA 2012), which provided American bison population data for 2002 and 2007. American bison populations for 1997 through1999 were provided by a survey from the National Bison Association (1999). For 1990 through 1996 populations were derived by estimating the totals from the "Historic and Current Bison Populations" graph in the National Bison Association (1999) report and holding the smaller populations constant (e.g., zoos, overseas animals, public herds in the United States and Canada, and U.S. Native American herds) and applying proportions from 1997 to the totals for the historic years to separate the U.S. and Canadian private herds. For 2000 and 2001, as well as 2003 through 2006, populations were interpolated between the known estimates. For 2008 through 2011, the American bison population was calculated based on USDA bison slaughter data (USDA 2012) and scaled from the 2007 Census of Agriculture population estimate.

Population data for mules, burros, and donkeys was available for 1987, 1992, 1997, 2002, and 2007 from USDA's Census of Agriculture (USDA 1992, 1997, 2012). For all non-reported years between 1987 and 2007, population estimates were linearly interpolated between each reported year. For 2007 through 2011, populations were held constant.

Methane emissions from sheep, goats, swine, horses, mules, burros, and donkeys were estimated by multiplying national population estimates by the default IPCC emission factor (IPCC 2006). For American bison the emission factor for buffalo (IPCC 2006) was used and adjusted based on the ratio of live weights of 300 kg for buffalo (IPCC 2006) and 1,130 pounds (513 kg) for American Bison (National Bison Association 2011) to the 0.75 power. This methodology for determining emission factors is recommended by IPCC (2006) for animals with similar digestive systems. Table A-186 shows the emission factors used for these other livestock.

Enteric fermentation emissions from all livestock types are shown in Table A-187 and Table A-188.

Table A-185: Population Estimates for American Bison and Mules, Burros, and Donkeys (1,000 head)

| Livestock Type | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| American Bison | 47 | 104 | 194 | 213 | 232 | 225 | 218 | 212 | 205 | 198 | 207 | 202 | 189 | 159 |
| Mules, Burros, and Donkeys | 63 | 101 | 112 | 109 | 105 | 141 | 177 | 212 | 248 | 284 | 284 | 284 | 284 | 284 |

Sources: USDA (1992, 1997, 2012), National Bison Association (1999).

Table A-186: Emission Factors for Other Livestock (kg $CH_4$/head/year)

| Livestock Type | Emission Factor |
|---|---|
| Sheep | 8 |
| Goats | 5 |
| Horses | 18 |
| Swine | 1.5 |
| Mules and Asses | 10.0 |
| American Bison | 82.2 |

Source: IPCC (2006), except American Bison, as described in text.

Table A-187: $CH_4$ Emissions from Enteric Fermentation (Tg $CO_2$ Eq.)

| Livestock Type | 1990 | 1995 | 2000 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|
| Beef Cattle | 96.2 | 109.7 | 102.6 | 101.4 | 103.0 | 104.0 | 103.1 | 102.0 | 101.0 | 98.8 |
| Dairy Cattle | 31.8 | 30.2 | 30.7 | 30.4 | 31.1 | 32.4 | 32.9 | 33.2 | 33.0 | 33.3 |
| Horses | 1.9 | 1.9 | 2.0 | 3.5 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 |
| Sheep | 1.9 | 1.5 | 1.2 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.9 | 0.9 |
| Swine | 1.7 | 1.9 | 1.9 | 1.9 | 1.9 | 2.1 | 2.1 | 2.1 | 2.0 | 2.1 |
| Goats | 0.3 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| American Bison | 0.1 | 0.2 | 0.3 | 0.4 | 0.4 | 0.3 | 0.4 | 0.3 | 0.3 | 0.3 |
| Mules, Burros, and Donkeys | + | + | + | + | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Total** | **133.8** | **145.7** | **138.8** | **139.0** | **141.4** | **143.8** | **143.4** | **142.6** | **141.3** | **139.3** |

Notes: Totals may not sum due to independent rounding.
+ indicates emissions are less than 0.05.

Table A-188: $CH_4$ Emissions from Enteric Fermentation (Gg)

| Livestock Type | 1990 | 1995 | 2000 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|
| Beef Cattle | 4,581 | 5,226 | 4,884 | 4,829 | 4,904 | 4,953 | 4,909 | 4,857 | 4,810 | 4,705 |
| Dairy Cattle | 1,513 | 1,440 | 1,460 | 1,449 | 1,479 | 1,544 | 1,564 | 1,581 | 1,569 | 1,585 |
| Horses | 91 | 92 | 94 | 166 | 171 | 171 | 171 | 171 | 171 | 171 |
| Sheep | 91 | 72 | 56 | 49 | 50 | 49 | 48 | 46 | 45 | 44 |
| Swine | 81 | 88 | 88 | 92 | 93 | 98 | 101 | 99 | 97 | 98 |
| Goats | 13 | 12 | 12 | 15 | 15 | 16 | 16 | 16 | 16 | 16 |
| American Bison | 4 | 9 | 16 | 17 | 17 | 16 | 17 | 17 | 16 | 13 |
| Mules, Burros, and Donkeys | 1 | 1 | 1 | 2 | 2 | 3 | 3 | 3 | 3 | 3 |
| **Total** | **6,373** | **6,939** | **6,612** | **6,618** | **6,731** | **6,850** | **6,829** | **6,789** | **6,727** | **6,635** |

Note: Totals may not sum due to independent rounding.

## 3.11. Methodology for Estimating $CH_4$ and $N_2O$ Emissions from Manure Management

The following steps were used to estimate methane ($CH_4$) and nitrous oxide ($N_2O$) emissions from the management of livestock manure. Nitrous oxide emissions associated with pasture, range, or paddock systems and daily spread systems are included in the emission estimates for Agricultural Soil Management (see the Agricultural Soils Management Annex).

#### Step 1: Livestock Population Characterization Data

Annual animal population data for 1990 through 2011 for all livestock types, except bison, goats, horses, mules and asses were obtained from the USDA National Agricultural Statistics Service (NASS). The population data used in the emissions calculations for cattle, swine, and sheep were downloaded from the USDA NASS Quick Stats Database (USDA 2012a). Poultry population data were obtained from USDA NASS reports (USDA 1995a, 1995b, 1998, 1999, 2004a, 2004b, 2009b, 2009c, 2009d, 2009e, 2010a, 2010b, 2011a, 2011b, 2012b, and 2012c). Goat population data for 1992, 1997, 2002, and 2007 were obtained from the *Census of Agriculture* (USDA 2009a). as were horse, mule and ass population data for 1997, 2002 and 2007, and bison population for 2002 and 2007 Bison population data for 1990-1999 were obtained from the National Bison Association (1999). Additional data sources used and adjustments to these data sets are described below.

*Cattle:* For all cattle groups (cows, heifers, steers, bulls, and calves), the USDA data provide cattle inventories from January (for each state) and July (as a U.S. total only) of each year. Cattle inventories change over the course of the year, sometimes significantly, as new calves are born and as cattle are moved into feedlots and subsequently slaughtered; therefore, to develop the best estimate for the annual animal population, the populations and the individual characteristics, such as weight and weight gain, pregnancy, and lactation of each animal type were tracked in the Cattle Enteric Fermentation Model (CEFM). For animals that have relatively static populations throughout the year, such as mature cows and bulls, the January 1 values were used. For animals that have fluctuating populations throughout the year, such as calves and growing heifers and steer, the populations are modeled based on a transition matrix that uses annual population data from USDA along with USDA data on animal births, placement into feedlots, and slaughter statistics.

*Swine:* The USDA provides quarterly data for each swine subcategory: breeding, market under 50 pounds (under 23 kg), market 50 to 119 pounds (23 to 54 kg), market 120 to 179 pounds (54 to 81 kg), and market 180 pounds and over (greater than 82 kg). The average of the quarterly data was used in the emission calculations. For states where only December inventory is reported, the December data were used directly.

*Sheep:* Population data for lamb and sheep on feed are not available after 1993 (USDA 1994). The number of lamb and sheep on feed for 1994 through 2011 were calculated using the average of the percent of lamb and sheep on feed from 1990 through 1993. In addition, all of the sheep and lamb "on feed" are not necessarily on "feedlots;" they may be on pasture/crop residue supplemented by feed. Data for those animals on feed that are in feedlots versus pasture/crop residue were provided only for lamb in 1993. To calculate the populations of sheep and lamb in feedlots for all years, it was assumed that the percentage of sheep and lamb on feed that are in feedlots versus pasture/crop residue is the same as that for lambs in 1993 (Anderson 2000).

*Goats:* Annual goat population data by state were available for 1992, 1997, 2002, and 2007 (USDA 2009a). The data for 1992 were used for 1990 through 1992 and the data for 2007 were used for 2007 through 2011. Data for 1993 through 1996, 1998 through 2001, and 2003 through 2006 were extrapolated based on the 1992, 1997, and 2002 Census data.

*Horses:* Annual horse population data by state were available for 1997, 2002, and 2007 (USDA 2009a). Data for 1990 through 1996, 1998 through 2001, 2003 through 2006 , and 2008 through 2011 were extrapolated based on the 1997, 2002, and 2007 Census data.

*Mules and Asses:* Annual mule and ass (burro and donkey) population data by state were available for 1997, 2002, and 2007 (USDA 2009a). Data for 1990 through 1996, 1998 through 2001, 2003 through 2006 , and 2008 through 2011 were extrapolated based on the 1997, 2002, and 2007 Census data.

*Bison:* Annual bison population data by state were available for 2002, and 2007 (USDA 2009a). Data for 1990 through 1999 were obtained from the Bison Association (1999). Data for 2000, 2001, 2003 through 2006, and 2008 through 2011 were extrapolated based on the 2002 and 2007 Census data.

*Poultry:* The USDA provides population data for hens (one year old or older), pullets (hens younger than one year old), other chickens, and production (slaughter) data for broilers and turkeys (USDA 1995a, 1995b, 1998, 1999, 2004a, 2004b, 2009b, 2009c, 2009d, 2009e, 2010a, 2010b, 2011a, 2011b, 2012b, and 2012c). All poultry population data

were adjusted to account for states that report non-disclosed populations to USDA NASS. The combined populations of the states reporting non-disclosed populations are reported as "other" states. State populations for the non-disclosed states were estimated by equally distributing the population attributed to "other" states to each of the non-disclosed states.

Because only production data are available for boilers and turkeys, population data are calculated by dividing the number of animals produced by the number of production cycles per year, or the turnover rate. Based on personal communications with John Lange, an agricultural statistician with USDA NASS, the broiler turnover rate ranges from 3.4 to 5.5 over the course of the inventory. For turkeys, the turnover rate ranges from 2.4 to 3.0.A summary of the livestock population characterization data used to calculate $CH_4$ and $N_2O$ emissions is presented in Table A- 189.

#### Step 2: Waste Characteristics Data

Methane and $N_2O$ emissions calculations are based on the following animal characteristics for each relevant livestock population:

- Volatile solids (VS) excretion rate;
- Maximum methane producing capacity ($B_o$) for U.S. animal waste;
- Nitrogen excretion rate (Nex); and
- Typical animal mass (TAM).

Table A- 190 presents a summary of the waste characteristics used in the emissions estimates. Published sources were reviewed for U.S.-specific livestock waste characterization data that would be consistent with the animal population data discussed in Step 1. The USDA's Agricultural Waste Management Field Handbook (AWMFH; USDA 1996, 2008) is one of the primary sources of waste characteristics. Data from the 1996 and 2008 USDA AWMFH were used to estimate VS and Nex for most animal groups across the time series of the inventory, as shown in Table A- 191 (ERG 2010b and 2010c). The AWMFH data were developed using the calculation method developed by the American Society of Agricultural and Biological Engineers, which is based on U.S. animal dietary intake and performance measures. Although these values are lower than the IPCC values, these values are more appropriate for U.S. systems because they have been calculated using U.S.-specific data. The VS and Nex data for breeding swine are from a combination of the types of animals that make up this animal group, namely gestating and farrowing swine and boars. It is assumed that a group of breeding swine is typically broken out as 80 percent gestating sows, 15 percent farrowing swine, and 5 percent boars (Safley 2000). Due to the change in USDA reporting of hens and pullets, new nitrogen and VS excretion rates were calculated for the combined population of hens and pullets; a weighted average rate was calculated based on hen and pullet population data from 1990 to 2004. In cases where data were not available in the more recent USDA document, data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 1998) or the 2006 IPPC Guideline were used as a supplement.

The method for calculating VS excretion and Nex from beef and dairy cows, heifers, and steers is based on the relationship between animal performance characteristics such as diet, lactation, and weight gain and energy utilization. The method used is outlined by the IPCC Tier II methodology, and is modeled in the enteric fermentation portion of the inventory (documented in Moffriod and Pape 2012) in order to take advantage of the detailed diet and animal performance data assembled as part of the Tier II analysis for cattle. For bison, VS and Nex were assumed to be the same as beef cattle not on feed; the VS and Nex values for beef bulls not on feed were used for bison.

Volatile solids content of manure is the fraction of the diet consumed by cattle that is not digested and thus excreted as fecal material; fecal material combined with urinary excretions constitutes manure. The enteric fermentation model requires the estimation of gross energy intake and its fractional digestibility to estimate enteric $CH_4$ emissions (see the Enteric Fermentation Annex for details on the enteric energy model). These two inputs are used to calculate the indigestible energy per animal unit as gross energy minus digestible energy plus the amount of gross energy for urinary energy excretion per animal unit (2 or 4 percent). This value is then converted to VS production per animal unit using the typical conversion of dietary gross energy to dry organic matter of 18.45 MJ/kg, after subtracting out the ash content of manure. The current equation recommended by the 2006 IPCC Guidelines is:

$$\text{VS production (kg)} = \left[\left(\text{GE - DE}\right) + \left(\text{UE} \times \text{GE}\right)\right] \times \frac{1 - ASH}{18.45}$$

Where,

GE = Gross energy intake (MJ)
DE = Digestible energy (MJ)

(UE × GE) = Urinary energy expressed as fraction of GE, assumed to be 0.04 except for feedlots which are reduced 0.02 as a result of the high grain content of their diet.

ASH = Ash content of manure calculated as a fraction of the dry matter feed intake (assumed to be 0.08).

18.45 = Conversion factor for dietary GE per kg of dry matter (MJ per kg). This value is relatively constant across a wide range of forage and grain-based feeds commonly consumed by livestock.

Nitrogen uptake in cattle is carried out through dietary protein intake. However, when feed intake of protein exceeds the nutrient requirements of the animal, the excess nitrogen is excreted, primarily through the urine. To calculate the nitrogen excreted by each animal type, the CEFM utilizes the energy balance calculations recommended by the IPCC (2006) for gross energy and the energy required for growth along with inputs of weight gain, milk production, and the percent of crude protein in the diets. The total nitrogen excreted is measured in the CEFM as nitrogen consumed minus nitrogen retained by the animal for growth and in milk. The basic equation for calculating Nex is shown below, followed by the equations for each of the constituent parts.

$$\mathrm{N}_{\mathrm{excreted}} = \mathrm{N}_{\mathrm{consumed}} - \left(\mathrm{N}_{\mathrm{growth}} + \mathrm{N}_{\mathrm{milk}}\right)$$

Where,

$N_{excreted}$ = Daily N excreted per animal, kg per animal per day.
$N_{consumed}$ = Daily N intake per animal, kg per animal per day
$N_{growth}$ = Nitrogen retained by the animal for growth, kg per animal per day
$N_{milk}$ = Nitrogen retained in milk, kg per animal per day

The equation for N consumed is based on the 2006 IPCC Guidelines, and is estimated as:

$$N_{consumed} = \left[\frac{GE}{18.45} * \left(\frac{\frac{CP\%}{100}}{6.25}\right)\right]$$

Where:

$N_{consumed}$ = Daily N intake per animal, kg per animal per day
GE = Gross energy intake, as calculated in the CEFM, MJ per animal per day
18.45 = Conversion factor for dietary GE per kg of dry matter, MJ per kg.
CP% = Percent crude protein in diet, input into the CEFM
6.25 = Conversion from kg of dietary protein to kg of dietary N, kg feed per kg N

The portion of consumed N that is retained as product equals the nitrogen required for weight gain plus that in milk. The nitrogen retained in body weight gain by stockers, replacements, or feedlot animals is calculated using the net energy for growth (NEg), weight gain (WG), and other conversion factors and constants. The equation matches current 2006 IPCC Guidelines recommendations, and is as follows:

$$N_{growth} = \frac{\frac{\left\{WG * \left[268 - \frac{(7.03 * NEg)}{WG}\right]\right\}}{1000}}{6.25}$$

Where,

$N_{growth}$ = Nitrogen retained by the animal for growth, kg per animal per day
WG = Daily weight gain of the animal, kg per day

| | |
|---|---|
| 268 | = Constant from 2006 IPCC Guidelines |
| 7.03 | = Constant from 2006 IPCC Guidelines |
| NEg | = Net energy required for growth, MJ per animal per day |
| 1,000 | = Conversion from grams to kilograms |
| 6.25 | = Conversion from kg of dietary protein to kg of dietary N, kg feed per kg N |

The N content of milk produced also currently matches the 2006 IPCC Guidelines. Milk N retained as product is calculated using the following equation:

$$N_{milk} = \frac{milk * \left(\frac{pr\%}{100}\right)}{6.38}$$

Where,

| | |
|---|---|
| $N_{milk}$ | = Nitrogen retained in milk, kg per animal per day |
| milk | = Milk production, kg per day |
| pr% | = Percent protein in milk, estimated from the fat content as 1.9 + 0.4 * %Fat |
| 100 | = Conversion from percent to value (e.g., 4% to 0.04) |
| 6.38 | = Conversion from kg Protein to kg N |

The VS and N equations above were used to calculate VS and Nex rates for each state, cattle type, and year. Table A- 192 presents the state-specific VS and Nex production rates used for cattle in 2011.

**Step 3: Waste Management System Usage Data**

Table A- 193 summarizes 2011 manure distribution data among waste management systems (WMS) at beef feedlots, dairies, dairy heifer facilities, and swine, layer, broiler, and turkey operations. Manure from the remaining animal types (beef cattle not on feed, bison, goats, horses, mules and asses and sheep) is managed on pasture, range, or paddocks, on drylot, or with solids storage systems. Additional information on the development of the manure distribution estimates for each animal type is presented below. Definitions of each WMS type are presented in Table A- 194.

*Beef Cattle, Dairy Heifers and Bison*: The beef feedlot and dairy heifer WMS data were developed using information from EPA's Office of Water's engineering cost analyses conducted to support the development of effluent limitations guidelines for Concentrated Animal Feeding Operations (EPA 2002b). Based on EPA site visits and state contacts supporting this work and additional contacts with the national USDA office to estimate the percent of beef steers and heifers in feedlots (Milton 2000), feedlot manure is almost exclusively managed in drylots. Therefore, for these animal groups, the percent of manure deposited in drylots is assumed to be 100 percent. In addition, there is a small amount of manure contained in runoff, which may or may not be collected in runoff ponds. The runoff from feedlots was calculated by region in *Calculations: Percent Distribution of Manure for Waste Management Systems* (ERG 2000b) and was used to estimate the percentage of manure managed in runoff ponds in addition to drylots; this percentage ranges from 0.4 to 1.3 percent. The percentage of manure generating emissions from beef feedlots is therefore greater than 100 percent. The remaining population categories of beef cattle outside of feedlots are managed through pasture, range, or paddock systems, which are utilized for the majority of the population of beef cattle in the country. Bison WMS data were assumed to be the same as beef cattle not on feed.

*Dairy Cows:* The WMS data for dairy cows were developed using data from the Census of Agriculture, EPA's Office of Water, USDA, and expert sources. Farm-size distribution data are reported in the 1992, 1997, 2002, and 2007 Census of Agriculture (USDA 2009a). It was assumed that the data provided for 1992 were the same as that for 1990 and 1991, and data provided for 2007 were the same as that for 2008 through 2011. Data for 1993 through 1996,1998 through 2001, and 2003 through 2006 were extrapolated using the 1992, 1997, 2002, and 2007 data. The percent of waste by system was estimated using the USDA data broken out by geographic region and farm size.

Based on EPA site visits and state contacts, manure from dairy cows at medium (200 through 700 head) and large (greater than 700 head) operations are managed using either flush systems or scrape/slurry systems. In addition, they may have a solids separator in place prior to their storage component. Estimates of the percent of farms that use each type

of system (by geographic region) were developed by EPA's Office of Water, and were used to estimate the percent of waste managed in lagoons (flush systems), liquid/slurry systems (scrape systems), and solid storage (separated solids) (EPA 2002b). Manure management system data for small (fewer than 200 head) dairies were obtained from USDA (Ott 2000). These operations are more likely to use liquid/slurry and solid storage management systems than anaerobic lagoon systems. The reported manure management systems were deep pit, liquid/slurry (includes slurry tank, slurry earth-basin, and aerated lagoon), anaerobic lagoon, and solid storage (includes manure pack, outside storage, and inside storage).

Data regarding the use of daily spread and pasture, range, or paddock systems for dairy cattle were obtained from personal communications with personnel from several organizations. These organizations include state NRCS offices, state extension services, state universities, USDA NASS, and other experts (Deal 2000, Johnson 2000, Miller 2000, Stettler 2000, Sweeten 2000, and Wright 2000). Contacts at Cornell University provided survey data on dairy manure management practices in New York (Poe et al. 1999). Census of Agriculture population data for 1992, 1997, 2002, and 2007 (USDA 2009a) were used in conjunction with the state data obtained from personal communications to determine regional percentages of total dairy cattle and dairy waste that are managed using these systems. These percentages were applied to the total annual dairy cow and heifer state population data for 1990 through 2011, which were obtained from the USDA NASS (USDA 2012a).

Of the dairies using systems other than daily spread and pasture, range, or paddock systems, some dairies reported using more than one type of manure management system. Due to limitations in how USDA reports the manure management data, the total percent of systems for a region and farm size is greater than 100 percent. However, manure is typically partitioned to use only one manure management system, rather than transferred between several different systems. Emissions estimates are only calculated for the final manure management system used for each portion of manure. To avoid double counting emissions, the reported percentages of systems in use were adjusted to equal a total of 100 percent using the same distribution of systems. For example, if USDA reported that 65 percent of dairies use deep pits to manage manure and 55 percent of dairies use anaerobic lagoons to manage manure, it was assumed that 54 percent (i.e., 65 percent divided by 120 percent) of the manure is managed with deep pits and 46 percent (i.e., 55 percent divided by 120 percent) of the manure is managed with anaerobic lagoons (ERG 2000a).

*Swine:* The distribution of manure managed in each WMS was estimated using data from a USDA report and EPA's Office of Water site visits (USDA 1998, ERG 2000a). For operations with less than 200 head, manure management system data were obtained from USDA (USDA 1998). It was assumed that those operations use pasture, range, or paddock systems. For swine operations with greater than 200 head, the percent of waste managed in each system was estimated using the EPA and USDA data broken out by geographic region and farm size. Farm-size distribution data reported in the 1992, 1997, 2002, and 2007 Census of Agriculture (USDA 2009a) were used to determine the percentage of all swine utilizing the various manure management systems. It was assumed that the swine farm size data provided for 1992 were the same as that for 1990 and 1991, and data provided for 2007 were the same as that for 2008 through 2011. Data for 1993 through 1996, 1998 through 2001, and 2003 through 2006 were extrapolated using the 1992, 1997, 2002, and 2007 data. The reported manure management systems were deep pit, liquid/slurry (includes above- and below-ground slurry), anaerobic lagoon, and solid storage (includes solids separated from liquids).

Some swine operations reported using more than one management system; therefore, the total percent of systems reported by USDA for a region and farm size was greater than 100 percent. Typically, this means that a portion of the manure at a swine operation is handled in one system (e.g., liquid system), and a separate portion of the manure is handled in another system (e.g., dry system). However, it is unlikely that the same manure is moved from one system to another, which could result in increased emissions, so reported systems data were normalized to 100 percent for incorporation into the WMS distribution, using the same method as described above for dairy operations.

*Sheep:* Waste management system data for sheep were obtained from USDA NASS sheep report for years 1990 through 1993 (USDA 1994). Data for 2001 are obtained from USDA APHIS sheep report (USDA,APHIS 2003). The data for years 1994-2000 are calculated assuming a linear progression from 1993 to 2001. Due to lack of additional data, data for years 2002 and beyond are assumed to be the same as 2001. It was assumed that all sheep manure not deposited in feedlots was deposited on pasture, range, or paddock lands (Anderson 2000).

*Goats, Horses, and Mules and Asses:* Waste management system data for 1990 to 2011 were obtained from Appendix H of *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). It was assumed that all manure not deposited in pasture, range, or paddock lands was managed in dry systems. For mules and asses, the WMS was assumed to be the same as horses.

*Poultry—Hens (one year old or older), Pullets (hens less than one year old), and Other Chickens:* Waste management system data for 1992 were obtained from *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). These data were also used to represent 1990 and 1991. The percentage of layer operations using a shallow pit flush house with anaerobic lagoon or high-rise house without bedding was obtained for 1999 from a United Egg

Producers voluntary survey (UEP 1999). These data were augmented for key poultry states (AL, AR, CA, FL, GA, IA, IN, MN, MO, NC, NE, OH, PA, TX, and WA) with USDA data (USDA,APHIS 2000). It was assumed that the change in system usage between 1990 and 1999 is proportionally distributed among those years of the inventory. It was assumed that system usage in 2000 through 2011 was equal to that estimated for 1999. Data collected for EPA's Office of Water, including information collected during site visits (EPA 2002b), were used to estimate the distribution of waste by management system and animal type.

*Poultry—Broilers and Turkeys:* The percentage of turkeys and broilers on pasture was obtained from *Global Methane Emissions from Livestock and Poultry Manure* (EPA 1992). It was assumed that one percent of poultry waste is deposited in pastures, ranges, and paddocks (EPA 1992). The remainder of waste is assumed to be deposited in operations with bedding management.

#### Step 4: Emission Factor Calculations

Methane conversion factors (MCFs) and $N_2O$ emission factors (EFs) used in the emission calculations were determined using the methodologies presented below.

##### *Methane Conversion Factors (MCFs)*

Climate-based IPCC default MCFs (IPCC 2006) were used for all dry systems; these factors are presented in Table A- 195. A U.S.-specific methodology was used to develop MCFs for all lagoon and liquid systems.

For animal waste managed in dry systems, the appropriate IPCC default MCF was applied based on annual average temperature data. The average county and state temperature data were obtained from the National Climate Data Center (NOAA 2012) and each state and year in the inventory was assigned a climate classification of cool, temperate or warm. Although there are some specific locations in the U.S. that may be included in the warm climate category, no aggregated state-level annual average temperatures are included in this category. In addition, some counties in a particular state may be included in the cool climate category, although the aggregated state-level annual average temperature may be included in the temperate category. Although considering the temperatures at a state level instead of a county level may be causing some specific locations to be classified into an inappropriate climate category, using the state level annual average temperature provides an estimate that is appropriate for calculating the national average.

For anaerobic lagoons and other liquid systems a climate-based approach based on the van't Hoff-Arrhenius equation was developed to estimate MCFs that reflects the seasonal changes in temperatures, and also accounts for long-term retention time. This approach is consistent with the recently revised guidelines from IPCC (IPCC 2006). The van't Hoff-Arrhenius equation, with a base temperature of 30°C, is shown in the following equation (Safley and Westerman 1990):

$$f = \exp\left[\frac{E(T_2 - T_1)}{RT_1T_2}\right]$$

Where,

$T_1$ = 303.15K
$T_2$ = Ambient temperature (K) for climate zone (in this case, a weighted value for each state)
E = Activation energy constant (15,175 cal/mol)
R = Ideal gas constant (1.987 cal/K mol)

The factor *f* represents the proportion of VS that are biologically available for conversion to $CH_4$ based on the temperature of the system. For those animal populations using liquid manure management systems or manure runoff ponds (i.e., dairy cow, dairy heifer, layers, beef in feedlots, and swine) monthly average state temperatures were based on the counties where the specific animal population resides (i.e., the temperatures were weighted based on the percent of animals located in each county). County population data were calculated from state-level population data from NASS and county-state distribution data from the 1992, 1997, 2002, and 2007 Census data (USDA 2009a). County population distribution data for 1990 and 1991 were assumed to be the same as 1992; county population distribution data for 1993 through 1996 were extrapolated based on 1992 and 1997 data; county population data for 1998 through 2001 were extrapolated based on 1997 and 2002 data; county population data for 2003 through 2006 were extrapolated based on 2002 and 2007 data; and county population data for 2008 to 2011 were assumed to be the same as 2007.

Annual MCFs for liquid systems are calculated as follows for each animal type, state, and year of the inventory:

- The weighted-average temperature for a state is calculated using the county population estimates and average monthly temperature in each county. Monthly temperatures are used to calculate a monthly van't Hoff-Arrhenius "f" factor, using the equation presented above. A minimum temperature of 5°C is used for uncovered anaerobic lagoons and 7.5°C is used for liquid/slurry and deep pit systems.
- Monthly production of VS added to the system is estimated based on the number of animals present.
- For lagoon systems, the calculation of methane includes a management and design practices (MDP) factor. This factor, equal to 0.8, was developed based on model comparisons to empirical $CH_4$ measurement data from anaerobic lagoon systems in the United States (ERG 2001). The MDP factor represents a variety of factors that may affect methane production in lagoon systems.
- The amount of VS available for conversion to $CH_4$ is assumed to be equal to the amount of VS produced during the month (from Step 3). For anaerobic lagoons, the amount of VS available also includes VS that may remain in the system from previous months.
- The amount of VS consumed during the month is equal to the amount available for conversion multiplied by the "f" factor.
- For anaerobic lagoons, the amount of VS carried over from one month to the next is equal to the amount available for conversion minus the amount consumed. Lagoons are also modeled to have a solids clean-out once per year, occurring after the month of September.
- The estimated amount of $CH_4$ generated during the month is equal to the monthly VS consumed multiplied by the maximum $CH_4$ potential of the waste ($B_o$).

The annual MCF is then calculated as:

$$MCF_{annual} = \frac{CH_4\ generated_{annual}}{VS\ produced_{annual} \times B_o}$$

Where,

$MCF_{annual}$ = Methane conversion factor
$VS\ produced_{annual}$ = Volatile solids excreted annually
$B_o$ = Maximum $CH_4$ producing potential of the waste

In order to account for the carry-over of VS from one year to the next, it is assumed that a portion of the VS from the previous year are available in the lagoon system in the next year. For example, the VS from October, November, and December of 2005 are available in the lagoon system starting January of 2006 in the MCF calculation for lagoons in 2006. Following this procedure, the resulting MCF for lagoons accounts for temperature variation throughout the year, residual VS in a system (carry-over), and management and design practices that may reduce the VS available for conversion to $CH_4$. It is assumed that liquid-slurry systems have a retention time less than 30 days, so the liquid-slurry MCF calculation doesn't reflect the VS carry-over.

The liquid system MCFs are presented in Table A- 196 by state, WMS, and animal group for 2011.

#### *Nitrous Oxide Emission Factors*

Direct $N_2O$ emission factors for manure management systems (kg $N_2O$-N/kg excreted N) were set equal to the most recent default IPCC factors (IPCC 2006), presented in Table A- 197.

Indirect $N_2O$ emission factors account for two fractions of nitrogen losses: volatilization of ammonia ($NH_3$) and $NO_X$ ($Frac_{gas}$) and runoff/leaching ($Frac_{runoff/leach}$). IPCC default indirect $N_2O$ emission factors were used to estimate indirect $N_2O$ emissions. These factors are 0.010 kg $N_2O$-N/kg N for volatilization and 0.0075 kg $N_2O$/kg N for runoff/leaching.

Country-specific estimates of N losses were developed for $Frac_{gas}$ and $Frac_{runoff/leach}$ for the United States. The vast majority of volatilization losses are $NH_3$. Although there are also some small losses of $NO_X$, no quantified estimates were available for use and those losses are believed to be small (about 1 percent) in comparison to the $NH_3$ losses. Therefore, $Frac_{gas}$ values were based on WMS-specific volatilization values estimated from U.S. EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). To estimate $Frac_{runoff/leach}$, data from

EPA's Office of Water were used that estimate the amount of runoff from beef, dairy, and heifer operations in five geographic regions of the country (EPA 2002b). These estimates were used to develop U.S. runoff factors by animal type, WMS, and region. Nitrogen losses from leaching are believed to be small in comparison to the runoff losses; therefore, $Frac_{runoff/leach}$ was set equal to the runoff loss factor. Nitrogen losses from volatilization and runoff/leaching are presented in Table A- 198.

**Step 5: $CH_4$ and $N_2O$ Emission Calculations**

To calculate $CH_4$ emissions for animals other than cattle, first the amount of volatile solids excreted in manure that is managed in each WMS was estimated:

$$\text{VS excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \frac{\text{TAM}}{1000} \times \text{VS} \times \text{WMS} \times 365.25$$

Where,

| | | |
|---|---|---|
| $\text{VS excreted}_{\text{State, Animal, WMS}}$ | = | Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr) |
| $\text{Population}_{\text{State, Animal}}$ | = | Annual average state animal population by animal type (head) |
| TAM | = | Typical animal mass (kg) |
| VS | = | Volatile solids production rate (kg VS/1000 kg animal mass/day) |
| WMS | = | Distribution of manure by WMS for each animal type in a state (percent) |
| 365.25 | = | Days per year |

Using the CEFM VS data for cattle, the amount of VS excreted was calculated using the following equation:

$$\text{VS excreted}_{\text{State,Animal,WMS}} = \text{Population}_{\text{State,Animal}} \times \text{VS} \times \text{WMS}$$

Where,

| | | |
|---|---|---|
| $\text{VS excreted}_{\text{State, Animal, WMS}}$ | = | Amount of VS excreted in manure managed in each WMS for each animal type (kg/yr) |
| $\text{Population}_{\text{State, Animal}}$ | = | Annual average state animal population by animal type (head) |
| VS | = | Volatile solids production rate (kg VS/animal/year) |
| WMS | = | Distribution of manure by WMS for each animal type in a state (percent) |

For all animals, the estimated amount of VS was used to calculate $CH_4$ emissions using the following equation:

$$CH_4 = \sum_{\text{State, Animal, WMS}} \left(\text{VS excreted}_{\text{State, Animal, WMS}} \times B_o \times \text{MCF} \times 0.662\right)$$

Where,

| | | |
|---|---|---|
| $CH_4$ | = | $CH_4$ emissions (kg $CH_4$/yr) |
| $\text{VS excreted}_{\text{WMS, State}}$ | = | Amount of VS excreted in manure managed in each WMS (kg/yr) |
| $B_o$ | = | Maximum $CH_4$ producing capacity ($m^3$ $CH_4$/kg VS) |
| $\text{MCF}_{\text{animal, state, WMS}}$ | = | MCF for the animal group, state and WMS (percent) |
| 0.662 | = | Density of methane at $25^o$ C (kg $CH_4/m^3$ $CH_4$) |

A calculation was developed to estimate the amount of $CH_4$ emitted from anaerobic digestion (AD) systems utilizing $CH_4$ capture and combustion technology. First, AD systems were assumed to produce 90 percent of the maximum $CH_4$ producing capacity. This value is applied for all climate regions and AD system types. However, the actual amount of $CH_4$ produced by each AD system is very variable and will change based on operational and climate conditions and an assumption of 90 percent is likely overestimating $CH_4$ production from some systems and underestimating $CH_4$ production in other systems. The $CH_4$ production of AD systems is calculated using the equation below:

$$CH_4 \text{ Production } AD_{AD\,System} = \text{Population } AD_{AD\,System} \times \frac{TAM}{1000} \times VS \times B_o \times 0.662 \times 365.25 \times 0.90$$

Where,

| | | |
|---|---|---|
| $CH_4$ Production $AD_{AD\ system}$ | = | $CH_4$ production from a particular AD system, (kg/yr) |
| Population $AD_{state}$ | = | Number of animals on a particular AD system |
| VS | = | Volatile solids production rate (kg VS/1000 kg animal mass-day) |
| TAM | = | Typical Animal Mass (kg/head) |
| $B_o$ | = | Maximum $CH_4$ producing capacity (CH4 $m^3$/kg VS) |
| 0.662 | = | Density of $CH_4$ at $25^o$ C (kg $CH_4/m^3$ $CH_4$) |
| 365.25 | = | Days/year |
| 0.90 | = | $CH_4$ production factor for AD systems |

Next, the collection efficiency (CE) and destruction efficiency (DE) was considered of the AD system. The CE of covered lagoon systems was assumed to be 75 percent, and the CE of complete mix and plug flow AD systems was assumed to be 99 percent (EPA 2008). The $CH_4$ DE from flaring or burning in an engine was assumed to be 98 percent; therefore, the amount of $CH_4$ that would not be flared or combusted was assumed to be 2 percent (EPA 2008). The amount of $CH_4$ produced by systems with anaerobic digestion was calculated with the following equation:

$$CH_4 \text{ Emissions } AD = \sum_{State,\,Animal,\,AD\,Systems} \left( \begin{array}{l} \left[CH_4 \text{ Production } AD_{AD\,system} \times CE_{AD\,system} \times (1 - DE)\right] \\ + \left[CH_4 \text{ Production } AD_{AD\,system} \times (1 - CE_{AD\,system})\right] \end{array} \right)$$

Where:

| | | |
|---|---|---|
| $CH_4$ Emissions AD | = | $CH_4$ emissions from AD systems, (kg/yr) |
| $CH_4$ Production $AD_{AD\ system}$ | = | $CH_4$ production from a particular AD system, (kg/yr) |
| $CE_{AD\ system}$ | = | Collection efficiency of the AD system, varies by AD system type |
| DE | = | Destruction efficiency of the AD system, 0.98 for all systems |

In addition to $CH_4$ emissions, also total $N_2O$ emissions were estimated from manure management systems. Total $N_2O$ emissions were calculated by summing direct and indirect $N_2O$ emissions. The first step in estimating direct and indirect $N_2O$ emissions was calculating the amount of N excreted in manure and managed in each WMS for animals other than cattle using the following equation:

$$\text{N excreted}_{State,\,Animal,\,WMS} = \text{Population}_{State,\,Animal} \times WMS \times \frac{TAM}{1000} \times Nex \times 365.25$$

Where,

| | | |
|---|---|---|
| N excreted $_{State,\ Animal,\ WMS}$ | = | Amount of N excreted in manure managed in each WMS for each animal type (kg/yr) |
| Population $_{state}$ | = | Annual average state animal population by animal type (head) |
| WMS | = | Distribution of manure by waste management system for each animal type in a state (percent) |
| TAM | = | Typical animal mass (kg) |
| Nex | = | Total Kjeldahl nitrogen excretion rate (kg N/1000 kg animal mass/day) |
| 365.25 | = | Days per year |

Using the CEFM Nex data for cattle, the amount of N excreted was calculated using the following equation:

$$\text{N excreted}_{\text{State, Animal, WMS}} = \text{Population}_{\text{State, Animal}} \times \text{WMS} \times \text{Nex}$$

Where,

| | | |
|---|---|---|
| $\text{N excreted}_{\text{State, Animal, WMS}}$ | = | Amount of N excreted in manure managed in each WMS for each animal type (kg/yr) |
| $\text{Population}_{\text{state}}$ | = | Annual average state animal population by animal type (head) |
| WMS | = | Distribution of manure by waste management system for each animal type in a state (percent) |
| Nex | = | Total Kjeldahl N excretion rate (kg N/animal/year) |

For all animals, direct $N_2O$ emissions were calculated as follows:

$$\text{Direct } N_2O = \sum_{\text{State, Animal, WMS}} \left( \text{N excreted}_{\text{State, Animal, WMS}} \times EF_{\text{WMS}} \times \frac{44}{28} \right)$$

Where,

| | | |
|---|---|---|
| Direct $N_2O$ | = | Direct $N_2O$ emissions (kg $N_2O$/yr) |
| $\text{N excreted}_{\text{State, Animal, WMS}}$ | = | Amount of N excreted in manure managed in each WMS for each animal type (kg/yr) |
| $EF_{\text{WMS}}$ | = | Direct $N_2O$ emission factor from IPCC guidelines (kg $N_2O$-N /kg N) |
| 44/28 | = | Conversion factor of $N_2O$-N to $N_2O$ |

Indirect $N_2O$ emissions were calculated for all animals with the following equation:

$$\text{Indirect } N_2O = \sum_{\text{State, Animal, WMS}} \left( \left[ \text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{gas, WMS}}}{100} \times EF_{\text{volatilization}} \times \frac{44}{28} \right] + \left[ \text{N excreted}_{\text{State, Animal, WMS}} \times \frac{\text{Frac}_{\text{runoff/leach, WMS}}}{100} \times EF_{\text{runoff/leach}} \times \frac{44}{28} \right] \right)$$

Where,

| | | |
|---|---|---|
| Indirect $N_2O$ | = | Indirect $N_2O$ emissions (kg $N_2O$/yr) |
| $\text{N excreted}_{\text{State, Animal, WMS}}$ | = | Amount of N excreted in manure managed in each WMS for each animal type (kg/yr) |
| $\text{Frac}_{\text{gas,WMS}}$ | = | Nitrogen lost through volatilization in each WMS |
| $\text{Frac}_{\text{runoff/leach,WMS}}$ | = | Nitrogen lost through runoff and leaching in each WMS; data were not available for leaching so the value reflects only runoff |
| $EF_{\text{volatilization}}$ | = | Emission factor for volatilization (0.010 kg $N_2O$-N/kg N) |
| $EF_{\text{runoff/leach}}$ | = | Emission factor for runoff/leaching (0.0075 kg $N_2O$-N/kg N) |
| 44/28 | = | Conversion factor of $N_2O$-N to $N_2O$ |

Emission estimates of $CH_4$ and $N_2O$ by animal type are presented for all years of the inventory in Table A- 199 and Table A- 200respectively. Emission estimates for 2011 are presented by animal type and state in Table A- 201 and Table A- 202 respectively.

Table A-189: Livestock Population (1,000 Head)

| Animal Type | 1990 | 1995 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dairy Cattle | 14,144 | 13,590 | 13,217 | 13,165 | 13,215 | 13,021 | 13,165 | 13,398 | 13,487 | 13,658 | 13,761 | 13,612 | 13,690 |
| Dairy Cows | 10,015 | 9,482 | 9,172 | 9,106 | 9,142 | 8,988 | 9,004 | 9,104 | 9,145 | 9,257 | 9,333 | 9,086 | 9,150 |
| Dairy Heifer | 4,129 | 4,108 | 4,045 | 4,060 | 4,073 | 4,033 | 4,162 | 4,294 | 4,343 | 4,401 | 4,429 | 4,526 | 4,541 |
| Swine[1] | 53,941 | 58,899 | 58,913 | 60,028 | 59,827 | 60,735 | 61,073 | 61,887 | 65,417 | 67,408 | 65,990 | 64,768 | 65,589 |
| Market <50 lb. | 18,359 | 19,656 | 19,659 | 19,863 | 19,929 | 20,222 | 20,228 | 20,514 | 21,812 | 19,964 | 19,444 | 19,124 | 19,382 |
| Market 50-119 lb. | 11,734 | 12,836 | 12,900 | 13,284 | 13,138 | 13,400 | 13,519 | 13,727 | 14,557 | 17,219 | 16,995 | 16,699 | 16,968 |
| Market 120-179 lb. | 9,440 | 10,545 | 10,708 | 11,013 | 11,050 | 11,227 | 11,336 | 11,443 | 12,185 | 12,931 | 12,567 | 12,313 | 12,437 |
| Market >180 lb. | 7,510 | 8,937 | 9,465 | 9,738 | 9,701 | 9,922 | 9,997 | 10,113 | 10,673 | 11,193 | 11,079 | 10,854 | 11,011 |
| Breeding | 6,899 | 6,926 | 6,181 | 6,129 | 6,011 | 5,963 | 5,993 | 6,090 | 6,190 | 6,102 | 5,905 | 5,778 | 5,791 |
| Beef Cattle[2] | 87,228 | 95,683 | 89,118 | 89,102 | 88,232 | 86,441 | 86,954 | 88,070 | 87,639 | 86,450 | 85,812 | 85,183 | 83,743 |
| Feedlot Steers | 6,357 | 7,233 | 7,932 | 8,116 | 8,416 | 8,018 | 8,116 | 8,724 | 8,674 | 8,481 | 8,446 | 8,563 | 8,730 |
| Feedlot Heifers | 3,192 | 3,831 | 4,569 | 4,557 | 4,676 | 4,521 | 4,536 | 4,801 | 4,730 | 4,589 | 4,508 | 4,628 | 4,822 |
| NOF Bulls | 2,160 | 2,385 | 2,274 | 2,244 | 2,248 | 2,201 | 2,214 | 2,258 | 2,214 | 2,207 | 2,184 | 2,190 | 2,155 |
| NOF Calves | 22,561 | 23,499 | 22,389 | 22,325 | 21,997 | 21,781 | 21,678 | 21,621 | 21,483 | 21,155 | 21,001 | 20,861 | 20,648 |
| NOF Heifers | 10,182 | 11,829 | 9,832 | 9,843 | 9,564 | 9,321 | 9,550 | 9,716 | 9,592 | 9,350 | 9,448 | 9,348 | 8,897 |
| NOF Steers | 10,321 | 11,716 | 8,724 | 8,883 | 8,347 | 8,067 | 8,185 | 8,248 | 8,302 | 8,233 | 8,515 | 8,223 | 7,641 |
| NOF Cows | 32,455 | 35,190 | 33,398 | 33,134 | 32,983 | 32,531 | 32,674 | 32,703 | 32,644 | 32,435 | 31,712 | 31,371 | 30,850 |
| Sheep | 11,358 | 8,989 | 6,908 | 6,623 | 6,321 | 6,065 | 6,135 | 6,200 | 6,120 | 5,950 | 5,747 | 5,620 | 5,480 |
| Sheep On Feed | 1,180 | 1,771 | 3,256 | 3,143 | 3,049 | 2,923 | 2,971 | 3,026 | 3,000 | 2,911 | 2,806 | 2,778 | 2,692 |
| Sheep NOF | 10,178 | 7,218 | 3,652 | 3,480 | 3,272 | 3,142 | 3,164 | 3,174 | 3,120 | 3,039 | 2,941 | 2,842 | 2,788 |
| Goats | 2,516 | 2,357 | 2,475 | 2,530 | 2,652 | 2,774 | 2,897 | 3,019 | 3,141 | 3,141 | 3,141 | 3,141 | 3,141 |
| Poultry[3] | 1,537,074 | 1,826,977 | 2,060,398 | 2,097,691 | 2,085,268 | 2,130,877 | 2,150,410 | 2,154,236 | 2,166,936 | 2,175,990 | 2,088,828 | 2,104,335 | 2,095,103 |
| Hens >1 yr. | 273,467 | 299,071 | 340,317 | 340,209 | 340,979 | 343,922 | 348,203 | 349,888 | 346,613 | 339,859 | 341,005 | 341,884 | 338,472 |
| Pullets | 73,167 | 81,369 | 95,656 | 95,289 | 100,346 | 101,429 | 96,809 | 96,596 | 103,816 | 99,458 | 102,301 | 105,738 | 101,928 |
| Chickens | 6,545 | 7,637 | 8,126 | 8,353 | 8,439 | 8,248 | 8,289 | 7,938 | 8,164 | 7,589 | 8,487 | 7,390 | 6,851 |
| Broilers | 1,066,209 | 1,331,940 | 1,525,413 | 1,562,015 | 1,544,155 | 1,589,209 | 1,613,091 | 1,612,327 | 1,619,400 | 1,638,055 | 1,554,582 | 1,567,927 | 1,565,018 |
| Turkeys | 117,685 | 106,960 | 90,887 | 91,826 | 91,349 | 88,069 | 84,018 | 87,487 | 88,943 | 91,029 | 82,453 | 81,396 | 82,833 |
| Horses | 2,146 | 2,770 | 3,519 | 3,644 | 3,721 | 3,798 | 3,875 | 3,952 | 4,029 | 4,106 | 4,183 | 4,260 | 4,336 |
| Mules and Asses | 148 | 130 | 109 | 105 | 141 | 177 | 212 | 248 | 284 | 319 | 355 | 391 | 427 |
| Bison | 47 | 104 | 213 | 232 | 225 | 218 | 212 | 205 | 198 | 192 | 185 | 179 | 173 |

Note: Totals may not sum due to independent rounding.

[1] Prior to 2008, the Market <50 lbs category was <60 lbs and the Market 50-119 lbs category was Market 60-119 lbs; USDA updated the categories to be more consistent with international animal categories.

[2] NOF = Not on Feed

[3] Pullets includes laying pullets, pullets younger than 3 months, and pullets older than 3 months.

Table A-190: Waste Characteristics Data

| Animal Group | TAM (kg) | TAM Source | Total Kjeldahl Nitrogen, $N_{ex}$ (kg/day per 1,000 kg mass) | $N_{ex}$ Source | Maximum Methane Generation Potential, $B_o$ ($m^3$ $CH_4$/kg VS added) | $B_o$ Source | Volatile Solids, VS (kg/day per 1,000 kg mass) | VS Source |
|---|---|---|---|---|---|---|---|---|
| Dairy Cows | 680 | CEFM | Table A- 93 | CEFM | 0.24 | Morris 1976 | Table A- 93 | CEFM |
| Dairy Heifers | 406-408 | CEFM | Table A- 93 | CEFM | 0.17 | Bryant et. al. 1976 | Table A- 93 | CEFM |
| Feedlot Steers | 419-457 | CEFM | Table A- 93 | CEFM | 0.33 | Hashimoto 1981 | Table A- 93 | CEFM |
| Feedlot Heifers | 384-430 | CEFM | Table A- 93 | CEFM | 0.33 | Hashimoto 1981 | Table A- 93 | CEFM |
| NOF Bulls | 831-917 | CEFM | Table A- 93 | CEFM | 0.17 | Hashimoto 1981 | Table A- 93 | CEFM |
| NOF Calves | 118 | USDA 1996 | Table A- 192 | USDA 1996a, 2008 | 0.17 | Hashimoto 1981 | Table A- 192 | USDA 1996a, 2008 |
| NOF Heifers | 296-407 | CEFM | | CEFM | 0.17 | Hashimoto 1981 | | CEFM |
| NOF Steers | 314-335 | CEFM | Table A- 93 | CEFM | 0.17 | Hashimoto 1981 | Table A- 93 | CEFM |
| NOF Cows | 554-611 | CEFM | Table A- 93 | CEFM | 0.17 | Hashimoto 1981 | Table A- 93 | CEFM |
| Bison | 578.5 | Meagher 1986 | NOF Bulls | NOF Bulls | 0.17 | NOF Bulls | NOF Bulls | NOF Bulls |
| Market Swine <50 lbs. | 13 | ERG 2010a | Table A- 192 | USDA 1996a, 2008 | 0.48 | Hashimoto 1984 | Table A- 192 | USDA 1996a, 2008 |
| Market Swine <60 lbs. | 16 | Safley 2000 | Table A- 192 | USDA 1996a, 2008 | 0.48 | Hashimoto 1984 | Table A- 192 | USDA 1996a, 2008 |
| Market Swine 50-119 lbs. | 39 | ERG 2010a | Table A- 192 | USDA 1996a, 2008 | 0.48 | Hashimoto 1984 | Table A- 192 | USDA 1996a, 2008 |
| Market Swine 60-119 lbs. | 41 | Safley 2000 | Table A- 192 | USDA 1996a, 2008 | 0.48 | Hashimoto 1984 | Table A- 192 | USDA 1996a, 2008 |
| Market Swine 120-179 lbs. | 68 | Safley 2000 | Table A- 192 | USDA 1996a, 2008 | 0.48 | Hashimoto 1984 | Table A- 192 | USDA 1996a, 2008 |
| Market Swine >180 lbs. | 91 | Safley 2000 | Table A- 192 | USDA 1996a, 2008 | 0.48 | Hashimoto 1984 | Table A- 192 | USDA 1996a, 2008 |
| Breeding Swine | 198 | Safley 2000 | Table A- 192 | USDA 1996a, 2008 | 0.48 | Hashimoto 1984 | Table A- 192 | USDA 1996a, 2008 |
| Feedlot Sheep | 25 | EPA 1992 | Table A- 192 | ASAE 1998, USDA 2008 | 0.36 | EPA 1992 | Table A- 192 | ASAE 1998, USDA 2008 |
| NOF Sheep | 80 | EPA 1992 | Table A- 192 | ASAE 1998, USDA 2008 | 0.19 | EPA 1992 | Table A- 192 | ASAE 1998, USDA 2008 |
| Goats | 64 | ASAE 1999 | Table A- 192 | ASAE 1998 | 0.17 | EPA 1992 | Table A- 192 | ASAE 1998 |
| Horses | 450 | ASAE 1999 | Table A- 192 | ASAE 1998, USDA 2008 | 0.33 | EPA 1992 | Table A- 192 | ASAE 1998, USDA 2008 |
| Mules and Asses | 130 | IPCC 2006 | Table A- 192 | IPCC 2006 | 0.33 | Horses | IPCC 2006 | IPCC 2006 |
| Hens >/= 1 yr | 1.8 | ASAE 1999 | Table A- 192 | USDA 1996a, 2008 | 0.39 | Hill 1982 | Table A- 192 | USDA 1996a, 2008 |
| Pullets | 1.8 | ASAE 1999 | Table A- 192 | USDA 1996a, 2008 | 0.39 | Hill 1982 | Table A- 192 | USDA 1996a, 2008 |
| Other Chickens | 1.8 | ASAE 1999 | Table A- 192 | USDA 1996a, 2008 | 0.39 | Hill 1982 | Table A- 192 | USDA 1996a, 2008 |
| Broilers | 0.9 | ASAE 1999 | Table A- 192 | USDA 1996a, 2008 | 0.36 | Hill 1984 | Table A- 192 | USDA 1996a, 2008 |
| Turkeys | 6.8 | ASAE 1999 | Table A- 192 | USDA 1996a, 2008 | 0.36 | Hill 1984 | Table A- 192 | USDA 1996a, 2008 |

Table A- 191: Estimated Volatile Solids and Nitrogen Excreted Production Rate by year for Animals Other Than Cattle (kg/day/1000 kg animal mass)

| Animal Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **VS** | | | | | | | | | | | | | | | | | | | | | | |
| Swine, Market <50 lbs. | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 | 8.8 |
| Swine, Market 50-119 lbs. | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 |
| Swine, Market 120-179lbs. | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 |
| Swine, Market >180 lbs. | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 |
| Swine Breeding | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 |
| NOF Calves | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.5 | 6.6 | 6.7 | 6.8 | 6.9 | 7.1 | 7.2 | 7.3 | 7.4 | 7.5 | 7.6 | 7.7 | 7.7 | 7.7 | 7.7 |
| Sheep | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 | 9.2 | 9.1 | 9.0 | 8.9 | 8.8 | 8.8 | 8.7 | 8.6 | 8.5 | 8.4 | 8.3 | 8.3 | 8.3 | 8.3 |
| Goats | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 | 9.5 |
| Hens >1yr. | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.2 | 10.2 | 10.2 | 10.2 | 10.2 | 10.2 |
| Pullets | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.1 | 10.2 | 10.2 | 10.2 | 10.2 | 10.2 | 10.2 |
| Chickens | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 | 10.9 | 10.9 | 10.9 | 10.9 | 10.9 | 10.9 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 | 11.0 |
| Broilers | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.2 | 15.3 | 15.5 | 15.7 | 15.8 | 16.0 | 16.2 | 16.3 | 16.5 | 16.7 | 16.8 | 17.0 | 17.0 | 17.0 | 17.0 |
| Turkeys | 9.7 | 9.7 | 9.7 | 9.7 | 9.7 | 9.7 | 9.7 | 9.6 | 9.5 | 9.4 | 9.3 | 9.2 | 9.1 | 9.0 | 8.9 | 8.8 | 8.7 | 8.6 | 8.5 | 8.5 | 8.5 | 8.5 |
| Horses | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 | 9.6 | 9.2 | 8.8 | 8.4 | 8.1 | 7.7 | 7.3 | 6.9 | 6.5 | 6.1 | 6.1 | 6.1 | 6.1 |
| Mules and Asses | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 |
| Swine, Market <50 lbs. | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.63 | 0.65 | 0.68 | 0.71 | 0.73 | 0.76 | 0.79 | 0.81 | 0.84 | 0.87 | 0.89 | 0.92 | 0.92 | 0.92 | 0.92 |
| Swine, Market 50-119 lbs. | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.43 | 0.44 | 0.45 | 0.46 | 0.47 | 0.48 | 0.49 | 0.50 | 0.51 | 0.52 | 0.53 | 0.54 | 0.54 | 0.54 | 0.54 |
| Swine, Market 120-179lbs. | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.43 | 0.44 | 0.45 | 0.46 | 0.47 | 0.48 | 0.49 | 0.50 | 0.51 | 0.52 | 0.53 | 0.54 | 0.54 | 0.54 | 0.54 |
| Swine, Market >180 lbs. | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.43 | 0.44 | 0.45 | 0.46 | 0.47 | 0.48 | 0.49 | 0.50 | 0.51 | 0.52 | 0.53 | 0.54 | 0.54 | 0.54 | 0.54 |
| Swine, Breeding | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.23 | 0.23 | 0.23 | 0.22 | 0.22 | 0.22 | 0.22 | 0.21 | 0.21 | 0.21 | 0.21 | 0.20 | 0.20 | 0.20 | 0.20 |
| NOF Calves | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.31 | 0.33 | 0.34 | 0.35 | 0.36 | 0.38 | 0.39 | 0.40 | 0.41 | 0.43 | 0.44 | 0.45 | 0.45 | 0.45 | 0.45 |
| Sheep | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.42 | 0.43 | 0.43 | 0.43 | 0.44 | 0.44 | 0.44 | 0.44 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 |
| Goats | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 |
| Hens >1yr. | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.71 | 0.72 | 0.73 | 0.73 | 0.74 | 0.75 | 0.76 | 0.77 | 0.77 | 0.78 | 0.79 | 0.79 | 0.79 | 0.79 |
| Pullets | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 | 0.71 | 0.72 | 0.73 | 0.73 | 0.74 | 0.75 | 0.76 | 0.77 | 0.77 | 0.78 | 0.79 | 0.79 | 0.79 | 0.79 |
| Chickens | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.85 | 0.88 | 0.90 | 0.92 | 0.94 | 0.97 | 0.99 | 1.01 | 1.03 | 1.06 | 1.08 | 1.10 | 1.10 | 1.10 | 1.10 |
| Broilers | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 1.09 | 1.08 | 1.07 | 1.05 | 1.04 | 1.03 | 1.02 | 1.01 | 1.00 | 0.98 | 0.97 | 0.96 | 0.96 | 0.96 | 0.96 |
| Turkeys | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 | 0.74 | 0.73 | 0.72 | 0.71 | 0.70 | 0.69 | 0.68 | 0.67 | 0.66 | 0.65 | 0.64 | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 |
| Horses | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.29 | 0.29 | 0.28 | 0.28 | 0.27 | 0.27 | 0.26 | 0.26 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| Mules and Asses | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |

Table A-192: Estimated Volatile Solids and Nitrogen Excreted Production Rate by State for Cattle for 2011 (kg/animal/year)

| State | Volatile Solids | | | | | | | | Nitrogen Excreted | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dairy Cow | Dairy Heifers | Beef NOF Cow | Beef NOF Heifers | Beef NOF Steer | Beef OF Heifers | Beef OF Steer | Beef NOF Bull[a] | Dairy Cow | Dairy Heifers | Beef NOF Cow | Beef NOF Heifers | Beef NOF Steer | Beef OF Heifers | Beef OF Steer | Beef NOF Bull[a] |
| Alabama | 2,138 | 1,254 | 1,664 | 1,093 | 968 | 668 | 649 | 1,721 | 130 | 69 | 73 | 50 | 42 | 53 | 54 | 83 |
| Alaska | 2,130 | 1,254 | 1,891 | 1,274 | 1,112 | 621 | 609 | 1,956 | 128 | 69 | 59 | 42 | 33 | 49 | 51 | 69 |
| Arizona | 2,852 | 1,254 | 1,891 | 1,242 | 1,112 | 690 | 668 | 1,956 | 159 | 69 | 59 | 40 | 33 | 55 | 56 | 69 |
| Arkansas | 1,988 | 1,254 | 1,664 | 1,088 | 968 | 674 | 655 | 1,721 | 122 | 69 | 73 | 50 | 42 | 54 | 55 | 83 |
| California | 2,831 | 1,254 | 1,891 | 1,210 | 1,112 | 673 | 653 | 1,956 | 158 | 69 | 59 | 39 | 33 | 53 | 55 | 69 |
| Colorado | 2,850 | 1,254 | 1,891 | 1,188 | 1,112 | 665 | 646 | 1,956 | 159 | 69 | 59 | 38 | 33 | 53 | 54 | 69 |
| Connecticut | 2,519 | 1,254 | 1,674 | 1,109 | 974 | 641 | 626 | 1,731 | 145 | 69 | 74 | 52 | 42 | 51 | 52 | 84 |
| Delaware | 2,466 | 1,254 | 1,674 | 1,070 | 974 | 656 | 639 | 1,731 | 143 | 69 | 74 | 49 | 42 | 52 | 53 | 84 |
| Florida | 2,578 | 1,254 | 1,664 | 1,106 | 968 | 657 | 640 | 1,721 | 149 | 69 | 73 | 51 | 42 | 52 | 53 | 83 |
| Georgia | 2,525 | 1,254 | 1,664 | 1,086 | 968 | 643 | 628 | 1,721 | 147 | 69 | 73 | 50 | 42 | 51 | 52 | 83 |
| Hawaii | 2,176 | 1,254 | 1,891 | 1,254 | 1,112 | 652 | 636 | 1,956 | 130 | 69 | 59 | 41 | 33 | 52 | 53 | 69 |
| Idaho | 2,812 | 1,254 | 1,891 | 1,205 | 1,112 | 661 | 643 | 1,956 | 157 | 69 | 59 | 38 | 33 | 52 | 54 | 69 |
| Illinois | 2,545 | 1,254 | 1,589 | 996 | 920 | 683 | 662 | 1,643 | 146 | 69 | 75 | 49 | 43 | 54 | 55 | 85 |
| Indiana | 2,636 | 1,254 | 1,589 | 1,002 | 920 | 667 | 648 | 1,643 | 150 | 69 | 75 | 49 | 43 | 53 | 54 | 85 |
| Iowa | 2,691 | 1,254 | 1,589 | 975 | 920 | 672 | 653 | 1,643 | 152 | 69 | 75 | 47 | 43 | 53 | 55 | 85 |
| Kansas | 2,672 | 1,254 | 1,589 | 974 | 920 | 673 | 653 | 1,643 | 151 | 69 | 75 | 47 | 43 | 53 | 55 | 85 |
| Kentucky | 2,222 | 1,254 | 1,664 | 1,075 | 968 | 674 | 655 | 1,721 | 134 | 69 | 73 | 49 | 42 | 54 | 55 | 83 |
| Louisiana | 2,066 | 1,254 | 1,664 | 1,102 | 968 | 632 | 618 | 1,721 | 125 | 69 | 73 | 51 | 42 | 50 | 51 | 83 |
| Maine | 2,495 | 1,254 | 1,674 | 1,089 | 974 | 629 | 616 | 1,731 | 144 | 69 | 74 | 50 | 42 | 50 | 51 | 84 |
| Maryland | 2,493 | 1,254 | 1,674 | 1,089 | 974 | 701 | 677 | 1,731 | 144 | 69 | 74 | 50 | 42 | 56 | 57 | 84 |
| Massachusetts | 2,363 | 1,254 | 1,674 | 1,091 | 974 | 662 | 644 | 1,731 | 138 | 69 | 74 | 50 | 42 | 52 | 54 | 84 |
| Michigan | 2,830 | 1,254 | 1,589 | 1,004 | 920 | 674 | 655 | 1,643 | 158 | 69 | 75 | 49 | 43 | 54 | 55 | 85 |
| Minnesota | 2,518 | 1,254 | 1,589 | 1,001 | 920 | 662 | 644 | 1,643 | 145 | 69 | 75 | 49 | 43 | 52 | 54 | 85 |
| Mississippi | 2,242 | 1,254 | 1,664 | 1,097 | 968 | 679 | 658 | 1,721 | 135 | 69 | 73 | 50 | 42 | 54 | 55 | 83 |
| Missouri | 2,191 | 1,254 | 1,589 | 1,029 | 920 | 701 | 677 | 1,643 | 131 | 69 | 75 | 51 | 43 | 56 | 57 | 85 |
| Montana | 2,636 | 1,254 | 1,664 | 1,089 | 968 | 656 | 639 | 1,721 | 150 | 69 | 73 | 50 | 42 | 52 | 53 | 83 |
| Nebraska | 2,637 | 1,254 | 1,891 | 1,186 | 1,112 | 672 | 652 | 1,956 | 150 | 69 | 59 | 37 | 33 | 53 | 55 | 69 |
| Nevada | 2,810 | 1,254 | 1,589 | 1,026 | 920 | 691 | 669 | 1,643 | 157 | 69 | 75 | 51 | 43 | 55 | 56 | 85 |
| New Hampshire | 2,625 | 1,254 | 1,891 | 1,252 | 1,112 | 714 | 688 | 1,956 | 149 | 69 | 59 | 41 | 33 | 57 | 58 | 69 |
| New Jersey | 2,369 | 1,254 | 1,674 | 1,088 | 974 | 659 | 642 | 1,731 | 138 | 69 | 74 | 50 | 42 | 52 | 54 | 84 |
| New Mexico | 2,956 | 1,254 | 1,674 | 1,080 | 974 | 644 | 629 | 1,731 | 164 | 69.0 | 127.2 | 85.6 | 74.7 | 53.2 | 54.3 | 139 |
| New York | 2,670 | 1,254 | 1,891 | 1,238 | 1,112 | 701 | 677 | 1,956 | 151 | 69.0 | 97.0 | 66.0 | 56.7 | 58.2 | 58.8 | 108 |
| North Carolina | 2,651 | 1,254 | 1,674 | 1,099 | 974 | 644 | 629 | 1,731 | 152 | 69.0 | 127.2 | 87.5 | 74.7 | 53.2 | 54.3 | 139 |
| North Dakota | 2,452 | 1,254 | 1,664 | 1,068 | 968 | 742 | 712 | 1,721 | 142 | 69.0 | 120.1 | 80.3 | 70.3 | 61.7 | 62.0 | 132 |
| Ohio | 2,532 | 1,254 | 1,589 | 1,017 | 920 | 694 | 671 | 1,643 | 145 | 69.0 | 121.4 | 81.0 | 70.9 | 57.6 | 58.2 | 133 |
| Oklahoma | 2,410 | 1,254 | 1,589 | 1,010 | 920 | 671 | 651 | 1,643 | 140 | 69.0 | 121.4 | 80.3 | 70.9 | 55.5 | 56.4 | 133 |
| Oregon | 2,630 | 1,254 | 1,664 | 1,067 | 968 | 674 | 655 | 1,721 | 150 | 69.0 | 120.1 | 80.2 | 70.3 | 55.8 | 56.7 | 132 |
| Pennsylvania | 2,563 | 1,254 | 1,891 | 1,226 | 1,112 | 674 | 655 | 1,956 | 147 | 69.0 | 97.0 | 65.2 | 56.7 | 55.8 | 56.7 | 108 |
| Rhode Island | 2,437 | 1,254 | 1,674 | 1,109 | 974 | 644 | 629 | 1,731 | 141 | 69.0 | 127.2 | 88.4 | 74.7 | 53.2 | 54.3 | 139 |
| South Carolina | 2,452 | 1,254 | 1,674 | 1,102 | 974 | 641 | 626 | 1,731 | 144 | 69.0 | 127.2 | 87.8 | 74.7 | 52.9 | 54.1 | 139 |
| South Dakota | 2,634 | 1,254 | 1,664 | 1,053 | 968 | 674 | 655 | 1,721 | 150 | 69.0 | 120.1 | 78.8 | 70.3 | 55.8 | 56.7 | 132 |
| Tennessee | 2,364 | 1,254 | 1,589 | 1,036 | 920 | 607 | 597 | 1,643 | 140 | 69.0 | 121.4 | 82.9 | 70.9 | 49.9 | 51.4 | 133 |
| Texas | 2,765 | 1,254 | 1,664 | 1,046 | 968 | 667 | 648 | 1,721 | 155 | 69.0 | 120.1 | 78.1 | 70.3 | 55.2 | 56.1 | 132 |

| State | Volatile Solids | | | | | | | | Nitrogen Excreted | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dairy Cow | Dairy Heifers | Beef NOF Cow | Beef NOF Heifers | Beef NOF Steer | Beef OF Heifers | Beef OF Steer | Beef NOF Bull[a] | Dairy Cow | Dairy Heifers | Beef NOF Cow | Beef NOF Heifers | Beef NOF Steer | Beef OF Heifers | Beef OF Steer | Beef NOF Bull[a] |
| Utah | 2,673 | 1,254 | 1,664 | 1,073 | 968 | 674 | 655 | 1,721 | 151 | 69.0 | 120.1 | 80.7 | 70.3 | 55.8 | 56.7 | 132 |
| Vermont | 2,514 | 1,254 | 1,891 | 1,233 | 1,112 | 657 | 640 | 1,956 | 145 | 69.0 | 97.0 | 65.7 | 56.7 | 54.3 | 55.4 | 108 |
| Virginia | 2,491 | 1,254 | 1,674 | 1,090 | 974 | 674 | 655 | 1,731 | 145 | 69.0 | 127.2 | 86.6 | 74.7 | 55.8 | 56.7 | 139 |
| Washington | 2,872 | 1,254 | 1,664 | 1,054 | 968 | 644 | 629 | 1,721 | 160 | 69.0 | 120.1 | 78.9 | 70.3 | 53.2 | 54.3 | 132 |
| West Virginia | 2,264 | 1,254 | 1,891 | 1,250 | 1,112 | 728 | 700 | 1,956 | 134 | 69.0 | 97.0 | 66.9 | 56.7 | 60.5 | 60.9 | 108 |
| Wisconsin | 2,642 | 1,254 | 1,589 | 1,025 | 920 | 669 | 650 | 1,643 | 150 | 69.0 | 121.4 | 81.9 | 70.9 | 55.4 | 56.3 | 133 |
| Wyoming | 2,632 | 1,254 | 1,891 | 1,229 | 1,112 | 672 | 653 | 1,956 | 150 | 69.0 | 97.0 | 65.4 | 56.7 | 55.6 | 56.5 | 108 |

Source: CEFM

[a]Beef NOF Bull values were used for Bison Nex and VS.

Table A-193: 2011 Manure Distribution Among Waste Management Systems by Operation (Percent)

| State | Beef Feedlots | | Dairies[1] | | | | | | Dairy Heifer Facilities | | | | Swine Operations[1] | | | | | Layer Operations | | Broiler and Turkey Operations | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dry Lot[2] | Liquid/ Slurry[2] | Pasture | Daily Spread | Solid Storage | Liquid/ Slurry | Anaerobic Lagoon | Deep Pit | Daily Spread[2] | Dry Lot[2] | Liquid/ Slurry[2] | Pasture[2] | Pasture | Solid Storage | Liquid/ Slurry | Anaerobic Lagoon | Deep Pit | Anaerobic Lagoon | Poultry without Litter | Pasture | Poultry with Litter |
| Alabama | 100 | 1 | 51 | 16 | 7 | 10 | 16 | 0 | 17 | 38 | 0 | 45 | 5 | 4 | 7 | 54 | 31 | 42 | 58 | 1 | 99 |
| Alaska | 100 | 1 | 5 | 9 | 34 | 19 | 24 | 9 | 6 | 90 | 1 | 4 | 64 | 2 | 10 | 7 | 17 | 25 | 75 | 1 | 99 |
| Arizona | 100 | 0 | 0 | 10 | 9 | 19 | 61 | 0 | 10 | 90 | 0 | 0 | 6 | 3 | 6 | 55 | 29 | 60 | 40 | 1 | 99 |
| Arkansas | 100 | 1 | 60 | 14 | 10 | 7 | 9 | 0 | 15 | 28 | 0 | 57 | 4 | 4 | 13 | 45 | 35 | 0 | 100 | 1 | 99 |
| California | 100 | 1 | 1 | 11 | 9 | 20 | 59 | 0 | 11 | 88 | 1 | 1 | 10 | 3 | 7 | 50 | 29 | 12 | 88 | 1 | 99 |
| Colorado | 100 | 0 | 1 | 1 | 11 | 23 | 64 | 0 | 1 | 98 | 0 | 1 | 1 | 6 | 26 | 17 | 50 | 60 | 40 | 1 | 99 |
| Connecticut | 100 | 1 | 6 | 43 | 16 | 20 | 13 | 2 | 43 | 51 | 0 | 6 | 78 | 1 | 6 | 5 | 11 | 5 | 95 | 1 | 99 |
| Delaware | 100 | 1 | 6 | 44 | 19 | 19 | 10 | 2 | 44 | 50 | 0 | 6 | 8 | 5 | 25 | 17 | 46 | 5 | 95 | 1 | 99 |
| Florida | 100 | 1 | 13 | 22 | 7 | 15 | 43 | 0 | 22 | 61 | 1 | 17 | 72 | 1 | 8 | 6 | 13 | 42 | 58 | 1 | 99 |
| Georgia | 100 | 1 | 37 | 18 | 9 | 12 | 23 | 0 | 18 | 42 | 0 | 40 | 4 | 4 | 8 | 53 | 31 | 42 | 58 | 1 | 99 |
| Hawaii | 100 | 1 | 10 | 0 | 9 | 23 | 57 | 0 | 0 | 99 | 1 | 1 | 31 | 3 | 19 | 14 | 32 | 25 | 75 | 1 | 99 |
| Idaho | 100 | 0 | 0 | 0 | 11 | 23 | 65 | 0 | 1 | 99 | 0 | 0 | 12 | 5 | 23 | 15 | 44 | 60 | 40 | 1 | 99 |
| Illinois | 100 | 1 | 4 | 6 | 39 | 31 | 16 | 5 | 8 | 87 | 0 | 5 | 1 | 5 | 29 | 14 | 52 | 2 | 98 | 1 | 99 |
| Indiana | 100 | 1 | 5 | 8 | 29 | 31 | 24 | 3 | 13 | 79 | 0 | 8 | 1 | 5 | 28 | 14 | 52 | 0 | 100 | 1 | 99 |
| Iowa | 100 | 1 | 4 | 8 | 34 | 30 | 20 | 4 | 10 | 83 | 0 | 6 | 1 | 4 | 9 | 54 | 33 | 0 | 100 | 1 | 99 |
| Kansas | 100 | 1 | 2 | 3 | 21 | 37 | 36 | 2 | 5 | 92 | 0 | 3 | 2 | 5 | 28 | 13 | 52 | 2 | 98 | 1 | 99 |
| Kentucky | 100 | 1 | 60 | 14 | 14 | 7 | 3 | 2 | 14 | 24 | 0 | 61 | 5 | 4 | 10 | 48 | 33 | 5 | 95 | 1 | 99 |
| Louisiana | 100 | 1 | 59 | 15 | 10 | 7 | 9 | 1 | 14 | 26 | 0 | 60 | 88 | 1 | 3 | 3 | 6 | 60 | 40 | 1 | 99 |
| Maine | 100 | 1 | 7 | 45 | 20 | 17 | 10 | 2 | 45 | 48 | 0 | 7 | 65 | 2 | 10 | 7 | 16 | 5 | 95 | 1 | 99 |
| Maryland | 100 | 1 | 7 | 44 | 22 | 16 | 8 | 3 | 44 | 49 | 0 | 7 | 7 | 5 | 25 | 17 | 47 | 5 | 95 | 1 | 99 |
| Massachusetts | 100 | 1 | 7 | 44 | 22 | 16 | 8 | 3 | 45 | 47 | 0 | 7 | 56 | 2 | 12 | 9 | 20 | 5 | 95 | 1 | 99 |
| Michigan | 100 | 1 | 2 | 4 | 24 | 38 | 29 | 3 | 6 | 91 | 0 | 3 | 4 | 5 | 26 | 17 | 48 | 2 | 98 | 1 | 99 |
| Minnesota | 100 | 1 | 5 | 8 | 39 | 28 | 17 | 4 | 10 | 84 | 0 | 6 | 1 | 5 | 26 | 18 | 50 | 0 | 100 | 1 | 99 |
| Mississippi | 100 | 1 | 54 | 15 | 10 | 8 | 12 | 0 | 15 | 28 | 0 | 57 | 2 | 4 | 6 | 58 | 31 | 60 | 40 | 1 | 99 |
| Missouri | 100 | 1 | 7 | 12 | 42 | 22 | 11 | 5 | 14 | 77 | 0 | 8 | 2 | 5 | 28 | 13 | 52 | 0 | 100 | 1 | 99 |
| Montana | 100 | 0 | 2 | 4 | 19 | 28 | 42 | 4 | 4 | 93 | 0 | 3 | 3 | 5 | 25 | 17 | 49 | 60 | 40 | 1 | 99 |

| | Beef Feedlots | | Dairies[1] | | | | | | Dairy Heifer Facilities | | | | Swine Operations[1] | | | | | Layer Operations | | Broiler and Turkey Operations | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| State | Dry Lot[2] | Liquid/ Slurry[2] | Pasture | Daily Spread | Solid Storage | Liquid/ Slurry | Anaerobic Lagoon | Deep Pit | Daily Spread[2] | Dry Lot[2] | Liquid/ Slurry[2] | Pasture[2] | Pasture | Solid Storage | Liquid/ Slurry | Anaerobic Lagoon | Deep Pit | Anaerobic Lagoon | Poultry without Litter | Pasture | Poultry with Litter |
| Nebraska | 100 | 1 | 2 | 4 | 26 | 35 | 29 | 3 | 6 | 90 | 0 | 4 | 1 | 5 | 28 | 14 | 51 | 2 | 98 | 1 | 99 |
| Nevada | 100 | 0 | 0 | 0 | 10 | 24 | 65 | 0 | 0 | 99 | 0 | 0 | 34 | 3 | 18 | 14 | 31 | 0 | 100 | 1 | 99 |
| New Hampshire | 100 | 1 | 7 | 44 | 19 | 18 | 10 | 2 | 44 | 49 | 0 | 7 | 64 | 2 | 10 | 8 | 17 | 5 | 95 | 1 | 99 |
| New Jersey | 100 | 1 | 7 | 45 | 25 | 13 | 6 | 3 | 45 | 47 | 0 | 8 | 36 | 3 | 18 | 14 | 30 | 5 | 95 | 1 | 99 |
| New Mexico | 100 | 0 | 0 | 10 | 9 | 19 | 61 | 0 | 10 | 90 | 0 | 0 | 100 | 0 | 0 | 0 | 0 | 60 | 40 | 1 | 99 |
| New York | 100 | 1 | 6 | 44 | 17 | 18 | 13 | 2 | 45 | 48 | 0 | 7 | 13 | 5 | 23 | 15 | 44 | 5 | 95 | 1 | 99 |
| North Carolina | 100 | 1 | 46 | 17 | 11 | 15 | 10 | 2 | 15 | 31 | 0 | 54 | 0 | 4 | 7 | 57 | 32 | 42 | 58 | 1 | 99 |
| North Dakota | 100 | 1 | 7 | 11 | 38 | 26 | 15 | 4 | 11 | 83 | 0 | 6 | 5 | 5 | 25 | 17 | 48 | 2 | 98 | 1 | 99 |
| Ohio | 100 | 1 | 6 | 11 | 38 | 26 | 15 | 4 | 14 | 78 | 0 | 8 | 3 | 5 | 28 | 14 | 51 | 0 | 100 | 1 | 99 |
| Oklahoma | 100 | 0 | 0 | 7 | 21 | 22 | 45 | 4 | 6 | 94 | 0 | 0 | 1 | 4 | 6 | 58 | 31 | 60 | 40 | 1 | 99 |
| Oregon | 100 | 1 | 16 | 0 | 11 | 22 | 50 | 1 | 0 | 80 | 1 | 20 | 48 | 2 | 14 | 11 | 24 | 25 | 75 | 1 | 99 |
| Pennsylvania | 100 | 1 | 8 | 46 | 24 | 12 | 6 | 2 | 47 | 44 | 0 | 9 | 4 | 5 | 26 | 18 | 48 | 0 | 100 | 1 | 99 |
| Rhode Island | 100 | 1 | 9 | 47 | 25 | 13 | 5 | 2 | 47 | 44 | 0 | 9 | 72 | 1 | 8 | 6 | 13 | 5 | 95 | 1 | 99 |
| South Carolina | 100 | 1 | 47 | 17 | 8 | 11 | 18 | 0 | 15 | 31 | 0 | 54 | 3 | 4 | 7 | 55 | 31 | 60 | 40 | 1 | 99 |
| South Dakota | 100 | 1 | 3 | 4 | 24 | 36 | 31 | 2 | 8 | 87 | 0 | 5 | 1 | 5 | 26 | 17 | 50 | 2 | 98 | 1 | 99 |
| Tennessee | 100 | 1 | 58 | 15 | 12 | 9 | 4 | 2 | 15 | 26 | 0 | 59 | 13 | 3 | 11 | 41 | 32 | 5 | 95 | 1 | 99 |
| Texas | 100 | 0 | 0 | 9 | 11 | 22 | 58 | 1 | 8 | 92 | 0 | 0 | 3 | 4 | 6 | 57 | 30 | 12 | 88 | 1 | 99 |
| Utah | 100 | 0 | 1 | 1 | 15 | 26 | 56 | 2 | 1 | 98 | 0 | 1 | 1 | 6 | 26 | 17 | 51 | 60 | 40 | 1 | 99 |
| Vermont | 100 | 1 | 6 | 44 | 17 | 19 | 13 | 2 | 44 | 49 | 0 | 7 | 63 | 2 | 10 | 8 | 18 | 5 | 95 | 1 | 99 |
| Virginia | 100 | 1 | 56 | 15 | 11 | 10 | 5 | 2 | 15 | 28 | 0 | 57 | 4 | 4 | 7 | 54 | 31 | 5 | 95 | 1 | 99 |
| Washington | 100 | 1 | 11 | 0 | 11 | 22 | 56 | 1 | 0 | 83 | 1 | 17 | 43 | 3 | 15 | 11 | 28 | 12 | 88 | 1 | 99 |
| West Virginia | 100 | 1 | 8 | 46 | 23 | 14 | 7 | 2 | 45 | 48 | 0 | 7 | 59 | 2 | 11 | 7 | 20 | 5 | 95 | 1 | 99 |
| Wisconsin | 100 | 1 | 5 | 9 | 38 | 28 | 17 | 4 | 12 | 82 | 0 | 7 | 13 | 4 | 23 | 17 | 42 | 2 | 98 | 1 | 99 |
| Wyoming | 100 | 0 | 4 | 6 | 19 | 23 | 43 | 4 | 12 | 81 | 0 | 7 | 4 | 5 | 25 | 16 | 49 | 60 | 40 | 1 | 99 |

[1] In the methane inventory for manure management, the percent of dairy cows and swine with anaerobic digestion systems is estimated using data from EPA's AgSTAR Program.

[2] Because manure from beef feedlots and dairy heifers may be managed for long periods of time in multiple systems (i.e., both drylot and runoff collection pond), the percent of manure that generates emissions is greater than 100 percent.

Table A-194: Manure Management System Descriptions

| Manure Management System | Description[1] |
|---|---|
| Pasture | The manure from pasture and range grazing animals is allowed to lie as is, and is not managed. $N_2O$ emissions from deposited manure are covered under the $N_2O$ from Agricultural Soils category. |
| Daily Spread | Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion. $N_2O$ emissions during storage and treatment are assumed to be zero. $N_2O$ emissions from land application are covered under the Agricultural Soils category. |
| Solid Storage | The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked due to the presence of a sufficient amount of bedding material or loss of moisture by evaporation. |
| Dry Lot | A paved or unpaved open confinement area without any significant vegetative cover where accumulating manure may be removed periodically. Dry lots are most typically found in dry climates but also are used in humid climates. |
| Liquid/ Slurry | Manure is stored as excreted or with some minimal addition of water to facilitate handling and is stored in either tanks or earthen ponds, usually for periods less than one year. |
| Anaerobic Lagoon | Uncovered anaerobic lagoons are designed and operated to combine waste stabilization and storage. Lagoon supernatant is usually used to remove manure from the associated confinement facilities to the lagoon. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the volatile solids loading rate, and other operational factors. Anaerobic lagoons accumulate sludge over time, diminishing treatment capacity. Lagoons must be cleaned out once every 5 to 15 years, and the sludge is typically applied to agricultural lands. The water from the lagoon may be recycled as flush water or used to irrigate and fertilize fields. Lagoons are sometimes used in combination with a solids separator, typically for dairy waste. Solids separators help control the buildup of nondegradable material such as straw or other bedding materials. |
| Anaerobic Digester | Animal excreta with or without straw are collected and anaerobically digested in a large containment vessel or covered lagoon. Digesters are designed and operated for waste stabilization by the microbial reduction of complex organic compounds to CO2 and CH4, which is captured and flared or used as a fuel. |
| Deep Pit | Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility. Typical storage periods range from 5 to 12 months, after which manure is removed from the pit and transferred to a treatment system or applied to land. |
| Poultry with Litter | Enclosed poultry houses use bedding derived from wood shavings, rice hulls, chopped straw, peanut hulls, or other products, depending on availability. The bedding absorbs moisture and dilutes the manure produced by the birds. Litter is typically cleaned out completely once a year. These manure systems are typically used for all poultry breeder flocks and for the production of meat type chickens (broilers) and other fowl. |
| Poultry without Litter | In high-rise cages or scrape-out/belt systems, manure is excreted onto the floor below with no bedding to absorb moisture. The ventilation system dries the manure as it is stored. When designed and operated properly, this high-rise system is a form of passive windrow composting. |

[1] Manure management system descriptions are from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (Volume 4: Agriculture, Forestry and Other Land Use, Chapter 10: Emissions from Livestock and Manure Management, Tables 10.18 and 10.21) and the *Development Document for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations* (EPA-821-R-03-001, December 2002).

Table A-195: Methane Conversion Factors (percent) for Dry Systems

| Waste Management System | Cool Climate MCF | Temperate Climate MCF | Warm Climate MCF |
|---|---|---|---|
| Aerobic Treatment | 0 | 0 | 0 |
| Cattle Deep Litter (<1 month) | 0.03 | 0.03 | 0.3 |
| Cattle Deep Litter (>1 month) | 0.21 | 0.44 | 0.76 |
| Composting - In Vessel | 0.005 | 0.005 | 0.005 |
| Composting - Static Pile | 0.005 | 0.005 | 0.005 |
| Composting-Extensive/ Passive | 0.005 | 0.01 | 0.015 |
| Composting-Intensive | 0.005 | 0.01 | 0.015 |
| Daily Spread | 0.001 | 0.005 | 0.01 |
| Dry Lot | 0.01 | 0.015 | 0.05 |
| Fuel | 0.1 | 0.1 | 0.1 |
| Pasture | 0.01 | 0.015 | 0.02 |
| Poultry with bedding | 0.015 | 0.015 | 0.015 |
| Poultry without bedding | 0.015 | 0.015 | 0.015 |

| Waste Management System | Cool Climate MCF | Temperate Climate MCF | Warm Climate MCF |
|---|---|---|---|
| Solid Storage | 0.02 | 0.04 | 0.05 |

Table A-196: Methane Conversion Factors by State for Liquid Systems for 2011 (percent)

| State | Dairy | | Swine | | Beef | Poultry |
|---|---|---|---|---|---|---|
| | Anaerobic Lagoon | Liquid/Slurry and Deep Pit | Anaerobic Lagoon | Liquid/Slurry and Deep Pit | Liquid/Slurry | Anaerobic Lagoon |
| Alabama | 0.77 | 0.41 | 0.76 | 0.40 | 0.42 | 0.76 |
| Alaska | 0.47 | 0.15 | 0.47 | 0.15 | 0.15 | 0.47 |
| Arizona | 0.79 | 0.58 | 0.78 | 0.49 | 0.54 | 0.75 |
| Arkansas | 0.76 | 0.39 | 0.77 | 0.43 | 0.40 | 0.76 |
| California | 0.75 | 0.33 | 0.73 | 0.31 | 0.41 | 0.75 |
| Colorado | 0.65 | 0.22 | 0.68 | 0.24 | 0.24 | 0.65 |
| Connecticut | 0.70 | 0.26 | 0.71 | 0.26 | 0.26 | 0.70 |
| Delaware | 0.76 | 0.35 | 0.76 | 0.35 | 0.35 | 0.76 |
| Florida | 0.80 | 0.55 | 0.80 | 0.54 | 0.54 | 0.80 |
| Georgia | 0.78 | 0.44 | 0.77 | 0.42 | 0.42 | 0.76 |
| Hawaii | 0.76 | 0.57 | 0.76 | 0.57 | 0.57 | 0.76 |
| Idaho | 0.67 | 0.23 | 0.65 | 0.21 | 0.21 | 0.67 |
| Illinois | 0.73 | 0.31 | 0.72 | 0.30 | 0.29 | 0.73 |
| Indiana | 0.71 | 0.28 | 0.72 | 0.29 | 0.29 | 0.72 |
| Iowa | 0.70 | 0.26 | 0.70 | 0.26 | 0.26 | 0.70 |
| Kansas | 0.75 | 0.36 | 0.75 | 0.35 | 0.35 | 0.75 |
| Kentucky | 0.74 | 0.33 | 0.74 | 0.33 | 0.32 | 0.74 |
| Louisiana | 0.78 | 0.48 | 0.78 | 0.50 | 0.50 | 0.78 |
| Maine | 0.65 | 0.21 | 0.65 | 0.21 | 0.21 | 0.65 |
| Maryland | 0.74 | 0.32 | 0.74 | 0.32 | 0.33 | 0.75 |
| Massachusetts | 0.68 | 0.24 | 0.69 | 0.25 | 0.25 | 0.69 |
| Michigan | 0.68 | 0.24 | 0.69 | 0.25 | 0.24 | 0.68 |
| Minnesota | 0.68 | 0.24 | 0.69 | 0.25 | 0.25 | 0.67 |
| Mississippi | 0.77 | 0.44 | 0.76 | 0.42 | 0.44 | 0.77 |
| Missouri | 0.74 | 0.34 | 0.74 | 0.33 | 0.33 | 0.74 |
| Montana | 0.61 | 0.19 | 0.63 | 0.20 | 0.21 | 0.63 |
| Nebraska | 0.71 | 0.27 | 0.71 | 0.28 | 0.27 | 0.71 |
| Nevada | 0.69 | 0.24 | 0.71 | 0.26 | 0.23 | 0.70 |
| New Hampshire | 0.66 | 0.23 | 0.67 | 0.23 | 0.22 | 0.67 |
| New Jersey | 0.73 | 0.31 | 0.74 | 0.31 | 0.30 | 0.74 |
| New Mexico | 0.75 | 0.35 | 0.73 | 0.30 | 0.32 | 0.71 |
| New York | 0.68 | 0.24 | 0.69 | 0.24 | 0.24 | 0.69 |
| North Carolina | 0.75 | 0.34 | 0.77 | 0.40 | 0.32 | 0.75 |
| North Dakota | 0.66 | 0.22 | 0.66 | 0.22 | 0.22 | 0.65 |
| Ohio | 0.71 | 0.28 | 0.72 | 0.28 | 0.28 | 0.71 |
| Oklahoma | 0.77 | 0.47 | 0.77 | 0.43 | 0.44 | 0.77 |
| Oregon | 0.63 | 0.20 | 0.64 | 0.20 | 0.22 | 0.64 |
| Pennsylvania | 0.71 | 0.28 | 0.72 | 0.29 | 0.28 | 0.72 |
| Rhode Island | 0.71 | 0.27 | 0.71 | 0.27 | 0.27 | 0.71 |
| South Carolina | 0.77 | 0.42 | 0.78 | 0.43 | 0.41 | 0.77 |
| South Dakota | 0.69 | 0.25 | 0.70 | 0.25 | 0.25 | 0.69 |
| Tennessee | 0.74 | 0.33 | 0.75 | 0.36 | 0.34 | 0.74 |
| Texas | 0.77 | 0.48 | 0.78 | 0.50 | 0.44 | 0.78 |
| Utah | 0.67 | 0.23 | 0.69 | 0.24 | 0.24 | 0.67 |
| Vermont | 0.65 | 0.22 | 0.65 | 0.22 | 0.22 | 0.66 |
| Virginia | 0.73 | 0.30 | 0.75 | 0.34 | 0.31 | 0.74 |
| Washington | 0.63 | 0.20 | 0.64 | 0.21 | 0.22 | 0.64 |
| West Virginia | 0.71 | 0.28 | 0.71 | 0.28 | 0.28 | 0.71 |
| Wisconsin | 0.67 | 0.23 | 0.68 | 0.24 | 0.24 | 0.68 |
| Wyoming | 0.63 | 0.20 | 0.64 | 0.21 | 0.22 | 0.64 |

Table A-197: Direct Nitrous Oxide Emission Factors for 2011 (kg $N_2O$-N/kg Kjdl N)

| Waste Management System | Direct $N_2O$ Emission Factor |
|---|---|
| Aerobic Treatment (forced aeration) | 0.005 |
| Aerobic Treatment (natural aeration) | 0.01 |
| Anaerobic Digester | 0 |
| Anaerobic Lagoon | 0 |
| Cattle Deep Bed (active mix) | 0.07 |
| Cattle Deep Bed (no mix) | 0.01 |
| Composting_in vessel | 0.006 |
| Composting_intensive | 0.1 |
| Composting_passive | 0.01 |
| Composting_static | 0.006 |
| Daily Spread | 0 |
| Deep Pit | 0.002 |
| Dry Lot | 0.02 |
| Fuel | 0 |
| Liquid/Slurry | 0.005 |
| Pasture | 0 |
| Poultry with bedding | 0.001 |
| Poultry without bedding | 0.001 |
| Solid Storage | 0.005 |

Table A-198: Indirect Nitrous Oxide Loss Factors (percent)

| Animal Type | Waste Management System | Volatilization Nitrogen Loss | Runoff/Leaching Nitrogen Loss[1] | | | | |
|---|---|---|---|---|---|---|---|
| | | | Central | Pacific | Mid-Atlantic | Midwest | South |
| Beef Cattle | Dry Lot | 23 | 1.1 | 3.9 | 3.6 | 1.9 | 4.3 |
| Beef Cattle | Liquid/Slurry | 26 | 0 | 0 | 0 | 0 | 0 |
| Beef Cattle | Pasture | 0 | 0 | 0 | 0 | 0 | 0 |
| Dairy Cattle | Anaerobic Lagoon | 43 | 0.2 | 0.8 | 0.7 | 0.4 | 0.9 |
| Dairy Cattle | Daily Spread | 10 | 0 | 0 | 0 | 0 | 0 |
| Dairy Cattle | Deep Pit | 24 | 0 | 0 | 0 | 0 | 0 |
| Dairy Cattle | Dry Lot | 15 | 0.6 | 2 | 1.8 | 0.9 | 2.2 |
| Dairy Cattle | Liquid/Slurry | 26 | 0.2 | 0.8 | 0.7 | 0.4 | 0.9 |
| Dairy Cattle | Pasture | 0 | 0 | 0 | 0 | 0 | 0 |
| Dairy Cattle | Solid Storage | 27 | 0.2 | 0 | 0 | 0 | 0 |
| Bison | Pasture | 0 | 0 | 0 | 0 | 0 | 0 |
| Goats | Dry Lot | 23 | 1.1 | 3.9 | 3.6 | 1.9 | 4.3 |
| Goats | Pasture | 0 | 0 | 0 | 0 | 0 | 0 |
| Horses | Dry Lot | 23 | 0 | 0 | 0 | 0 | 0 |
| Horses | Pasture | 0 | 0 | 0 | 0 | 0 | 0 |
| Mules and Asses | Dry Lot | 23 | 0 | 0 | 0 | 0 | 0 |
| Mules and Asses | Pasture | 0 | 0 | 0 | 0 | 0 | 0 |
| Poultry | Anaerobic Lagoon | 54 | 0.2 | 0.8 | 0.7 | 0.4 | 0.9 |
| Poultry | Liquid/Slurry | 26 | 0.2 | 0.8 | 0.7 | 0.4 | 0.9 |
| Poultry | Pasture | 0 | 0 | 0 | 0 | 0 | 0 |
| Poultry | Poultry with bedding | 26 | 0 | 0 | 0 | 0 | 0 |
| Poultry | Poultry without bedding | 34 | 0 | 0 | 0 | 0 | 0 |
| Poultry | Solid Storage | 8 | 0 | 0 | 0 | 0 | 0 |
| Sheep | Dry Lot | 23 | 1.1 | 3.9 | 3.6 | 1.9 | 4.3 |
| Sheep | Pasture | 0 | 0 | 0 | 0 | 0 | 0 |
| Swine | Anaerobic Lagoon | 58 | 0.2 | 0.8 | 0.7 | 0.4 | 0.9 |
| Swine | Deep Pit | 34 | 0 | 0 | 0 | 0 | 0 |
| Swine | Liquid/Slurry | 26 | 0.2 | 0.8 | 0.7 | 0.4 | 0.9 |
| Swine | Pasture | 0 | 0 | 0 | 0 | 0 | 0 |
| Swine | Solid Storage | 45 | 0 | 0 | 0 | 0 | 0 |

[1] Data for nitrogen losses due to leaching were not available, so the values represent only nitrogen losses due to runoff.

Table A- 199: Methane Emissions from Livestock Manure Management (Gg) [a]

| Animal Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dairy Cattle** | 599 | 615 | 598 | 623 | 663 | 693 | 702 | 734 | 781 | 854 | 900 | 960 | 997 | 1047 | 1000 | 1069 | 1101 | 1224 | 1238 | 1233 | 1239 | 1262 |
| Dairy Cows | 592 | 608 | 591 | 616 | 656 | 686 | 695 | 727 | 774 | 846 | 893 | 952 | 990 | 1039 | 993 | 1062 | 1094 | 1216 | 1230 | 1225 | 1231 | 1254 |
| Dairy Heifer | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 8 | 8 | 8 | 8 | 8 |
| **Swine** | 624 | 676 | 639 | 680 | 741 | 764 | 730 | 783 | 892 | 849 | 834 | 854 | 879 | 860 | 857 | 914 | 901 | 982 | 938 | 896 | 948 | 941 |
| Market Swine | 484 | 524 | 500 | 534 | 585 | 608 | 582 | 626 | 720 | 692 | 680 | 696 | 720 | 706 | 706 | 753 | 741 | 814 | 780 | 748 | 792 | 787 |
| Market <50 lbs. | 102 | 110 | 104 | 109 | 119 | 121 | 116 | 125 | 141 | 133 | 131 | 134 | 137 | 135 | 135 | 142 | 141 | 155 | 109 | 103 | 110 | 110 |
| Market 50-119 lbs. | 101 | 111 | 105 | 110 | 120 | 124 | 117 | 127 | 144 | 138 | 136 | 138 | 144 | 140 | 141 | 150 | 148 | 163 | 174 | 167 | 177 | 0 |
| Market 120-179 lbs. | 136 | 147 | 140 | 151 | 164 | 170 | 163 | 175 | 201 | 193 | 189 | 192 | 199 | 196 | 196 | 210 | 206 | 227 | 229 | 218 | 231 | 228 |
| Market >180 lbs. | 145 | 156 | 152 | 165 | 182 | 194 | 185 | 198 | 235 | 229 | 225 | 232 | 240 | 234 | 234 | 251 | 246 | 269 | 268 | 259 | 273 | 272 |
| Breeding Swine | 140 | 152 | 139 | 146 | 156 | 155 | 148 | 157 | 172 | 157 | 155 | 158 | 158 | 154 | 151 | 161 | 160 | 168 | 157 | 148 | 156 | 154 |
| **Beef Cattle** | 128 | 128 | 131 | 131 | 137 | 141 | 139 | 136 | 139 | 139 | 133 | 136 | 133 | 133 | 131 | 135 | 138 | 136 | 132 | 131 | 134 | 132 |
| Feedlot Steers | 14 | 14 | 14 | 13 | 14 | 14 | 14 | 13 | 13 | 14 | 15 | 15 | 15 | 16 | 15 | 15 | 16 | 16 | 16 | 16 | 16 | 16 |
| Feedlot Heifers | 7 | 7 | 7 | 7 | 8 | 8 | 8 | 8 | 8 | 8 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| NOF Bulls | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| NOF Calves | 8 | 8 | 8 | 8 | 9 | 9 | 8 | 8 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 10 | 10 | 9 | 9 | 9 | 9 |
| NOF Heifers | 12 | 12 | 13 | 14 | 14 | 15 | 15 | 14 | 15 | 14 | 13 | 13 | 13 | 13 | 12 | 13 | 13 | 13 | 13 | 13 | 13 | 12 |
| NOF Steers | 12 | 12 | 13 | 14 | 13 | 14 | 14 | 13 | 13 | 12 | 11 | 11 | 11 | 10 | 10 | 10 | 10 | 11 | 10 | 11 | 11 | 10 |
| NOF Cows | 69 | 69 | 70 | 71 | 74 | 76 | 76 | 74 | 76 | 76 | 71 | 73 | 71 | 71 | 71 | 73 | 74 | 73 | 70 | 69 | 71 | 70 |
| **Sheep** | 7 | 7 | 7 | 6 | 6 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **Goats** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Poultry** | 131 | 132 | 127 | 131 | 131 | 128 | 126 | 128 | 130 | 126 | 127 | 131 | 129 | 130 | 129 | 129 | 131 | 134 | 129 | 128 | 129 | 127 |
| Hens >1 yr. | 73 | 72 | 70 | 73 | 72 | 69 | 68 | 67 | 70 | 66 | 67 | 70 | 67 | 68 | 66 | 66 | 66 | 67 | 64 | 64 | 64 | 64 |
| Total Pullets | 25 | 26 | 23 | 23 | 23 | 22 | 21 | 23 | 23 | 21 | 22 | 22 | 22 | 22 | 23 | 22 | 23 | 25 | 23 | 23 | 24 | 23 |
| Chickens | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 4 | 4 | 3 | 3 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 3 |
| Broilers | 19 | 20 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 28 | 29 | 29 | 30 | 31 | 32 | 32 | 33 | 31 | 31 | 31 |
| Turkeys | 10 | 10 | 10 | 10 | 9 | 9 | 9 | 9 | 8 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 6 | 6 | 6 |
| **Horses** | 9 | 10 | 10 | 10 | 11 | 11 | 12 | 12 | 13 | 13 | 13 | 13 | 13 | 13 | 12 | 12 | 12 | 11 | 10 | 11 | 11 | 11 |
| **Mules and Asses** | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| **Bison** | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |

[a] Accounts for $CH_4$ reductions due to capture and destruction of $CH_4$ at facilities using anaerobic digesters.
+ Emission estimate is less than 0.5 Gg.

Table A- 200: Total (Direct and Indirect) Nitrous Oxide Emissions from Livestock Manure Management (Gg)

| Animal Type | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dairy Cattle** | 17.1 | 17.0 | 17.0 | 17.3 | 17.4 | 17.7 | 17.7 | 17.9 | 18.0 | 17.6 | 17.9 | 18.2 | 18.5 | 18.7 | 17.8 | 18.3 | 18.9 | 18.9 | 18.6 | 18.8 | 18.9 | 19.0 |
| Dairy Cows | 10.0 | 10.1 | 10.0 | 10.0 | 10.1 | 10.3 | 10.3 | 10.4 | 10.5 | 10.2 | 10.5 | 10.5 | 10.6 | 10.8 | 10.3 | 10.5 | 10.8 | 10.8 | 10.6 | 10.8 | 10.6 | 10.8 |
| Dairy Heifer | 7.0 | 6.9 | 7.1 | 7.2 | 7.3 | 7.4 | 7.4 | 7.4 | 7.5 | 7.4 | 7.5 | 7.7 | 7.8 | 7.9 | 7.5 | 7.8 | 8.1 | 8.1 | 8.0 | 8.0 | 8.2 | 8.3 |
| **Swine** | 4.0 | 4.2 | 4.3 | 4.4 | 4.6 | 4.5 | 4.4 | 4.7 | 5.1 | 5.0 | 5.0 | 5.1 | 5.3 | 5.4 | 5.6 | 5.7 | 5.9 | 6.3 | 6.5 | 6.3 | 6.2 | 6.3 |
| Market Swine | 3.0 | 3.1 | 3.3 | 3.3 | 3.5 | 3.5 | 3.3 | 3.6 | 4.0 | 4.1 | 4.1 | 4.2 | 4.4 | 4.5 | 4.7 | 4.9 | 5.0 | 5.5 | 5.6 | 5.5 | 5.4 | 5.5 |
| Market <50 lbs. | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.9 | 0.9 | 0.9 | 1.0 | 1.1 | 0.8 | 0.8 | 0.8 | 0.8 |
| Market 50-119 lbs. | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.9 | 0.9 | 0.9 | 1.0 | 1.0 | 1.1 | 1.3 | 1.2 | 1.2 | 1.2 |
| Market 120-179 lbs. | 0.9 | 0.9 | 0.9 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.1 | 1.1 | 1.1 | 1.2 | 1.2 | 1.3 | 1.3 | 1.4 | 1.4 | 1.5 | 1.6 | 1.6 | 1.6 | 1.6 |
| Market >180 lbs. | 0.9 | 1.0 | 1.0 | 1.0 | 1.1 | 1.1 | 1.1 | 1.2 | 1.3 | 1.3 | 1.3 | 1.4 | 1.5 | 1.5 | 1.6 | 1.6 | 1.6 | 1.8 | 1.9 | 1.9 | 1.8 | 1.9 |
| Breeding Swine | 1.0 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.0 | 1.1 | 1.1 | 1.0 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 | 0.8 |
| **Beef Cattle** | 19.8 | 20.3 | 20.1 | 19.1 | 20.9 | 21.8 | 21.4 | 21.5 | 21.6 | 24.0 | 25.0 | 24.1 | 24.8 | 25.0 | 23.6 | 24.0 | 25.7 | 25.6 | 25.2 | 25.1 | 25.3 | 25.8 |
| Feedlot Steers | 13.4 | 13.6 | 13.5 | 12.8 | 13.9 | 14.4 | 14.0 | 13.9 | 14.1 | 15.5 | 16.1 | 15.4 | 16.0 | 16.3 | 15.3 | 15.5 | 16.7 | 16.7 | 16.5 | 16.5 | 16.6 | 16.8 |
| Feedlot Heifers | 6.4 | 6.6 | 6.6 | 6.3 | 7.0 | 7.4 | 7.4 | 7.6 | 7.6 | 8.5 | 8.9 | 8.6 | 8.7 | 8.8 | 8.4 | 8.5 | 9.0 | 8.9 | 8.7 | 8.6 | 8.7 | 9.1 |
| **Sheep** | 0.4 | 0.4 | 0.4 | 0.4 | 0.6 | 0.7 | 0.8 | 0.9 | 0.9 | 1.0 | 1.1 | 1.2 | 1.2 | 1.2 | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.1 | 1.1 | 1.1 |
| **Goats** | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Poultry** | 4.7 | 4.8 | 4.9 | 5.0 | 5.1 | 5.1 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.4 | 5.3 | 5.4 | 5.4 | 5.4 | 5.4 | 5.4 | 5.2 | 5.2 | 5.2 |
| Hens >1 yr. | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.1 | 1.1 | 1.1 | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| Total Pullets | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Chickens | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Broilers | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.8 | 2.9 | 2.9 | 2.9 | 2.9 | 3.0 | 2.9 | 2.9 | 3.0 | 2.9 | 2.9 | 2.9 | 2.7 | 2.8 | 2.8 |
| Turkeys | 1.2 | 1.2 | 1.2 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.0 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.7 | 0.7 |
| **Horses** | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| **Mules and Asses** | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| **Bison** | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |

+ Emission estimate is less than 0.5 Gg.

Note: Bison are maintained entirely on unmanaged WMS; there are no bison $N_2O$ emissions from managed systems.

Table A- 201: Methane Emissions by State from Livestock Manure Management for 2011 (Gg)[a]

| State | Beef on Feedlots | Beef Not on Feed | Dairy Cow | Dairy Heifer | Swine—Market | Swine—Breeding | Layer | Broiler | Turkey | Sheep | Goats | Horses | Mules and Asses | Bison |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alabama | 0.0346 | 2.4602 | 0.6515 | 0.0161 | 2.3216 | 0.6680 | 8.7315 | 3.7088 | 0.0253 | 0.0082 | 0.0302 | 0.3430 | 0.0024 | 0.0007 |
| Alaska | 0.0002 | 0.0196 | 0.0277 | 0.0003 | 0.0019 | 0.0010 | 0.1930 | + | 0.0253 | 0.0055 | 0.0001 | 0.0056 | + | 0.0036 |
| Arizona | 0.6316 | 1.0190 | 50.3292 | 0.1410 | 2.8942 | 0.7384 | 0.6852 | + | 0.0253 | 0.1057 | 0.0158 | 0.2834 | 0.0005 | 0.0011 |
| Arkansas | 0.0141 | 3.4463 | 0.4121 | 0.0106 | 0.6760 | 2.0289 | 0.5181 | 3.7314 | 0.7628 | 0.0082 | 0.0190 | 0.2770 | 0.0017 | 0.0017 |
| California | 1.3298 | 3.9348 | 400.4971 | 1.9531 | 1.6038 | 0.1815 | 4.3748 | 0.2162 | 0.3751 | 0.4229 | 0.0490 | 0.7219 | 0.0016 | 0.0097 |
| Colorado | 1.6613 | 2.7186 | 26.2835 | 0.1121 | 4.8012 | 2.7413 | 3.8647 | + | 0.0253 | 0.1739 | 0.0122 | 0.2817 | 0.0007 | 0.0398 |
| Connecticut | 0.0007 | 0.0181 | 1.0260 | 0.0161 | 0.0051 | 0.0027 | 0.2531 | + | 0.0253 | 0.0040 | 0.0011 | 0.0287 | 0.0001 | 0.0002 |
| Delaware | 0.0007 | 0.0107 | 0.3030 | 0.0054 | 0.0449 | 0.0239 | 0.0778 | 0.7885 | 0.0253 | 0.0055 | 0.0009 | 0.0096 | + | + |
| Florida | 0.0163 | 3.2518 | 20.0564 | 0.0865 | 0.0602 | 0.0430 | 7.0406 | 0.2245 | 0.0253 | 0.0082 | 0.0216 | 0.4507 | 0.0015 | 0.0044 |
| Georgia | 0.0292 | 1.8536 | 7.2760 | 0.0625 | 2.1748 | 0.9610 | 14.0726 | 4.9950 | 0.0253 | 0.0082 | 0.0315 | 0.2591 | 0.0020 | 0.0017 |
| Hawaii | 0.0053 | 0.3233 | 0.3985 | 0.0029 | 0.0928 | 0.0639 | 0.3015 | + | 0.0253 | 0.0082 | 0.0034 | 0.0267 | 0.0001 | 0.0006 |
| Idaho | 0.3718 | 1.5697 | 118.4054 | 0.4794 | 0.1568 | 0.0834 | 0.6069 | + | 0.0253 | 0.1104 | 0.0044 | 0.1460 | 0.0006 | 0.0005 |
| Illinois | 0.2652 | 0.9904 | 8.6768 | 0.0744 | 42.0334 | 10.3908 | 0.2354 | + | 0.0253 | 0.0263 | 0.0084 | 0.2088 | 0.0006 | 0.0027 |
| Indiana | 0.2095 | 0.6276 | 13.6880 | 0.0992 | 34.9466 | 6.2170 | 0.8058 | 0.2155 | 0.3988 | 0.0235 | 0.0118 | 0.1475 | 0.0006 | 0.0033 |
| Iowa | 2.2287 | 3.0020 | 21.0013 | 0.2062 | 286.7625 | 31.4530 | 1.7161 | 0.2155 | 0.0253 | 0.0940 | 0.0140 | 0.1487 | 0.0006 | 0.0055 |
| Kansas | 4.0556 | 5.2006 | 21.1968 | 0.1404 | 21.9157 | 4.1342 | 0.0443 | + | 0.0253 | 0.0329 | 0.0124 | 0.2363 | 0.0007 | 0.0205 |
| Kentucky | 0.0185 | 2.6320 | 1.5880 | 0.0887 | 4.8791 | 1.1063 | 0.5714 | 1.1222 | 0.0253 | 0.0160 | 0.0245 | 0.4300 | 0.0018 | 0.0009 |
| Louisiana | 0.0161 | 1.6593 | 0.7510 | 0.0139 | 0.0127 | 0.0099 | 2.2112 | 0.2162 | 0.0253 | 0.0082 | 0.0081 | 0.2323 | 0.0011 | 0.0005 |
| Maine | 0.0015 | 0.0431 | 1.3905 | 0.0279 | 0.0113 | 0.0076 | 0.2875 | + | 0.0253 | 0.0040 | 0.0015 | 0.0256 | 0.0001 | 0.0008 |
| Maryland | 0.0193 | 0.1276 | 2.6459 | 0.0494 | 0.2299 | 0.0452 | 0.2266 | 1.1262 | 0.0253 | 0.0055 | 0.0042 | 0.0758 | 0.0002 | 0.0022 |
| Massachusetts | 0.0007 | 0.0196 | 0.5298 | 0.0125 | 0.0447 | 0.0140 | 0.0120 | + | 0.0253 | 0.0040 | 0.0021 | 0.0540 | 0.0002 | 0.0001 |
| Michigan | 0.2721 | 0.4542 | 44.8947 | 0.2327 | 8.8036 | 2.0014 | 0.6339 | 0.2155 | 0.0253 | 0.0348 | 0.0070 | 0.2148 | 0.0006 | 0.0061 |
| Minnesota | 0.5045 | 1.3717 | 31.9261 | 0.4561 | 65.3587 | 10.9752 | 0.3394 | 0.1506 | 1.1590 | 0.0611 | 0.0092 | 0.1928 | 0.0006 | 0.0027 |
| Mississippi | 0.0289 | 1.8272 | 0.6517 | 0.0191 | 5.4654 | 1.2410 | 7.8331 | 2.8477 | 0.0253 | 0.0082 | 0.0115 | 0.2107 | 0.0016 | + |
| Missouri | 0.0868 | 4.6019 | 6.1641 | 0.0821 | 24.3559 | 7.8186 | 0.2728 | 1.0325 | 0.4362 | 0.0381 | 0.0241 | 0.3404 | 0.0017 | 0.0044 |
| Montana | 0.0444 | 3.6147 | 1.7300 | 0.0104 | 1.2233 | 0.3580 | 0.3624 | + | 0.0253 | 0.1081 | 0.0031 | 0.2495 | 0.0005 | 0.0205 |
| Nebraska | 4.1237 | 6.6653 | 7.6711 | 0.0319 | 26.4994 | 7.6461 | 0.5629 | 0.2155 | 0.0253 | 0.0348 | 0.0086 | 0.1555 | 0.0004 | 0.0453 |
| Nevada | 0.0125 | 0.5552 | 6.4121 | 0.0150 | 0.0166 | 0.0014 | 0.0224 | + | 0.0253 | 0.0320 | 0.0030 | 0.0443 | 0.0001 | 0.0004 |
| New Hampshire | 0.0004 | 0.0125 | 0.7169 | 0.0124 | 0.0102 | 0.0037 | 0.0710 | + | 0.0253 | 0.0040 | 0.0010 | 0.0251 | 0.0001 | 0.0002 |
| New Jersey | 0.0008 | 0.0254 | 0.2804 | 0.0070 | 0.0685 | 0.0112 | 0.0762 | + | 0.0253 | 0.0055 | 0.0027 | 0.0717 | 0.0002 | 0.0003 |
| New Mexico | 0.0451 | 1.3338 | 79.5223 | 0.2167 | 0.0003 | 0.0002 | 0.6482 | + | 0.0253 | 0.0517 | 0.0089 | 0.1296 | 0.0003 | 0.0078 |
| New York | 0.0450 | 0.4465 | 31.2704 | 0.5511 | 0.6586 | 0.1880 | 0.4753 | 0.2155 | 0.0253 | 0.0329 | 0.0100 | 0.2032 | 0.0004 | 0.0036 |
| North Carolina | 0.0144 | 0.9509 | 2.6134 | 0.0523 | 141.1274 | 31.6546 | 10.8448 | 2.8582 | 0.8003 | 0.0190 | 0.0369 | 0.2948 | 0.0020 | 0.0013 |
| North Dakota | 0.1037 | 2.2303 | 1.3380 | 0.0156 | 0.9034 | 0.6889 | 0.0415 | + | 0.0253 | 0.0367 | 0.0011 | 0.1004 | 0.0001 | 0.0076 |
| Ohio | 0.2853 | 0.8546 | 20.1273 | 0.1997 | 17.7580 | 3.4498 | 0.9319 | 0.2158 | 0.1246 | 0.0606 | 0.0174 | 0.2345 | 0.0009 | + |

| State | Beef on Feedlots | Beef Not on Feed | Dairy Cow | Dairy Heifer | Swine—Market | Swine—Breeding | Layer | Broiler | Turkey | Sheep | Goats | Horses | Mules and Asses | Bison |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oklahoma | 0.8853 | 8.2123 | 9.9779 | 0.0460 | 35.1779 | 15.5849 | 3.4313 | 0.7798 | 0.0253 | 0.0529 | 0.0470 | 0.5844 | 0.0030 | 0.0219 |
| Oregon | 0.1348 | 1.4459 | 17.1748 | 0.1098 | 0.0476 | 0.0290 | 0.8668 | 0.2155 | 0.0253 | 0.1010 | 0.0095 | 0.1906 | 0.0006 | 0.0013 |
| Pennsylvania | 0.1345 | 0.7312 | 17.5584 | 0.5310 | 10.8364 | 1.9444 | 0.7478 | 0.5633 | 0.1869 | 0.0460 | 0.0148 | 0.2599 | 0.0014 | 0.0046 |
| Rhode Island | 0.0001 | 0.0041 | 0.0354 | 0.0009 | 0.0034 | 0.0040 | 0.0746 | + | 0.0253 | 0.0040 | 0.0002 | 0.0103 | + | + |
| South Carolina | 0.0114 | 0.7213 | 1.2061 | 0.0189 | 4.0939 | 0.3713 | 4.7449 | 0.8114 | 0.2876 | 0.0082 | 0.0163 | 0.1489 | 0.0011 | 0.0004 |
| South Dakota | 0.6439 | 4.3077 | 11.3873 | 0.0395 | 11.2068 | 3.4242 | 0.1368 | + | 0.1097 | 0.1245 | 0.0027 | 0.1550 | 0.0003 | 0.0727 |
| Tennessee | 0.0170 | 2.4110 | 1.4325 | 0.0623 | 2.5006 | 0.4569 | 0.2298 | 0.6889 | 0.0253 | 0.0164 | 0.0327 | 0.2994 | 0.0027 | 0.0017 |
| Texas | 6.6071 | 21.3610 | 100.8165 | 0.5302 | 12.1126 | 2.5553 | 4.3688 | 2.2901 | 0.0253 | 0.5991 | 0.4273 | 1.6165 | 0.0133 | 0.0190 |
| Utah | 0.0382 | 0.8593 | 16.1260 | 0.0629 | 5.6314 | 1.3597 | 2.9988 | + | 0.1072 | 0.1316 | 0.0043 | 0.1282 | 0.0003 | 0.0041 |
| Vermont | 0.0018 | 0.0633 | 6.0703 | 0.1006 | 0.0099 | 0.0045 | 0.0192 | + | 0.0253 | 0.0040 | 0.0016 | 0.0327 | 0.0001 | 0.0003 |
| Virginia | 0.0367 | 1.7517 | 2.9431 | 0.0854 | 4.3871 | 0.1651 | 0.3731 | 0.8826 | 0.4362 | 0.0423 | 0.0158 | 0.2137 | 0.0010 | 0.0021 |
| Washington | 0.3690 | 0.7439 | 43.8331 | 0.2060 | 0.1054 | 0.0554 | 1.2337 | 0.2155 | 0.0253 | 0.0263 | 0.0082 | 0.2207 | 0.0005 | 0.0029 |
| West Virginia | 0.0096 | 0.5570 | 0.3595 | 0.0086 | 0.0228 | 0.0139 | 0.1253 | 0.3092 | 0.0823 | 0.0160 | 0.0070 | 0.0929 | 0.0004 | 0.0005 |
| Wisconsin | 0.3969 | 1.1695 | 91.7408 | 1.0961 | 2.4926 | 0.7398 | 0.2940 | 0.1683 | 0.0253 | 0.0423 | 0.0140 | 0.2946 | 0.0008 | 0.0081 |
| Wyoming | 0.1001 | 1.9710 | 0.8329 | 0.0074 | 0.2685 | 0.3436 | 0.0087 | + | 0.0253 | 0.1715 | 0.0021 | 0.2070 | 0.0003 | 0.0277 |

+ Emission estimate is less than 0.00005 Gg.

[a] Accounts for $CH_4$ reductions due to capture and destruction of $CH_4$ at facilities using anaerobic digesters.

Table A- 202: Nitrous Oxide Emissions by State from Livestock Manure Management for 2011 (Gg)

| State | Beef Feedlot-Heifer | Beef Feedlot-Steers | Dairy Cow | Dairy Heifer | Swine-Market | Swine-Breeding | Layer | Broiler | Turkey | Sheep | Goats | Horses | Mules and Asses |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alabama | 0.0079 | 0.0147 | 0.0045 | 0.0053 | 0.0117 | 0.0025 | 0.0624 | 0.3281 | 0.0029 | 0.0045 | 0.0024 | 0.0118 | 0.0007 |
| Alaska | 0.0001 | 0.0001 | 0.0006 | 0.0004 | + | + | 0.0033 | + | 0.0029 | 0.0015 | + | 0.0003 | + |
| Arizona | 0.1715 | 0.3167 | 0.2242 | 0.1257 | 0.0134 | 0.0026 | 0.0035 | + | 0.0029 | 0.0165 | 0.0012 | 0.0097 | 0.0001 |
| Arkansas | 0.0033 | 0.0061 | 0.0038 | 0.0026 | 0.0037 | 0.0081 | 0.0733 | 0.3301 | 0.0884 | 0.0039 | 0.0015 | 0.0095 | 0.0005 |
| California | 0.3077 | 0.5701 | 2.0994 | 1.5712 | 0.0089 | 0.0007 | 0.0912 | 0.0191 | 0.0435 | 0.0747 | 0.0039 | 0.0248 | 0.0004 |
| Colorado | 0.7017 | 1.3019 | 0.1653 | 0.1713 | 0.0507 | 0.0214 | 0.0232 | + | 0.0029 | 0.0408 | 0.0014 | 0.0145 | 0.0003 |
| Connecticut | 0.0002 | 0.0005 | 0.0149 | 0.0114 | + | + | 0.0108 | + | 0.0029 | 0.0032 | 0.0001 | 0.0015 | + |
| Delaware | 0.0002 | 0.0004 | 0.0038 | 0.0035 | 0.0003 | 0.0001 | 0.0032 | 0.0700 | 0.0029 | 0.0044 | 0.0001 | 0.0005 | + |
| Florida | 0.0035 | 0.0064 | 0.0952 | 0.0430 | 0.0003 | 0.0002 | 0.0470 | 0.0199 | 0.0029 | 0.0045 | 0.0017 | 0.0155 | 0.0004 |
| Georgia | 0.0067 | 0.0124 | 0.0478 | 0.0227 | 0.0109 | 0.0036 | 0.0991 | 0.4419 | 0.0029 | 0.0045 | 0.0025 | 0.0089 | 0.0006 |
| Hawaii | 0.0011 | 0.0021 | 0.0020 | 0.0023 | 0.0005 | 0.0002 | 0.0033 | + | 0.0029 | 0.0015 | 0.0003 | 0.0009 | + |
| Idaho | 0.1585 | 0.2943 | 0.7684 | 0.7363 | 0.0018 | 0.0007 | 0.0035 | + | 0.0029 | 0.0259 | 0.0005 | 0.0075 | 0.0002 |
| Illinois | 0.1055 | 0.1951 | 0.1399 | 0.0932 | 0.3808 | 0.0688 | 0.0168 | + | 0.0029 | 0.0184 | 0.0010 | 0.0108 | 0.0003 |
| Indiana | 0.0829 | 0.1537 | 0.2345 | 0.1136 | 0.3265 | 0.0425 | 0.1119 | 0.0191 | 0.0464 | 0.0164 | 0.0014 | 0.0076 | 0.0002 |
| Iowa | 0.8947 | 1.6575 | 0.2988 | 0.2523 | 1.7438 | 0.1400 | 0.2383 | 0.0191 | 0.0029 | 0.0656 | 0.0017 | 0.0077 | 0.0002 |
| Kansas | 1.5568 | 2.8838 | 0.1742 | 0.1819 | 0.1781 | 0.0249 | 0.0031 | + | 0.0029 | 0.0230 | 0.0015 | 0.0122 | 0.0003 |
| Kentucky | 0.0066 | 0.0121 | 0.0299 | 0.0286 | 0.0277 | 0.0046 | 0.0237 | 0.0996 | 0.0029 | 0.0130 | 0.0029 | 0.0222 | 0.0007 |
| Louisiana | 0.0035 | 0.0065 | 0.0065 | 0.0030 | 0.0001 | + | 0.0113 | 0.0191 | 0.0029 | 0.0039 | 0.0006 | 0.0080 | 0.0003 |
| Maine | 0.0006 | 0.0011 | 0.0241 | 0.0191 | 0.0001 | 0.0001 | 0.0130 | + | 0.0029 | 0.0032 | 0.0002 | 0.0013 | + |
| Maryland | 0.0068 | 0.0126 | 0.0406 | 0.0321 | 0.0019 | 0.0003 | 0.0093 | 0.1000 | 0.0029 | 0.0044 | 0.0005 | 0.0039 | 0.0001 |
| Massachusetts | 0.0003 | 0.0005 | 0.0100 | 0.0083 | 0.0004 | 0.0001 | 0.0005 | + | 0.0029 | 0.0032 | 0.0002 | 0.0028 | 0.0001 |
| Michigan | 0.1106 | 0.2048 | 0.5465 | 0.3123 | 0.0904 | 0.0153 | 0.0468 | 0.0191 | 0.0029 | 0.0243 | 0.0008 | 0.0111 | 0.0003 |
| Minnesota | 0.2038 | 0.3784 | 0.6447 | 0.5673 | 0.6500 | 0.0805 | 0.0472 | 0.0134 | 0.1348 | 0.0426 | 0.0011 | 0.0099 | 0.0002 |
| Mississippi | 0.0066 | 0.0121 | 0.0062 | 0.0046 | 0.0272 | 0.0044 | 0.0406 | 0.2519 | 0.0029 | 0.0045 | 0.0009 | 0.0072 | 0.0004 |
| Missouri | 0.0340 | 0.0626 | 0.1097 | 0.0899 | 0.2175 | 0.0508 | 0.0380 | 0.0916 | 0.0507 | 0.0266 | 0.0029 | 0.0175 | 0.0007 |
| Montana | 0.0189 | 0.0351 | 0.0186 | 0.0151 | 0.0143 | 0.0031 | 0.0022 | + | 0.0029 | 0.0254 | 0.0004 | 0.0129 | 0.0002 |
| Nebraska | 1.6515 | 3.0598 | 0.0833 | 0.0420 | 0.2550 | 0.0541 | 0.0407 | 0.0191 | 0.0029 | 0.0243 | 0.0010 | 0.0080 | 0.0002 |
| Nevada | 0.0053 | 0.0098 | 0.0377 | 0.0231 | 0.0001 | + | 0.0031 | + | 0.0029 | 0.0075 | 0.0004 | 0.0023 | + |
| New Hampshire | 0.0001 | 0.0003 | 0.0119 | 0.0086 | 0.0001 | + | 0.0032 | + | 0.0029 | 0.0032 | 0.0001 | 0.0013 | + |
| New Jersey | 0.0003 | 0.0006 | 0.0054 | 0.0044 | 0.0005 | 0.0001 | 0.0032 | + | 0.0029 | 0.0044 | 0.0003 | 0.0037 | 0.0001 |
| New Mexico | 0.0184 | 0.0343 | 0.4006 | 0.2933 | + | + | 0.0035 | + | 0.0029 | 0.0121 | 0.0011 | 0.0067 | 0.0001 |
| New York | 0.0171 | 0.0315 | 0.4864 | 0.3715 | 0.0066 | 0.0014 | 0.0205 | 0.0191 | 0.0029 | 0.0267 | 0.0012 | 0.0105 | 0.0002 |
| North Carolina | 0.0051 | 0.0094 | 0.0259 | 0.0150 | 0.7047 | 0.1166 | 0.0779 | 0.2529 | 0.0927 | 0.0103 | 0.0029 | 0.0101 | 0.0005 |

| State | Beef Feedlot-Heifer | Beef Feedlot-Steers | Dairy Cow | Dairy Heifer | Swine-Market | Swine-Breeding | Layer | Broiler | Turkey | Sheep | Goats | Horses | Mules and Asses |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| North Dakota | 0.0433 | 0.0793 | 0.0252 | 0.0192 | 0.0097 | 0.0055 | 0.0031 | + | 0.0029 | 0.0256 | 0.0001 | 0.0052 | 0.0001 |
| Ohio | 0.1142 | 0.2106 | 0.3534 | 0.2281 | 0.1670 | 0.0237 | 0.1293 | 0.0192 | 0.0145 | 0.0489 | 0.0021 | 0.0121 | 0.0004 |
| Oklahoma | 0.2449 | 0.4539 | 0.0648 | 0.0435 | 0.1703 | 0.0550 | 0.0177 | 0.0690 | 0.0029 | 0.0245 | 0.0037 | 0.0201 | 0.0008 |
| Oregon | 0.0492 | 0.0912 | 0.1358 | 0.1215 | 0.0005 | 0.0002 | 0.0112 | 0.0191 | 0.0029 | 0.0268 | 0.0011 | 0.0098 | 0.0003 |
| Pennsylvania | 0.0491 | 0.0910 | 0.4006 | 0.3210 | 0.0986 | 0.0132 | 0.1039 | 0.0500 | 0.0217 | 0.0373 | 0.0018 | 0.0134 | 0.0006 |
| Rhode Island | + | 0.0001 | 0.0008 | 0.0005 | + | + | 0.0032 | + | 0.0029 | 0.0032 | + | 0.0005 | + |
| South Carolina | 0.0026 | 0.0049 | 0.0080 | 0.0050 | 0.0199 | 0.0013 | 0.0243 | 0.0718 | 0.0333 | 0.0045 | 0.0013 | 0.0051 | 0.0003 |
| South Dakota | 0.2602 | 0.4818 | 0.1277 | 0.0508 | 0.1097 | 0.0246 | 0.0100 | + | 0.0128 | 0.0869 | 0.0003 | 0.0080 | 0.0001 |
| Tennessee | 0.0058 | 0.0110 | 0.0210 | 0.0216 | 0.0143 | 0.0019 | 0.0096 | 0.0612 | 0.0029 | 0.0133 | 0.0039 | 0.0154 | 0.0011 |
| Texas | 1.8262 | 3.3865 | 0.5190 | 0.4920 | 0.0648 | 0.0101 | 0.0877 | 0.2026 | 0.0029 | 0.0937 | 0.0337 | 0.0555 | 0.0036 |
| Utah | 0.0162 | 0.0300 | 0.1160 | 0.0955 | 0.0580 | 0.0109 | 0.0175 | + | 0.0125 | 0.0309 | 0.0005 | 0.0066 | 0.0001 |
| Vermont | 0.0007 | 0.0013 | 0.1036 | 0.0698 | 0.0001 | + | 0.0009 | + | 0.0029 | 0.0032 | 0.0002 | 0.0017 | 0.0001 |
| Virginia | 0.0131 | 0.0243 | 0.0427 | 0.0318 | 0.0236 | 0.0007 | 0.0156 | 0.0783 | 0.0507 | 0.0343 | 0.0019 | 0.0110 | 0.0004 |
| Washington | 0.1342 | 0.2500 | 0.3152 | 0.2382 | 0.0011 | 0.0004 | 0.0295 | 0.0191 | 0.0029 | 0.0070 | 0.0010 | 0.0114 | 0.0002 |
| West Virginia | 0.0036 | 0.0065 | 0.0068 | 0.0056 | 0.0002 | 0.0001 | 0.0053 | 0.0274 | 0.0096 | 0.0130 | 0.0008 | 0.0048 | 0.0002 |
| Wisconsin | 0.1612 | 0.2988 | 1.7665 | 1.3307 | 0.0246 | 0.0054 | 0.0218 | 0.0149 | 0.0029 | 0.0295 | 0.0017 | 0.0152 | 0.0003 |
| Wyoming | 0.0426 | 0.0790 | 0.0075 | 0.0094 | 0.0049 | 0.0046 | 0.0001 | + | 0.0029 | 0.0402 | 0.0002 | 0.0107 | 0.0001 |

+ Emission estimate is less than 0.00005 Gg.

## 3.12. Methodology for Estimating $N_2O$ Emissions and Soil Organic C Stock Changes from Agricultural Soil Management (Cropland and Grassland)

Nitrous oxide ($N_2O$) emissions from agricultural soils result from the interaction of the natural processes of denitrification and nitrification with management practices that add or release mineral nitrogen (N) in the soil profile. Emissions can occur directly in the soil where the N is made available or can be transported to another location following volatilization, leaching, or runoff, and then converted into $N_2O$. Management also influences soil organic C stocks in agricultural soils by modifying the natural processes of photosynthesis (i.e., crop and forage production) and microbial decomposition. This sub-annex describes the methodologies used to calculate $N_2O$ emissions from agricultural soil management[68] and annual carbon (C) stock changes from mineral and organic soils classified as *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*[69]. This annex provides the underlying methodologies for both $N_2O$ emissions from agricultural soil management and soil organic C stock change from mineral and organic soils. There is considerable overlap in the methods and data sets used for these source categories, and the majority of emission are estimated with the same inventory analysis using the DAYCENT simulation model. All Tier 1 and 2 methods are based on the guidelines provided by the IPCC (2006).

A combination of Tier 1, 2 and 3 approaches is used to estimate direct and indirect $N_2O$ emissions, in addition to C stock changes in agricultural soils. More specifically, the methodologies used to estimate soil $N_2O$ emissions include:

1) Tier 3 method to estimate direct emissions from mineral soils for major crops, non-federal grasslands and land use change between cropland and grassland[70], using the DAYCENT process-based simulation model;
2) Tier 1 method to estimate direct $N_2O$ emissions from mineral soils for non-major crops and federal grasslands;
3) Tier 1 method to estimate direct $N_2O$ emissions due to drainage and cultivation of organic cropland soils;
4) a combination of the Tier 3 and 1 methods to estimate indirect $N_2O$ emissions associated with management of major crops, non-federal grasslands and land use change between cropland and grassland; and
5) Tier 1 method to estimate indirect emissions from non-major crops, federal grasslands and all other land uses.

The methodologies used to estimate soil organic C stock changes include:

1) Tier 3 method to estimate soil organic C stock changes in mineral soils for major crops, non-federal grasslands and land use change between grasslands and croplands, using the DAYCENT process-based simulation model;
2) Tier 2 methods with country-specific stock change factors for estimating mineral soil organic C stock changes for non-major crops and land use changes to cropland and grassland (other than the conversions between cropland and grassland);

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[68] Direct Soil $N_2O$ methods from forestlands and settlements are described elsewhere in Forestland Remaining Forestland and Settlements Remaining Settlements.

[69] Soil C stock change methods for forestland are described elsewhere in the Forestland Remaining Forestland section.

[70] The current inventory does not include estimates of direct $N_2O$ emissions for land use change from forestland to grassland or cropland.

3) Tier 2 methods with country-specific emission factors for estimating losses of C from organic soils that are partly or completely drained for agricultural production; and
4) Tier 2 methods for estimating additional changes in mineral soil C stocks due to sewage sludge additions to soils and enrollment changes in the Conservation Reserve Program (CRP) after 2007.

As described above, the Inventory uses a Tier 3 approach to estimate direct soil $N_2O$ emissions and C stock changes for the majority of agricultural lands. This approach has several advantages over the IPCC Tier 1 or 2 approaches:

- It utilizes actual weather data at sub-county scales, rather than a broad climate region classification, enabling quantification of inter-annual variability in $N_2O$ emissions and C stock changes at finer spatial scales;
- The model uses a more detailed characterization of spatially-mapped soil properties that influence soil C and N dynamics, as opposed to the broad soil taxonomic classifications of the IPCC methodology;
- The simulation approach provides a more detailed representation of management influences and their interactions than are represented by a discrete factor-based approach in the Tier 1 and 2 methods; and
- Soil $N_2O$ emissions and C stock changes are estimated on a more continuous, daily basis as a function of the interaction of climate, soil, and land management, compared with the linear rate changes that are estimated with the Tier 1 and 2 methods.

The DAYCENT process-based simulation model (daily time-step version of the Century model) has been selected for a Tier 3 approach based on several criteria:

- The model has been developed in the United States and extensively tested and verified for U.S. conditions (e.g., Parton et al. 1987, 1993). In addition, the model has been widely used by researchers and agencies in many other parts of the world for simulating soil C dynamics at local, regional and national scales (e.g., Brazil, Canada, India, Jordan, Kenya, Mexico), and soil $N_2O$ emissions (e.g., Canada, China, Ireland, New Zealand) (Abdalla et al. 2010, Li et al., Smith et al. 2008, Stehfest and Muller 2004) .
- The model is capable of simulating cropland, grassland, forest, and savanna ecosystems, and land-use transitions between these different land uses. It is, thus, well suited to model land-use change effects.
- The model is designed to simulate management practices that influence soil C dynamics and direct $N_2O$ emissions, with the exception of cultivated organic soils; cobbly, gravelly, or shaley soils; and a few crops that have not been parameterized for DAYCENT simulations (e.g., rice, perennial/horticultural crops, and tobacco). For these latter cases, an IPCC Tier 2 method has been used for soil C stock changes and IPCC Tier 1 method for $N_2O$ emissions. The model can also be used estimate the amount of N leaching and runoff, as well as volatilization of N, which is subject to indirect $N_2O$ emissions.
- Much of the data needed for the model is available from existing national databases. The exceptions are CRP enrollment after 2007, management of federal grasslands, and sewage sludge amendments to soils, which are not known at a sufficient resolution to use the Tier 3 model. Soil $N_2O$ emissions and C stock changes associated with these practices are addressed with a Tier 1 and 2 method.

Overall, the Tier 3 approach is used to estimate approximately 85-90 percent of direct soil $N_2O$ emissions and land area associated with estimation of soil organic C stock changes under agricultural management in the United States.

### Tier 3 Method Description and Model Evaluation

The DAYCENT process-based model (Parton et al. 1998; Del Grosso et al. 2001, 2011) simulates biogeochemical C and N fluxes between the atmosphere, vegetation, and soil; and provides a more complete estimation of soil C stock changes and $N_2O$ emissions than IPCC Tier 1/2 methods by more thoroughly accounting for the influence of environmental conditions including soil characteristics and weather patterns, specific crop and forage qualities that influence the C and N cycle, and management practices. The DAYCENT model utilizes the soil C modeling framework developed in Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), but has been refined to simulate dynamics at a daily time-step. Carbon and N dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production (McGill and Cole 1981). Coupling the two source categories (i.e., agricultural soil C and $N_2O$) in a single inventory analysis ensures that there is a consistent treatment of the processes and interactions between C and N cycling in soils. For example, plant growth is controlled by nutrient availability, water, and temperature stress. Plant growth along with the residue management determines the C inputs to soils, which influence the C stock changes, and removal of mineral N from the soil with plant growth influences the amount of N that can be converted into $N_2O$. Nutrient supply is a function of external nutrient additions as well as litter and soil organic matter (SOM) decomposition rates, and increasing decomposition can lead to a reduction in soil organic C stocks due to microbial respiration, and greater $N_2O$ emissions by enhancing mineral N availability in soils.

Key processes simulated by DAYCENT include plant production, organic matter formation and decomposition, soil water and temperature regimes by layer, in addition to nitrification and denitrification processes (Figure A- 7). The plant-growth submodel simulates C assimilation through photosynthesis; N uptake; dry matter production; partitioning of C within the crop or forage; senescence; and mortality. The primary function of the growth submodel is to estimate the amount, type, and timing of organic matter inputs to soil, and to represent the influence of the plant on soil water, temperature, and N balance. Yield and removal of harvested biomass are also simulated. Separate submodels are designed to simulate herbaceous plants (i.e., agricultural crops and grasses) and woody vegetation (i.e., trees and scrub). Maximum daily net primary production (NPP) is estimated using the NASA-CASA production algorithm (Potter et al.1993, 2007) and MODIS Enhanced Vegetation Index (EVI) products, MOD13Q1 and MYD13Q1, or an approximation of EVI data derived from the MODIS products (Gurung et al. 2009). The NASA-CASA production algorithm is only used for the following major crops: corn, soybeans, sorghum, cotton and wheat.[71] Other crops are simulated with a single value for the maximum daily net primary production (NPP) , instead of the more dynamic NASA-CASA algorithm. The maximum daily NPP rate is modified by air temperature and available water to capture temperature and moisture stress. If the NASA-CASA algorithm is not used in the simulation, then production is further subject to nutrient limitations (i.e., nitrogen). Model evaluation has shown that the NASA-CASA algorithm improves the precision of NPP estimates using the a) NASA-CASA algorithm and b) a single parameter value for maximum net primary production (Spencer et al., in prep; Figure A- 7

**To be provided:**

**Figure A-6: DAYCENT Model Flow Diagram**

). The $r^2$ is 83 percent for the NASA-CASA algorithm and 64 percent for the single parameter value approach.).

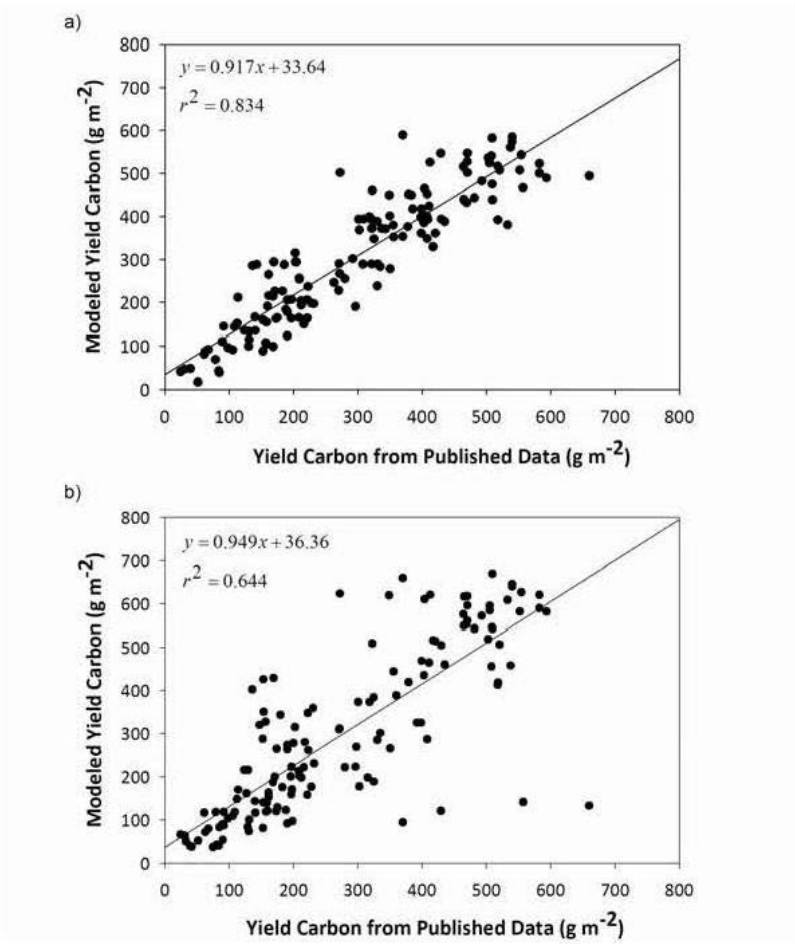
[71] It is a planned improvement to estimate NPP for additional crops and grass forage with the NASA-CASA method in the future.

Figure A- 7: DAYCENT Model Flow Diagram

**To be provided:**

**Figure A-6: DAYCENT Model Flow Diagram**

Figure A- 8: Modeled versus measured net primary production (g C $m^{-2}$)




Part a) presents results of the NASA-CASA algorithm ($r^2$ = 83%) and part b) presents the results of a single parameter value for maximum net primary production ($r^2$ = 64%).

The soil-water balance submodel calculates water balance components and changes in soil water availability, which influences both plant growth and decomposition/nutrient cycling processes. The moisture content of soils are simulated through a multi-layer profile based on precipitation, snow accumulation and melting, interception, soil and canopy evaporation, transpiration, soil water movement, runoff, and drainage.

Dynamics of soil organic C and N (Figure A- 12) are simulated for the surface and subsurface litter pools and the top 20 cm of the soil profile; mineral N dynamics are simulated through the whole soil profile. Organic C and N stocks are represented by two plant litter pools (metabolic and structural) and three soil organic matter (SOM) pools (active, slow, and passive). The metabolic litter pool represents the easily decomposable constituents of plant residues, while the structural litter pool is composed of more recalcitrant, ligno-cellulose plant materials. The three SOM pools represent a gradient in decomposability, from active SOM (representing microbial biomass and associated metabolites) having a rapid turnover (months to years), to passive SOM (representing highly processed, humified, condensed decomposition products), which is highly recalcitrant, with mean residence times on the order of several hundred years. The slow pool represents decomposition products of intermediate stability, having a mean residence time on the order of decades and is the fraction that tends to change the most in response to changes in land use and management. Soil texture influences turnover rates of the slow and passive pools. The clay and silt-sized mineral fraction of the soil provides physical protection from microbial decomposition, leading to enhanced greater SOM stabilization in finely textured soils. Soil temperature and moisture, tillage disturbance, aeration, and other factors influence the decomposition and loss of C from the soil organic matter pools.

Soil mineral N dynamics are modeled based on N inputs from fertilizer inputs (synthetic and organic), residue N inputs, soil organic matter mineralization, symbiotic and asymbiotic N fixation. Mineral N is available for plant and microbial uptake, and is largely controlled by the specified stoichiometric limits for these organisms (i.e., C:N ratios). Mineral and organic N losses are simulated with leaching and runoff, and nitrogen can be volatilized and lost from the soil during a variety of processes including nitrification and denitrification. $N_2O$ emissions from denitrification are a function of soil $NO_3^-$ concentration, water filled pore space (WFPS), heterotrophic (i.e., microbial) respiration, and texture. Nitrification is controlled by soil ammonium ($NH_4^+$) concentration, water filled pore space, temperature, and pH (See Box 1 for more information).

The final main component of the model is the management submodel, which includes options for specifying crop type, crop sequence (e.g., rotation), tillage, fertilization, organic matter addition (e.g., manure amendments), harvest (with variable residue removal), drainage, irrigation, burning, and grazing intensity. An input "schedule" file is used to simulate the timing of management activities and temporal trends; schedules can be organized into discrete time blocks to define a repeated sequence of events (e.g., a crop rotation or a frequency of disturbance such as a burning cycle for perennial grassland). Management options can be specified for any day of a year within a scheduling block, where management codes point to operation-specific parameter files (referred to as *.100 files), which contain the information used to simulate management effects within the model process algorithms. User-specified management activities can be defined by adding to or editing the contents of the *.100 files. Additional details of the model formulation are given in Parton et al. (1987, 1988, 1994, 1998), Del Grosso et al. (2001, 2011) and Metherell et al. (1993), and archived copies of the model source code are available.

[Begin Text Box]

Box 1. DAYCENT Model Simulation of Nitrification and Denitrification

The DAYCENT model simulates the two biogeochemical processes, nitrification and denitrification, that result in $N_2O$ emissions from soils (Del Grosso et al. 2000, Parton et al. 2001). Nitrification is calculated for the top 15 cm of soil, where nitrification mostly occurs, while denitrification is calculated for the entire soil profile accounting for denitrification near the surface and subsurface as nitrate leaches through the profile. The equations and key parameters controlling $N_2O$ emissions from nitrification and denitrification are described below.

Nitrification is controlled by soil ammonium ($NH_4^+$) concentration, WFPS, temperature (t), and pH according to the following equation:

$$Nit = NH_4 \times K_{max} \times F(t) \times F(WFPS) \times F(pH)$$

where,

| | | |
|---|---|---|
| Nit | = | the soil nitrification rate (g N/m$^2$/day) |
| $NH_4$ | = | the model-derived soil ammonium concentration (g N/m$^2$) |
| $K_{max}$ | = | the maximum fraction of $NH_4^+$ nitrified ($K_{max}$ = 0.10/day) |
| F(t) | = | the effect of soil temperature on nitrification (Figure A- 9a) |
| F(WFPS) | = | the effect of soil water content and soil texture on nitrification (Figure A- 9b) |
| F(pH) | = | the effect of soil pH on nitrification (Figure A- 9c) |

The current parameterization used in the model assumes that 1.2 percent of nitrified N is converted to $N_2O$.

The model assumes that denitrification rates are controlled by the availability of soil $NO_3^-$ (electron acceptor), labile C compounds (electron donor) and oxygen (competing electron acceptor). Heterotrophic soil respiration is used as a proxy for labile C availability, while oxygen availability is a function of soil physical properties that influence gas diffusivity, soil WFPS, and oxygen demand. The model selects the minimum of the $NO_3^-$ and $CO_2$ functions to establish a maximum potential denitrification rate. These rates vary for particular levels of electron acceptor and C substrate, and account for limitations of oxygen availability to estimate daily denitrification rates according to the following equation:

$$Den = \min[F(CO_2), F(NO_3)] \times F(WFPS)$$

where,

| | | |
|---|---|---|
| Den | = | the soil denitrification rate (µg N/g soil/day) |
| $F(CO_2)$ | = | a function relating N gas flux to soil respiration (Figure A- 10a) |
| $F(NO_3)$ | = | a function relating N gas flux to nitrate levels (Figure A- 10b) |
| F(WFPS) | = | a dimensionless multiplier (Figure A- 10c). |

The x inflection point of F(WFPS) is a function of respiration and soil gas diffusivity at field capacity ($D_{FC}$):

$$x\ inflection = 0.90 - M(CO_2)$$

where,

M = a multiplier that is a function of $D_{FC}$. In technical terms, the inflection point is the domain where either F(WFPS) not differentiable or its derivative is 0. In this case, the inflection point can be interpreted as the WFPS value at which denitrification reaches half of its maximum rate. In technical terms, the inflection point is the domain where either F(WFPS) not differentiable or its derivative is 0. In this case, the inflection point can be interpreted as the WFPS value at which denitrification reaches half of its maximum rate.

Respiration has a much stronger effect on the water curve in clay soils with low $D_{FC}$ than in loam or sandy soils with high $D_{FC}$ (Figure A- 10c). The model assumes that microsites in fine-textured soils can become anaerobic at relatively low water contents when oxygen demand is high.

After calculating total N gas flux, the ratio of $N_2/N_2O$ is estimated so that total N gas emissions can be partitioned between $N_2O$ and $N_2$:

$$R_{N2/N2O} = F_r(NO_3/CO_2) \times F_r(WFPS).$$

where,

| | | |
|---|---|---|
| $R_{N2/N2O}$ | = | the ratio of $N_2/N_2O$ |
| $F_r(NO_3/CO_2)$ | = | a function estimating the impact of the availability of electron donor relative to substrate |
| $F_r(WFPS)$ | = | a multiplier to account for the effect of soil water on $N_2$:$N_2O$. |

For $F_r(NO_3/CO_2)$, as the ratio of electron donor to substrate increases, a higher portion of N gas is assumed to be in the form of $N_2O$. For $F_r(WFPS)$, as WFPS increases, a higher portion of N gas is assumed to be in the form of $N_2$.

[End Box]

Figure A- 9: Effect of Soil Temperature, Water-Filled Pore Space, and pH on Nitrification Rates

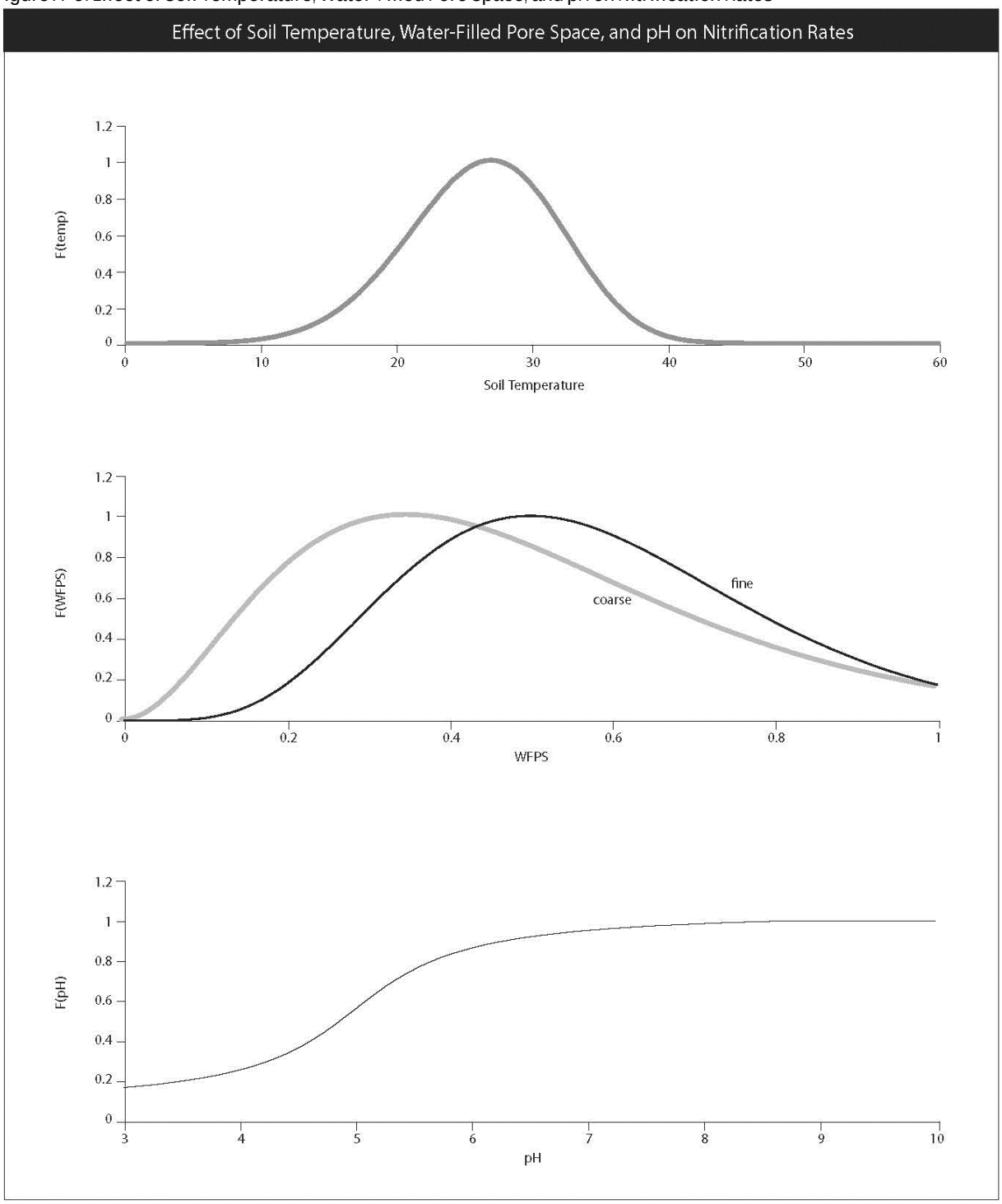
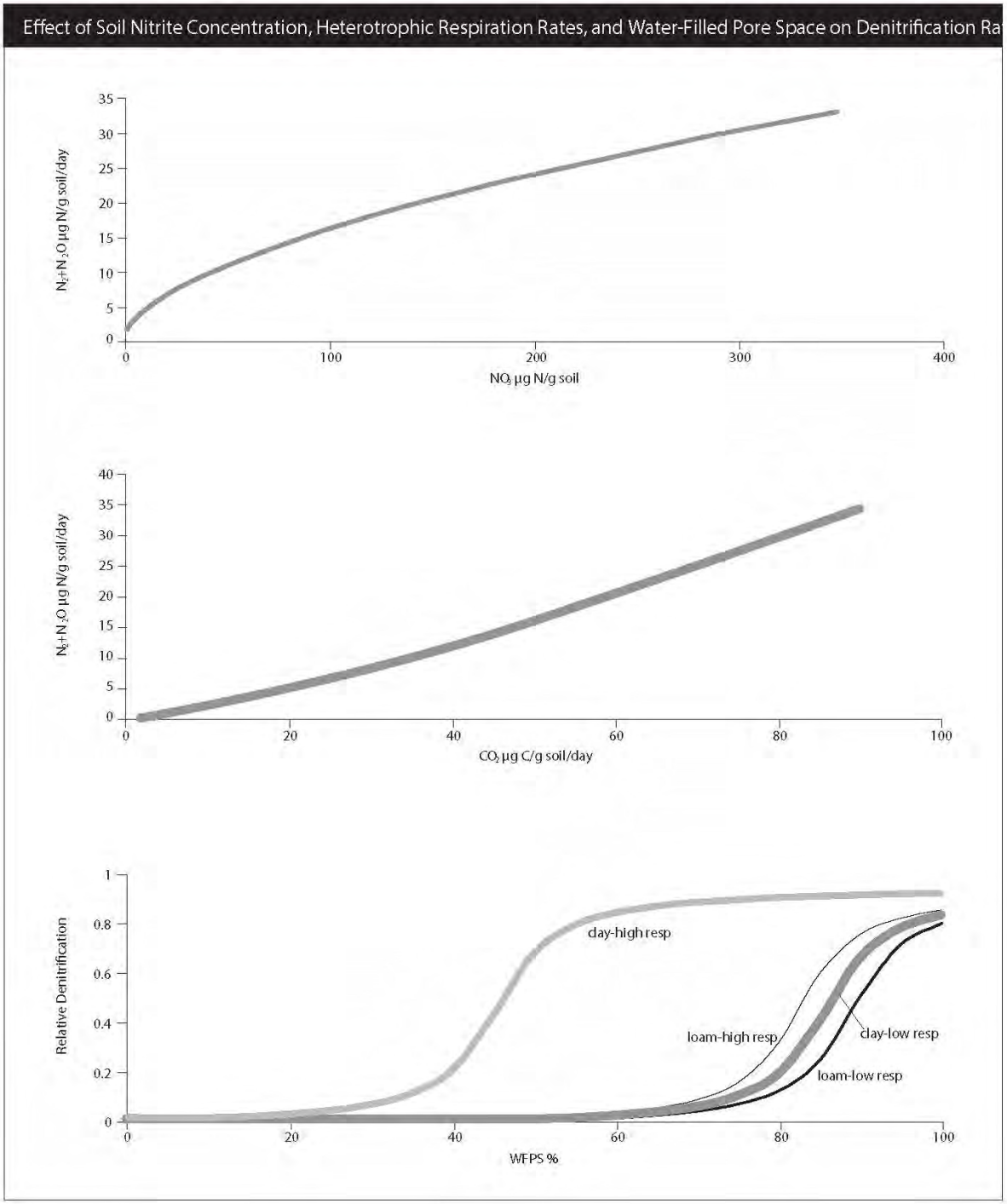


Figure A- 10: Effect of Soil Nitrite Concentration, Heterotrophic Respiration Rates, and Water-Filled Pore Space on Denitrification Rates



Comparison of model results and plot level data show that DAYCENT reliably simulates soil organic matter levels, and trace gas fluxes for a number of native and managed systems (Del Grosso et al. 2001, 2005). The model has been tested for application in U.S. agricultural lands and has been shown to capture the general trends in C storage across approximately 870 field plots from 47 experimental sites (Figure A- 11). Some biases and imprecision occur in predictions of soil organic C, which is reflected in the uncertainty associated with DAYCENT model results. Regardless, the Tier 3 approach has considerably less uncertainty than Tier 1 and 2 methods (Del Grosso et al., 2011 ;Figure A- 12). Similarly, comparisons with measured data showed that DAYCENT estimated $N_2O$ emissions more accurately and precisely than the IPCC Tier 1 methodology (Figure A- 13).

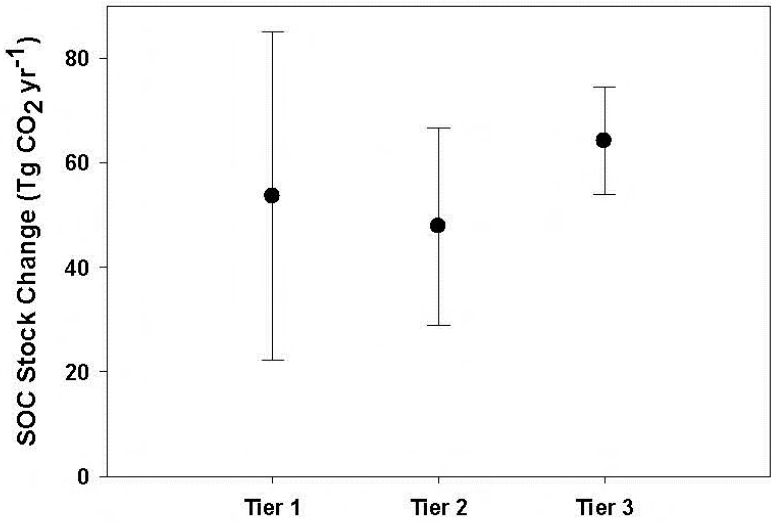
The linear regression of simulated vs. measured emissions for DAYCENT had higher $r^2$ and a fitted line closer to a perfect 1:1 relationship between measured and modeled $N_2O$ emissions (Del Grosso et al. 2005, 2008). This is not surprising, since DAYCENT includes site- specific factors (climate, soil properties, and previous management) that influence $N_2O$ emissions. Furthermore, DAYCENT also simulated $NO_3^-$ leaching (root mean square error = 20 percent) more accurately than IPCC Tier 1 methodology (root mean square error = 69 percent) (Del Grosso et al. 2005). Volatilization of N gases that contribute to indirect soil $N_2O$ emissions is the only component that has not been thoroughly tested, which is due to a lack of measurement data. Thus, the Tier 3 approach has reduced uncertainties in the agricultural soil C stock changes and $N_2O$ emissions compared to using lower Tier methods.

Figure A- 11: Comparisons of Results from DAYCENT Model and Measurements of Soil Organic C stocks

**To be provided:**

**Figure A-10: Comparisons of Results from DAYCENT Model and Measurements of Soil Organic C stocks**

Figure A- 12: Comparison of estimated soil organic C stock changes and uncertainties using Tier 1 (IPCC 2006), Tier 2 (Ogle et al. 2003, 2006) and Tier 3 methods




Source: Tier 1 (IPCC 2007), Tier 2 (Ogle et al. 2003, 2006), Tier 3 (Ogle et al. 2010).

Figure A- 13: Comparisons of Results from DAYCENT Model and IPCC Tier 1 Method with Measurements of Soil N2O Emissions

**To be provided:**

**Figure A-12: Comparisons of Results from DAYCENT Model and IPCC Tier 1 Method with Measurements of Soil N2O Emissions**

There are five steps in estimating soil organic C stock changes for *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland* and *Land Converted to Grassland*; direct $N_2O$ emissions from cropland and grassland soils; and indirect $N_2O$ emissions from volatilization, leaching, and runoff from all managed lands (i.e., croplands, grasslands, forest lands, and settlements). First, the activity data are derived from a combination of land-use, livestock, crop, and grassland management surveys, as well as expert knowledge. In the second, third, and fourth steps, soil organic C stock changes, direct and indirect $N_2O$ emissions are estimated using DAYCENT and/or the Tier 1 and 2 methods. In the fifth step, total emissions are computed by summing all components separately for soil organic C stock changes and $N_2O$ emissions. The remainder of this annex describes the methods underlying each step.

### Step 1: Derive Activity Data

The following describes how the activity data are derived to estimate soil organic C stock changes, in addition to direct and indirect $N_2O$ emissions. The activity data requirements include: (1) land base and history data, (2) crop-specific mineral N fertilizer rates,[72] (3) crop-specific manure amendment N rates and timing, (4) other N inputs, (5) tillage practices, (6) irrigation data, (7) Enhanced Vegetation Index (EVI), (8) daily weather data, and (9) edaphic characteristics.

#### *Step 1a: Activity Data for the Agricultural Land Base and Histories*

The U.S. Department of Agriculture's *National Resources Inventory* (NRI) (USDA-NRCS 2009) provides the basis for identifying the U.S. agricultural land base on non-federal lands, and classifying parcels into *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*. Note that the Inventory does not include estimates of C stock changes and $N_2O$ emissions for federal grasslands and a minor amount of croplands on federal lands (with the exception of soil $N_2O$ from PRP manure N, i.e., manure deposited by grazing livestock), even though these areas are part of the managed land base for the United States. Greenhouse gas emissions from soils on federal croplands and grasslands will be further evaluated and included in future inventories.

The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the U.S. Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit, typically a 160-acre (64.75 ha) square quarter-section, three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land-use information (Nusser and Goebel 1997). In principle, the expansion factors represent the amount of area with the land use and land use change history that is the same as the point location. It is important to note that the NRI is a sampling of land use, and therefore there is some uncertainty associated with scaling the point data to a region or the country using the expansion factors. In general, those uncertainties decline at larger scales, such as states compared to smaller county units, because of a larger sample size. An extensive amount of soils, land-use, and land management data have been collected through the survey (Nusser et al. 1998).[73] Primary sources for data include aerial photography and remote sensing imagery as well as field visits and county office records.

The annual NRI data product provides crop data for most years between 1979 and 2007, with the exception of 1983, 1988, and 1993. These years are gap-filled using an automated set of rules so that cropping sequences are filled with the most likely crop type given the historical cropping pattern at each NRI point location. Grassland data are reported on 5-year increments prior to 1998, but it is assumed that the land use is also grassland between the years of data collection (see Easter et al. 2008 for more information).

NRI points are included in the land base for the agricultural soil C and $N_2O$ emissions inventories if they are identified as cropland or grassland[74] between 1990 and 2007 (Table A-203).[75] The NRI data are reconciled with the Forest Inventory and Analysis Dataset, and in this process, the time series for *Grassland Remaining Grassland* and *Land Converted to Grassland* is modified to account for differences in forest land area between the two national

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[72] No data are currently available at the national scale to distinguish the type of fertilizer applied or timing of applications rates. It is a planned improvement to address variation in these practices in future inventories.

[73] In the current Inventory, NRI data only provide land-use and management statistics through 2007, but additional data will be incorporated in the future to extend the time series of land use and management data.

[74] Includes non-federal lands only, because federal lands are not classified into land uses as part of the NRI survey (i.e, they are only designated as federal lands).

[75] Land use for 2008 to 2011 is assumed to be the same as 2007, but will be updated after new NRI data are released.

surveys (See Section 7.1 for more information on the U.S. land representation). Overall, 529,687 NRI survey points are included in the inventory.

For each year, land parcels are subdivided into *Cropland Remaining Cropland*, *Land Converted to Cropland*, *Grassland Remaining Grassland*, and *Land Converted to Grassland*. Land parcels under cropping management in a specific year are classified as *Cropland Remaining Cropland* if the parcel is cropland for at least 20 years. Similarly land parcels under grassland management in a specific year of the inventory are classified as *Grassland Remaining Grassland* if they are designated as grassland for at least 20 years.[76] Otherwise, land parcels are classified as *Land Converted to Cropland* or *Land Converted to Grassland* based on the most recent use in the inventory time period. Lands are retained in the land-use change categories (i.e., *Land Converted to Cropland* and *Land Converted to Grassland*) for 20 years as recommended by the IPCC guidelines (IPCC 2006).

Table A-203: Total Land Areas for the Agricultural Soil C and $N_2O$ Inventory, Subdivided by Land Use Categories (Million Hectares)

| | Land Areas ($10^6$ ha) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Category** | **1990** | **1991** | **1992** | **1993** | **1994** | **1995** | **1996** | **1997** | **1998** | **1999** | **2000** |
| **Mineral Soils** | | | | | | | | | | | |
| Cropland Remaining Cropland | 152.72 | 152.52 | 152.26 | 147.96 | 146.80 | 146.47 | 146.11 | 145.72 | 141.47 | 141.52 | 141.54 |
| Land Converted to Cropland | 13.84 | 14.14 | 14.41 | 15.55 | 19.09 | 19.31 | 19.65 | 19.80 | 19.03 | 18.58 | 18.20 |
| Grassland Remaining Grassland | 176.07 | 175.81 | 175.53 | 169.51 | 168.26 | 168.17 | 168.10 | 168.06 | 165.09 | 165.18 | 165.18 |
| Land Converted to Grassland | 8.96 | 9.02 | 9.15 | 11.33 | 11.91 | 12.16 | 12.35 | 12.72 | 15.08 | 15.54 | 16.01 |
| Non-Agricultural Uses[a] | 16.00 | 16.00 | 16.00 | 21.70 | 21.70 | 21.70 | 21.70 | 21.70 | 27.59 | 27.59 | 27.59 |
| **Organic Soils** | | | | | | | | | | | |
| Cropland Remaining Cropland | 0.63 | 0.63 | 0.63 | 0.61 | 0.61 | 0.61 | 0.61 | 0.61 | 0.60 | 0.60 | 0.60 |
| Land Converted to Cropland | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 |
| Grassland Remaining Grassland | 0.37 | 0.37 | 0.37 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.28 | 0.28 | 0.28 |
| Land Converted to Grassland | 0.16 | 0.16 | 0.16 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.27 | 0.27 | 0.27 |
| Non-Agricultural Uses[a] | 0.16 | 0.16 | 0.16 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.27 | 0.27 | 0.27 |
| **Total** | **368.88** | **368.77** | **368.64** | **367.32** | **369.04** | **369.09** | **369.18** | **369.27** | **369.56** | **369.71** | **369.83** |

| **Category** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **2009** | **2010** | **2011** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mineral Soils** | | | | | | | | | | | |
| Cropland Remaining Cropland | 141.54 | 142.06 | 144.22 | 143.27 | 143.53 | 143.80 | 144.42 | 144.42 | 144.42 | 144.42 | 144.42 |
| Land Converted to Cropland | 17.90 | 17.31 | 14.62 | 14.50 | 14.01 | 13.54 | 12.68 | 12.68 | 12.68 | 12.68 | 12.68 |
| Grassland Remaining Grassland | 165.01 | 165.54 | 167.89 | 167.78 | 167.51 | 167.47 | 167.88 | 167.68 | 167.47 | 167.27 | 167.07 |
| Land Converted to Grassland | 16.44 | 16.02 | 14.32 | 15.12 | 15.12 | 14.93 | 14.41 | 14.34 | 14.27 | 14.20 | 14.14 |
| Non-Agricultural Uses[a] | 27.59 | 27.59 | 33.62 | 33.62 | 33.62 | 33.62 | 33.62 | 33.62 | 33.62 | 33.62 | 33.62 |
| **Organic Soils** | | | | | | | | | | | |
| Cropland Remaining Cropland | 0.60 | 0.60 | 0.62 | 0.62 | 0.62 | 0.62 | 0.62 | 0.62 | 0.62 | 0.62 | 0.62 |
| Land Converted to Cropland | 0.07 | 0.07 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| Grassland Remaining Grassland | 0.28 | 0.28 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| Land Converted to Grassland | 0.27 | 0.27 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 |
| Non-Agricultural Uses[a] | 0.27 | 0.27 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 |
| **Total** | **369.80** | **369.83** | **376.02** | **375.64** | **375.14** | **374.72** | **374.35** | **374.08** | **373.81** | **373.54** | **373.28** |

[a] The non-agricultural uses were converted to or from cropland or grassland between 1990 and 2007.

The Tier 3 method using the DAYCENT model is used to estimate soil C stock changes and $N_2O$ emissions for most of the NRI points that occur on mineral soils. Parcels of land that are not simulated with DAYCENT are allocated to the Tier 2 approach for estimating soil organic C stock change, and a Tier 1 method (IPCC 2006) to

[76] NRI points are classified according to land-use history records starting in 1982 when the NRI survey began, and consequently the classifications are based on less than 20 years from 1990 to 2001.

estimate soil $N_2O$ emissions (Table A- 201) (Note: Tier 1 method for soil $N_2O$ does not require land area data with the exception of emissions from drainage and cultivation of organic soils). The land base that is not simulated with DAYCENT includes (1) land parcels occurring on organic soils; (2) land parcels that include non-agricultural uses such as forest and federal lands in one or more years of the inventory; (3) land parcels on mineral soils that are very gravelly, cobbly, or shaley (i.e., classified as soils that have greater than 35 percent of soil volume comprised of gravel, cobbles, or shale); or (4) land parcels that are used to produce vegetables, perennial/horticultural crops, tobacco or rice, which are either grown continuously or in rotation with other crops. DAYCENT has not been fully tested or developed to simulate biogeochemical processes in soils used to produce non-major crops, horticultural or perennial crops, rice and agricultural use of organic soils. In addition, DAYCENT has not been adequately tested for soils with a high gravel, cobble, or shale content.

Table A-204: Total Land Area Estimated with Tier 2[a] and 3 Inventory Approaches (Million Hectares)

| | Land Areas ($10^6$ ha) | | |
|---|---|---|---|
| **Year** | **Tier 2/1** | **Tier 3** | **Total** |
| 1990 | 48.58 | 320.30 | 368.88 |
| 1991 | 48.58 | 320.19 | 368.77 |
| 1992 | 48.58 | 320.05 | 368.64 |
| 1993 | 47.41 | 319.91 | 367.32 |
| 1994 | 47.41 | 319.64 | 367.05 |
| 1995 | 47.41 | 319.69 | 367.11 |
| 1996 | 47.41 | 319.79 | 367.20 |
| 1997 | 47.41 | 319.88 | 367.29 |
| 1998 | 49.92 | 319.64 | 369.56 |
| 1999 | 49.92 | 319.79 | 369.71 |
| 2000 | 49.92 | 319.90 | 369.83 |
| 2001 | 49.92 | 319.88 | 369.80 |
| 2002 | 49.92 | 319.91 | 369.83 |
| 2003 | 56.13 | 319.89 | 376.02 |
| 2004 | 56.13 | 319.51 | 375.64 |
| 2005 | 56.13 | 319.01 | 375.14 |
| 2006 | 56.13 | 318.59 | 374.72 |
| 2007 | 56.13 | 318.23 | 374.35 |
| 2008 | 56.13 | 317.96 | 374.08 |
| 2009 | 56.13 | 317.96 | 374.08 |
| 2010 | 56.13 | 317.42 | 373.54 |
| 2011 | 56.13 | 317.15 | 373.28 |

NRI points on mineral soils are classified into specific crop rotations, continuous pasture/rangeland, and other non-agricultural uses for the Tier 2 inventory analysis based on the survey data (Table A-205). NRI points are assigned to IPCC input categories (low, medium, high, and high with organic amendments) according to the classification provided in IPCC (2006). In addition, NRI differentiates between improved and unimproved grassland, where improvements include irrigation and interseeding of legumes. In order to estimate uncertainties, probability distribution functions (PDFs) for the NRI land-use data are constructed as multivariate normal based on the total area estimates for each land-use/management category and associated covariance matrix. Through this approach, dependencies in land use are taken into account resulting from the likelihood that current use is correlated with past use. These dependencies occur because as some land use/management categories increase in area, the area of other land use/management categories will decline. The covariance matrix addresses these relationships.

Table A-205: Total Land Areas by Land-Use and Management System for the Tier 2 Soil Organic C Approach (Million Hectares)

| | Land Areas ($10^6$ ha) | | | |
|---|---|---|---|---|
| **Land-Use/Management System** | **1990-1992 (Tier 2)** | **1993-1997 (Tier 2)** | **1998-2002 (Tier 2)** | **2003-2007 (Tier 2)** |

| | | | | |
|---|---|---|---|---|
| **Cropland Systems** | **17.20** | **15.16** | **15.04** | **13.50** |
| Aquaculture | 0.00 | 0.00 | 0.01 | 0.01 |
| Conservation Reserve Program | 0.86 | 0.80 | 0.40 | 0.45 |
| Continuous Hay | 1.20 | 1.16 | 1.32 | 1.36 |
| Continuous Hay with Legumes or Irrigation | 0.29 | 0.27 | 0.31 | 0.29 |
| Continuous Perennial or Horticultural Crops | 0.71 | 0.59 | 0.51 | 0.41 |
| Continuous Rice | 0.00 | 0.00 | 0.00 | 0.00 |
| Continuous Row Crops | 2.96 | 2.31 | 2.55 | 2.50 |
| Continuous Row Crops and Small Grains | 2.01 | 1.57 | 1.37 | 1.29 |
| Continuous Small Grains | 0.66 | 0.57 | 0.53 | 0.44 |
| Irrigated Crops | 5.61 | 5.41 | 5.76 | 5.04 |
| Low Residue Annual Crops (e.g., Tobacco or Cotton) | 0.79 | 0.90 | 0.72 | 0.57 |
| Miscellaneous Crop Rotations | 0.00 | 0.01 | 0.00 | 0.00 |
| Rice in Rotation with other crops | 0.01 | 0.00 | 0.01 | 0.03 |
| Row Crops and Small Grains in with Hay and/or Pasture | 0.47 | 0.35 | 0.41 | 0.22 |
| Row Crops and Small Grains with Fallow | 0.05 | 0.04 | 0.04 | 0.04 |
| Row Crops in Rotation with Hay and/or Pasture | 0.28 | 0.30 | 0.35 | 0.20 |
| Row Crops with Fallow | 0.03 | 0.01 | 0.03 | 0.00 |
| Small Grains in Rotation with Hay and/or Pasture | 0.19 | 0.11 | 0.10 | 0.06 |
| Small Grains with Fallow | 0.47 | 0.29 | 0.18 | 0.21 |
| Vegetable Crops | 0.61 | 0.47 | 0.44 | 0.38 |
| **Grassland Systems** | **10.63** | **7.51** | **8.53** | **8.72** |
| Rangeland | 3.71 | 2.88 | 3.27 | 3.43 |
| Continuous Pasture | 6.84 | 4.56 | 5.17 | 5.16 |
| Continuous Pasture with Legumes or Irrigation | 0.08 | 0.07 | 0.10 | 0.13 |
| CRP | 0.00 | 0.00 | 0.00 | 0.00 |
| **Non-Agricultural Systems** | **10.44** | **14.03** | **17.05** | **20.08** |
| Federal | 2.42 | 2.90 | 3.05 | 3.74 |
| Forest | 1.52 | 1.64 | 1.64 | 1.64 |
| Water | 0.47 | 0.61 | 0.76 | 0.82 |
| Settlements | 3.23 | 5.71 | 8.11 | 9.53 |
| Miscellaneous | 2.80 | 3.17 | 3.49 | 4.35 |
| **Total** | **38.27** | **36.70** | **40.63** | **42.30** |

For the Tier 3 inventory estimates, the actual cropping and grassland histories are simulated with the DAYCENT model so it is not necessary to classify NRI points into management systems. Uncertainty in the areas associated with each management system is determined from the estimated sampling variance from the NRI survey (Nusser and Goebel 1997). See Step 2b for additional discussion.

Organic soils are also categorized into land-use systems based on drainage (IPCC 2006). Undrained soils are treated as having no loss of organic C or $N_2O$ emissions. Drained soils are subdivided into those used for cultivated cropland, which are assumed to have high drainage and relatively large losses of C, and those used for managed pasture, which are assumed to have less drainage with smaller losses of C. $N_2O$ emissions are assumed to be similar for both drained croplands and grasslands. Overall, the area of organic soils drained for cropland and grassland has remained relatively stable since 1990 (see Table A-206).

Table A-206: Total Land Areas for Drained Organic Soils By Land Management Category and Climate Region (Million Hectares)

| | Land Areas ($10^6$ ha) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cold Temperate | | | | Warm Temperate | | | | Tropical | | | |
| **IPCC Land-Use Category for Organic Soils** | **1992** | **1997** | **2002** | **2007** | **1992** | **1997** | **2002** | **2007** | **1992** | **1997** | **2002** | **2007** |
| Undrained | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.06 | 0.05 | 0.04 | 0.01 |
| Managed Pasture (Low Drainage) | 0.36 | 0.34 | 0.31 | 0.29 | 0.03 | 0.03 | 0.03 | 0.02 | 0.05 | 0.05 | 0.03 | 0.02 |
| Cultivated Cropland (High Drainage) | 0.32 | 0.31 | 0.33 | 0.28 | 0.10 | 0.10 | 0.07 | 0.08 | 0.20 | 0.20 | 0.18 | 0.18 |
| Other Land Uses[a] | 0.07 | 0.10 | 0.15 | 0.17 | 0.05 | 0.05 | 0.06 | 0.06 | 0.03 | 0.05 | 0.07 | 0.10 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total** | **0.76** | **0.76** | **0.80** | **0.75** | **0.19** | **0.19** | **0.16** | **0.16** | **0.34** | **0.34** | **0.31** | **0.31** |

[a]Urban, water, and miscellaneous non-cropland, which are part of the agricultural land base because these areas were converted from or into agricultural land uses between 1990 and 2007.

*Synthetic N Fertilizer Application:* Data on N fertilizer rates are based primarily on the USDA–Economic Research Service Cropping Practices Survey (USDA-ERS 1997, 2011). In these surveys, data on inorganic N fertilization rates are collected for major crops (corn, cotton, soybeans, sorghum, oats, barley, spring wheat and winter wheat) in the high production states and for a subset of low production states. These data are used to build a time series of fertilizer application rates for specific crops and regions for the 1990 through 1999 time period and 2000 through 2011 time period. If only a single survey is available for a crop, as is the case with sorghum, the rates for the one survey are used for both time periods.

Mean fertilizer rates and standard deviations for irrigated and rainfed crops are produced for each state. If a state is not surveyed for a particular crop or if there are not enough data to produce a state-level estimate, then data are aggregated to USDA Farm Production Regions in order to estimate a mean and standard deviation for fertilization rates (Farm Production Regions are groups of states in the United States with similar agricultural commodities). If Farm Production Region data are not available, crop data are aggregated to the entire United States (all major states surveyed) to estimate a mean and standard deviation for a particular crop in a state lacking sufficient data. Standard deviations for fertilizer rates are used to construct probability distribution functions (PDFs) with log-normal densities in order to address uncertainties in application rates (see Step 2a for discussion of uncertainty methods). The survey summaries also present estimates for fraction of crop acres receiving fertilizer, and these fractions are used to determine if a crop is receiving fertilizer. Alfalfa hay is assumed to not be fertilized, but grass hay is fertilized according to rates from published farm enterprise budgets (NRIAI 2003). Total fertilizer application data are found in Table A- 207.

Simulations are conducted for the period prior to 1990 in order to initialize the DAYCENT model (see Step 2a), and crop-specific regional fertilizer rates prior to 1990 are based largely on extrapolation/interpolation of fertilizer rates from the years with available data. For crops in some agricultural regions, little or no data are available, and, therefore, a geographic regional mean is used to simulate N fertilization rates (e.g., no data are available for the State of Alabama during the 1970s and 1980s for corn fertilization rates; therefore, mean values from the southeastern United States are used to simulate fertilization to corn fields in this state).

*Managed Livestock Manure*[77]*Amendments:* County-level manure addition estimates have been derived from manure N addition rates developed by the USDA Natural Resources Conservation Service (NRCS) (Edmonds et al. 2003). Working with the farm-level crop and animal data from the 1997 Census of Agriculture, USDA-NRCS has coupled estimates of manure N produced with estimates of manure N recoverability by animal waste management system to produce county-level rates of manure N application to cropland and pasture. Edmonds et al. (2003) defined a hierarchy that included 24 crops, permanent pasture, and cropland used as pasture. They estimated the area amended with manure and application rates in 1997 for both manure-producing farms and manure-receiving farms within a county and for two scenarios—before implementation of Comprehensive Nutrient Management Plans (baseline) and after implementation (Edmonds et al. 2003). The goal of nutrient management plans is to apply manure nutrients at a rate meeting plant demand, thus limiting leaching losses of nutrients to groundwater and waterways.

For DAYCENT simulations, the rates for manure-producing farms and manure-receiving farms have been area-weighted and combined to produce a single county-level estimate for the amount of land amended with manure and the manure N application rate for each crop in each county. The estimates were based on the assumption that Comprehensive Nutrient Management Plans have not been fully implemented. This is a conservative assumption because it allows for higher leaching rates due to some over-application of manure to soils. Several of the crops in Edmonds et al. (2003) have been area-weighted and combined into broader crop categories. For example, all small grain crops have been combined

[77] For purposes of the Inventory, total livestock manure is divided into two general categories: (1) managed manure, and (2) unmanaged manure. Managed manure includes manure that is stored in manure management systems such as pits and lagoons, as well as manure applied to soils through daily spread manure operations. Unmanaged manure encompasses all manure deposited on soils by animals on PRP.

into one category. In order to address uncertainty in these data, uniform probability distributions are constructed based on the proportion of land receiving manure versus the amount not receiving manure for each crop type and pasture. For example, if 20 percent of land producing corn in a county is amended with manure, randomly drawing a value equal to or greater than 0 and less than 20 would lead to a simulation with a manure amendment, while drawing a value greater than or equal to 20 and less than 100 would lead to no amendment in the simulation (see Step 2a for further discussion of uncertainty methods).

Edmonds et al. (2003) only provides manure application rate data for 1997, but the amount of managed manure available for soil application changes annually, so the area amended with manure is adjusted relative to 1997 to account for all the manure available for application in other years. Specifically, the manure N available for application in other years is divided by the manure N available in 1997. If the ratio is greater than 1, there is more manure N available in that county relative to the amount in 1997, and so it is assumed a larger area is amended with manure. In contrast, ratios less than one implied less area is amended with manure because there is a lower amount available in the year compared to 1997. The amendment area in each county for 1997 is multiplied by the ratio to reflect the impact of manure N availability on the area amended. The amount of managed manure N available for application to soils is calculated by determining the populations of animals that are on feedlots or otherwise housed, requiring collection and management of the manure, and the methods are described in the Manure Management section (Section 6.2) and annex (Annex 3.10). The total managed manure N applied to soils is found in Table A- 208.

To estimate C inputs associated with manure N application rates derived from Edmonds et al. (2003), carbon-nitrogen (C:N) ratios for livestock-specific manure types are adapted from the Agricultural Waste Management Field Handbook (USDA 1996), On-Farm Composting Handbook (NRAES 1992), and recoverability factors provided by Edmonds et al (2003). The C:N ratios are applied to county-level estimates of manure N excreted by animal type and management system to produce a weighted county average C:N ratio for manure amendments. The average C:N ratio is used to determine the associated C input for crop amendments derived from Edmonds et al. (2003).

To account for the common practice of reducing inorganic N fertilizer inputs when manure is added to a cropland soil, crop-specific reduction factors are derived from mineral fertilization data for land amended with manure versus land not amended with manure in the ERS 1995 Cropping Practices Survey (ERS 1997). Mineral N fertilization rates are reduced for crops receiving manure N based on a fraction of the amount of manure N applied, depending on the crop and whether it is irrigated or rainfed. The reduction factors are randomly selected from PDFs with normal densities in order to address uncertainties in the dependence between manure amendments and mineral fertilizer application.

*PRP Manure N:* Another key source of N for grasslands is Pasture/Range/Paddock (PRP) manure N deposition (i.e., manure deposited by grazing livestock). Nitrogen from PRP animal waste deposited on non-federal grasslands was generated internally by the DayCent model based on plant biomass and grazing intensity. The simulations assume that on a per unit area basis, more biomass is consumed by grazing animals in more productive pastures than in less productive rangelands. As biomass consumption increases, so does the amount of N deposited by grazing animals. The total PRP manure N added to soils is found in Table A- 208.

*Residue N Inputs:* Crop residue N, fixation by legumes, and N residue inputs from senesced grass litter are included as sources of N to the soil, and are estimated in the DAYCENT simulations as a function of vegetation type, weather, and soil properties. That is, while the model accounts for the contribution of N from crop residues to the soil profile and subsequent $N_2O$ emissions, this source of mineral soil N is not activity data in the sense that it is not a model input. The simulated total N inputs of above- and below-ground residue N and fixed N that is not harvested and not burned (the DAYCENT simulations assumed that 3 percent of non-harvested above ground residues for grain crops are burned[78]) are provided in Table A-209.

*Other N Inputs:* Other N inputs are estimated within the DAYCENT simulation, and thus input data are not required, including mineralization from decomposition of soil organic matter and asymbiotic fixation of N from the

[78] Another improvement is to reconcile the amount of crop residues burned with the Field Burning of Agricultural Residues source category (Section 6.5).

atmosphere. Mineralization of soil organic matter will also include the effect of land use change on this process as recommended by the IPCC (2006). The influence of additional inputs of N are estimated in the simulations so that there is full accounting of all emissions from managed lands, as recommended by IPCC (2006). The simulated total N inputs from other sources are provided in Table A-209.

*Tillage Practices:* Tillage practices are estimated for each cropping system based on data from the Conservation Technology Information Center[79] (CTIC 2004). CTIC compiles data on cropland area under five tillage classes by major crop species and year for each county. Because the surveys involve county-level aggregate area, they do not fully characterize tillage practices as they are applied within a management sequence (e.g., crop rotation). This is particularly true for area estimates of cropland under no-till, which include a relatively high proportion of "intermittent" no-till, where no-till in one year may be followed by tillage in a subsequent year. For example, a common practice in maize-soybean rotations is to use tillage in the maize crop while no-till is used for soybean, such that no-till practices are not continuous in time. Estimates of the area under continuous no-till are provided by experts at CTIC to account for intermittent tillage activity and its impact on soil C (Towery 2001).

Tillage practices are grouped into 3 categories: full, reduced, and no-tillage. Full tillage is defined as multiple tillage operations every year, including significant soil inversion (e.g., plowing, deep disking) and low surface residue coverage. This definition corresponds to the intensive tillage and "reduced" tillage systems as defined by CTIC (2004). No-till is defined as not disturbing the soil except through the use of fertilizer and seed drills and where no-till is applied to all crops in the rotation. Reduced tillage made up the remainder of the cultivated area, including mulch tillage and ridge tillage as defined by CTIC and intermittent no-till. The specific tillage implements and applications used for different crops, rotations, and regions to represent the three tillage classes are derived from the 1995 Cropping Practices Survey by the Economic Research Service (ERS 1997).

Tillage data are further processed to construct probability distribution functions (PDFs). Transitions between tillage systems are based on observed county-level changes in the frequency distribution of the area under full, reduced, and no-till from the 1980s through 2004. Generally, the fraction of full tillage decreased during this time span, with concomitant increases in reduced till and no-till management. Transitions that are modeled and applied to NRI points occurring within a county are full tillage to reduced and no-till, and reduced tillage to no-till. The remaining amount of cropland is assumed to have no change in tillage (e.g., full tillage remained in full tillage). Transition matrices are constructed from CTIC data to represent tillage changes for three time periods, 1980-1989, 1990-1999, 2000-2011. Areas in each of the three tillage classes—full till (FT), reduced till (RT), no-till (NT)—in 1989 (the first year the CTIC data are available) are used for the first time period, data from 1997 are used for the second time period, and data from 2004 are used for the last time period. Percentage areas of cropland in each county are calculated for each possible transition (e.g., FT→FT, FT→RT, FT→NT, RT→RT, RT→NT) to obtain a probability for each tillage transition at an NRI point. Since continuous NT constituted < 1 percent of total cropland prior to 1990, there are no transitions for NT→FT or NT→NT. Uniform probability distributions are established for each tillage scenario in the county. For example, a particular crop rotation had 80 percent chance of remaining in full tillage over the two decades, a 15 percent chance of a transition from full to reduced tillage and a 5 percent chance of a transition from full to no-till. The uniform distribution is subdivided into three segments with random draws in the Monte Carlo simulation (discussed in Step 2b) leading to full tillage over the entire time period if the value is greater than or equal to 0 and less than 80, a transition from full to reduced till if the random draw is equal to or greater than 80 and less than 95, or a transition from full to no-till if the draw is greater than or equal to 95. See step 2b for additional discussion of the uncertainty analysis.

*Irrigation:* NRI (USDA-NRCS 2009) differentiates between irrigated and non-irrigated land, but does not provide more detailed information on the type and intensity of irrigation. Hence, irrigation is modeled by assuming that applied water is sufficient to meet full crop demand (i.e., irrigation plus precipitation equaled potential evapotranspiration during the growing season).

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[79] National scale tillage data are no longer collected by CTIC, and a new data source will be needed, which is a planned improvement.

*Daily Weather Data:* Daily maximum/minimum temperature and precipitation data are based on gridded weather data from the North America Regional Reanalysis Product (NARR) (Mesinger et al. 2006). It is necessary to use computer-generated weather data because weather station data do not exist near all NRI points, and moreover weather station data are for a point in space. The NARR product uses this information with interpolation algorithms to derive weather patterns for areas between these stations. NARR weather data are available for the U.S. for 1980 through 2007 at a 32 km resolution. Each NRI point is assigned the NARR weather data for the grid cell containing the point.

*Enhanced Vegetation Index:* The Enhanced Vegetation Index (EVI) from the MODIS vegetation products, (MOD13Q1 and MYD13Q1) is an input to DAYCENT for estimating net primary production using the NASA-CASA production algorithm (Potter et al. 1993, 2007). MODIS imagery is collected on a nominal 8 day-time frequency when combining the two products. A best approximation of the daily time series of EVI data is derived using a smoothing process based on the Savitzky-Golay Filter (Savitzky and Golay 1964) after pre-screening for outliers and for cloud-free, high quality data as identified in the MODIS data product quality layer. The NASA-CASA production algorithm is only used for the following major crops: corn, soybeans, sorghum, cotton, wheat and other close-grown crops such as barley and oats[80].

The MODIS EVI products have a 250 m spatial resolution, and some pixels in images have mixed land uses and crop types at this resolution, which is problematic for estimating NPP associated with a specific crop at a NRI point. Therefore, a threshold of 90 percent purity in an individual pixel is the cutoff for estimating NPP using the EVI data derived from the imagery (i.e., pixels with less than 90 percent purity for a crop are assumed to generate bias in the resulting NPP estimates). The USDA-NASS crop data layer (CDL) (Johnson and Mueller 2010) is used to determine the purity levels of the EVI data. CDL data have a 30 to 58 m spatial resolution, depending on the year. The level of purity for individual pixels in the MODIS EVI products is determined by aggregating the crop cover data in CDL to the 250m resolution of the EVI data. In this step, the percent cover of individual crops is determined for the pixels. Pixels that did not meet a 90 percent purity level for any crop are eliminated from the dataset. CDL does not provide full coverage of crop maps for the conterminous United States until 2009 so it is not possible to evaluate purity for the entire cropland area prior to 2009.

The nearest pixel with at least 90 percent purity for a crop is assigned to the NRI point based on a 50 km buffer surrounding the survey location. EVI data are not assigned to a point if there are no pixels with at least 90 percent purity within 50 km buffer. Furthermore, MODIS products do not provide any data on EVI prior to 2000, which preceded the launch of the MODIS sensor on the Aqua and Terra Satellites. It is good practice to apply a method consistently across a time series (IPCC 2006), and so a statistical model is used to estimate EVI for the inventory time series prior to 2000 and also to fill gaps if no pixel has at least 90 percent purity within the 50 km buffer due to purity limitations, lack of CDL data to evaluate purity, or low quality data (Gurung et al. 2009).

*Soil Properties:* Soil texture and natural drainage capacity (i.e., hydric vs. non-hydric soil characterization) are the main soil variables used as input to the DAYCENT model. Texture is one of the main controls on soil C turnover and stabilization in the DAYCENT model, which uses particle size fractions of sand (50-2,000 μm), silt (2-50 μm), and clay (< 2 μm) as inputs. Hydric condition specifies whether soils are poorly-drained, and hence prone to water-logging, or moderately to well-drained (non-hydric), in their native (pre-cultivation) condition.[81] Poorly drained soils can be subject to anaerobic (lack of oxygen) conditions if water inputs (precipitation and irrigation) exceed water losses from drainage and evapotranspiration. Depending on moisture conditions, hydric soils can range from being fully aerobic to completely anaerobic, varying over the year. Decomposition rates are modified according to a linear function that varies from 0.3 under completely anaerobic conditions to 1.0 under fully aerobic conditions (default parameters in DAYCENT).[82] Other soil characteristics needed in the simulation, such as field capacity and wilting-point water contents, are estimated from

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[80] Additional crops and grassland will be used with the NASA-CASA method in the future, as a planned improvement.

[81] Artificial drainage (e.g., ditch- or tile-drainage) is simulated as a management variable.

[82] Hydric soils are primarily subject to anaerobic conditions outside the plant growing season (i.e., in the absence of active plant water uptake). Soils that are water-logged during much of the year are typically classified as organic soils (e.g., peat), which are not simulated with the DAYCENT model.

soil texture data using a standardized hydraulic properties calculator (Saxton et al. 1986). Soil input data are derived from Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). The data are based on field measurements collected as part of soil survey and mapping. Each NRI point is assigned the dominant soil component in the polygon containing the point from the SSURGO data product.

### *Step 1c: Obtain Additional Management Activity Data for the Tier 1 Method to estimate Soil $N_2O$ Emissions from Mineral Soils*

*Synthetic N Fertilizer:* A process-of-elimination approach is used to estimate synthetic N fertilizer additions to non-major crop types. The total amount of fertilizer used on-farms has been estimated by the USGS from 1990-2001 on a county scale from fertilizer sales data (Ruddy et al. 2006). For 2002 through 2011, county-level fertilizer used on-farms is adjusted based on annual fluctuations in total U.S. fertilizer sales (AAPFCO 1995 through 2011). In addition, fertilizer application data are available for major crops and grasslands (discussed in Step 1 sections for Major Crops and Grasslands). Thus, the amount of N applied to non-major crops is assumed to be the remainder of the fertilizer used on farms after subtracting the amount applied to major crops and grasslands. The differences are aggregated to the state level, and PDFs are derived based on uncertainties in the amount of N applied to major crops and grasslands. Total fertilizer application to non-major crops is found in Table A- 210.

*Managed Livestock Manure and Other Organic Amendments:* Manure N that is not applied to major crops and grassland is assumed to be applied to non-major crop types. Estimates of total national annual N additions from other commercial organic fertilizers are derived from organic fertilizer statistics (TVA 1991 through 1994; AAPFCO 1995 through 2011). AAPFCO fertilizer data are not yet available for 2011, so 2010 values are used as a placeholder until data become available. Commercial organic fertilizers include dried blood, tankage, compost, and other; dried manure and sewage sludge that are used as commercial fertilizer are subtracted from totals to avoid double counting. The dried manure N is counted with the non-commercial manure applications, and sewage sludge is assumed to be applied only to grasslands. The organic fertilizer data, which are recorded in mass units of fertilizer, had to be converted to mass units of N by multiplying the consumption values by the average organic fertilizer N contents provided in the annual fertilizer publications. These N contents are weighted average values, and vary from year to year (ranging from 2.3 percent to 3.9 percent over the period 1990 through 2008). The fertilizer consumption data are recorded in "fertilizer year" totals, (i.e., July to June), but are converted to calendar year totals. This is done by assuming that approximately 35 percent of fertilizer usage occurred from July to December and 65 percent from January to June (TVA 1992b). Values for July to December are not available after calendar year 2010 so a "least squares line" statistical extrapolation using the previous 22 years of data is used to arrive at an approximate value. PDFs are derived for the organic fertilizer applications assuming a default ±50 percent uncertainty. Annual consumption of other organic fertilizers is presented in Table A- 211. The fate of manure N is summarized in Table A- 208.

*PRP Manure N:* Soil $N_2O$ emissions from PRP manure N deposited on federal grasslands is estimated with a Tier 1 method. PRP manure N data are derived using methods described in the Manure Management section (Section 6.2) and Annex 3.10. PRP N deposited on federal grasslands is calculated using a process of elimination approach. The amount of PRP N generated by DAYCENT model simulations of non-federal grasslands was subtracted from total PRP N and this difference was assumed to be applied to federal grasslands. The total PRP manure N added to soils is found in Table A- 208.

*Sewage Sludge Amendments:* Sewage sludge is generated from the treatment of raw sewage in public or private wastewater treatment works and is typically used as a soil amendment or is sent to waste disposal facilities such as landfills. In this Inventory, all sewage sludge that is amended to agricultural soils is assumed to be applied to grasslands. Estimates of the amounts of sewage sludge N applied to agricultural lands are derived from national data on sewage sludge generation, disposition, and N content. Total sewage sludge generation data for 1988, 1996, and 1998, in dry mass units, are obtained from EPA (1999) and estimates for 2004 are obtained from an independent national biosolids survey (NEBRA 2007). These values are linearly interpolated to estimate values for the intervening years, and linearly extrapolated to estimate values for years since 2004. Sewage sludge generation data are not available after 2004 (Bastian 2007), so the 1990 through 2004 data are linearly extrapolated for the most recent years. The total sludge generation estimates are then converted to units of N by applying an average N content of 3.9 percent (McFarland 2001), and

disaggregated into use and disposal practices using historical data in EPA (1993) and NEBRA (2007). The use and disposal practices are agricultural land application, other land application, surface disposal, incineration, landfilling, ocean dumping (ended in 1992), and other disposal. The resulting estimates of sewage sludge N applied to agricultural land are used here; the estimates of sewage sludge N applied to other land and surface-disposed are used in estimating $N_2O$ fluxes from soils in *Settlements Remaining Settlements* (see section 7.5 of the Land Use, Land-Use Change, and Forestry chapter). Sewage sludge disposal data are provided in Table A- 212.

*Residue N Inputs*: Soil $N_2O$ emissions for residue N inputs from non-major crops are estimated with a Tier 1 method. Annual crop yield (metric tons per hectare) and area harvested (hectare) statistics for non-major N-fixing crops, including bean and pulse crops, are taken from U.S. Department of Agriculture crop production reports (USDA 1994, 1998, 2003, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012). Crop yield per hectare and area planted are multiplied to determine total crop yield for each crop, which is then converted to tons of dry matter product using the residue dry matter fractions shown in Table A- 213. Dry matter yield is then converted to tons of above- and below-ground biomass N. Above-ground biomass is calculated by using linear equations to estimate above-ground biomass given dry matter crop yields, and below-ground biomass is calculated by multiplying above-ground biomass by the below-to-above-ground biomass ratio. N inputs are estimated by multiplying above- and below-ground biomass by respective N concentrations. All ratios and equations used to calculate residue N inputs are from IPCC (2006) and Williams (2006). PDFs are derived assuming a ±50 percent uncertainty in the yield estimates (NASS does not provide uncertainty), along with uncertainties provided by the IPCC (2006) for dry matter fractions, above-ground residue, ratio of below-ground to above-ground biomass, and residue N fractions. The resulting annual biomass N inputs are presented in Table A- 214.

### *Step 1d: Obtain Additional Management Activity Data for the Tier 2 Method to estimate Soil C Stock Changes in Mineral Soils*

*Tillage Practices:* For the Tier 2 method used to estimate soil organic C stock changes, PDFs are constructed for the CTIC tillage data (CTIC 2004), as bivariate normal on a log-ratio scale to reflect negative dependence among tillage classes. This structure ensured that simulated tillage percentages are non-negative and summed to 100 percent. CTIC data do not differentiate between continuous and intermittent use of no-tillage, which is important for estimating SOC storage. Thus, regionally based estimates for continuous no-tillage (defined as 5 or more years of continuous use) are modified based on consultation with CTIC experts, as discussed in Step 1a (downward adjustment of total no-tillage acres reported, Towery 2001).

*Managed Livestock Manure Amendments:* USDA provides information on the amount of land amended with manure for 1997 based on manure production data and field-scale surveys detailing application rates that had been collected in the *Census of Agriculture* (Edmonds et al. 2003). Similar to the DAYCENT model discussion in Step1b, the amount of land receiving manure is based on the estimates provided by Edmonds et al. (2003), as a proportion of crop and grassland amended with manure within individual climate regions. The resulting proportions are used to re-classify a portion of crop and grassland into a new management category. Specifically, a portion of medium input cropping systems is re-classified as high input, and a portion of the high input systems is re-classified as high input with amendment. In grassland systems, the estimated proportions for land amended with manure are used to re-classify a portion of nominally-managed grassland as improved, and a portion of improved grassland as improved with high input. These classification approaches are consistent with the IPCC inventory methodology (IPCC 2006). Uncertainties in the amount of land amended with manure are based on the sample variance at the climate region scale, assuming normal density PDFs (i.e., variance of the climate region estimates, which are derived from county-scale proportions).

*Sewage Sludge Amendments:* Sewage sludge is generated from the treatment of raw sewage in public or private wastewater treatment works and is typically used as a soil amendment or is sent to waste disposal facilities such as landfills. In this Inventory, all sewage sludge that is amended to agricultural soils is assumed to be applied to grasslands. See section on sewage sludge in Step 1c for more information about the methods used to derive sewage sludge N estimates, and the total amount of sewage sludge N is given in Table A- 212. Sewage sludge N is assumed to be applied at the assimilative capacity provided in Kellogg et al. (2000), which is the amount of nutrients taken up by a crop and removed at harvest, representing the recommended application rate for manure amendments. This capacity varies from year to year, because it is based on specific crop yields during the respective year (Kellogg et al. 2000). Total sewage

sludge N available for application is divided by the assimilative capacity to estimate the total land area over which sewage sludge had been applied. The resulting estimates are used for the estimation of soil C stock change.

*CRP Enrollment after 2007:* The change in enrollment for the Conservation Reserve Program after 2007 is based on the amount of land under active contracts from 2008 through 2011 relative to 2007 (USDA-FSA 2011).

*Wetland Reserve:* Wetlands enrolled in the Conservation Reserve Program have been restored in the Northern Prairie Pothole Region through the Partners for Wildlife Program funded by the U.S. Fish and Wildlife Service. The area of restored wetlands is estimated from contract agreements (Euliss and Gleason 2002). While the contracts provide reasonable estimates of the amount of land restored in the region, they do not provide the information necessary to estimate uncertainty. Consequently, a ±50 percent range is used to construct the PDFs for the uncertainty analysis.

Table A- 207: Synthetic Fertilizer N Added to Major Crops (Gg N)

| | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fertilizer N | 8,299 | 8,722 | 8,779 | 8,310 | 8,402 | 8,631 | 8,820 | 8,670 | 8,512 | 9,188 | 8,864 | 8,626 | 8,915 | 8,962 |

Table A- 208: Fate of Livestock Manure Nitrogen (Gg N)

| Activity | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Managed Manure N Applied to Major Crops and Grasslands[a,b] | 961 | 889 | 1,062 | 1,020 | 1,024 | 1,016 | 1,018 | 1,017 | 981 | 1,083 | 1,083 | 1,083 | 1,089 | 1,092 |
| Managed Manure N Applied to Non-Major Crops[b] | 1,942 | 2,277 | 2,643 | 2,592 | 2,666 | 2,468 | 2,336 | 2,493 | 2,685 | 2,643 | 2,587 | 2,503 | 2,503 | 2,460 |
| Managed Manure N Applied to Grasslands | 41 | 43 | 44 | 44 | 44 | 43 | 44 | 45 | 45 | 46 | 45 | 44 | 44 | 44 |
| Pasture, Range, & Paddock Manure N | 4,091 | 4,556 | 4,122 | 4,128 | 4,115 | 4,170 | 4,059 | 4,135 | 4,138 | 4,070 | 4,017 | 3,977 | 3,934 | 3,845 |
| **Total** | 7,036 | 7,765 | 7,871 | 7,784 | 7,849 | 7,696 | 7,457 | 7,689 | 7,849 | 7,842 | 7,733 | 7,607 | 7,571 | 7,441 |

[a] Accounts for N volatilized and leached/runoff during treatment, storage and transport before soil application.
[b] Includes managed manure and daily spread manure amendments
[c] Totals may not sum exactly due to rounding.

Table A-209: Crop Residue N and Other N Inputs to Major Crops as Simulated by DAYCENT (Gg N)

| Activity | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Residue N[a] | 639 | 674 | 642 | 664 | 604 | 663 | 752 | 648 | 610 | 632 | 632 | 632 | 632 | 632 |
| Mineralization & Asymbiotic Fixation | 10,628 | 10,943 | 10,703 | 11,323 | 10,940 | 11,036 | 11,690 | 10,889 | 10,955 | 10,964 | 10,964 | 10,964 | 10,964 | 10,964 |

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Table A- 210: Synthetic Fertilizer N Added to Non-Major Crops (Gg N)

| | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fertilizer N | 1,061 | 1,099 | 1,481 | 1,183 | 1,386 | 1,487 | 1,612 | 1,279 | 1,622 | 1,422 | 1,058 | 909 | 1,093 | 1,129 |

Table A- 211: Other Organic Commercial Fertilizer Consumption on Agricultural Lands (Gg N)

| | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Other Commercial Organic Fertilizer N[a] | 4 | 10 | 9 | 7 | 8 | 8 | 9 | 10 | 12 | 15 | 12 | 10 | 9 | 10 |

[a] Includes dried blood, tankage, compost, other. Excludes dried manure and sewage sludge used as commercial fertilizer to avoid double counting.

Table A- 212: Sewage Sludge Nitrogen by Disposal Practice (Gg N)

| Disposal Practice | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Applied to Agricultural Soils | 52 | 69 | 84 | 86 | 89 | 91 | 94 | 98 | 101 | 104 | 106 | 109 | 112 | 112 |
| Other Land Application | 25 | 28 | 30 | 30 | 30 | 30 | 30 | 31 | 31 | 32 | 32 | 32 | 32 | 32 |
| Surface Disposal | 20 | 16 | 10 | 9 | 8 | 6 | 5 | 5 | 4 | 4 | 3 | 3 | 3 | 3 |
| **Total** | **98** | **113** | **124** | **125** | **127** | **128** | **130** | **134** | **136** | **139** | **141** | **144** | **147** | **147** |

Note: Totals may not sum due to independent rounding.

Table A- 213: Key Assumptions for Production of Non-Major Crops and Retention of Crop Residues

| Crop | Dry Matter Fraction of Harvested Product | Above-ground Residue | | Ratio of Below-ground Residue to Above-ground Biomass | Residue N Fraction | |
|---|---|---|---|---|---|---|
| | | Slope | Intercept | | Above-ground | Below-ground |
| Peanuts for Nuts | 0.94 | 1.07 | 1.54 | 0.20 | 0.016 | 0.014 |
| Dry Edible Beans | 0.90 | 0.36 | 0.68 | 0.19 | 0.010 | 0.010 |
| Dry Edible Peas | 0.91 | 1.13 | 0.85 | 0.19 | 0.008 | 0.008 |
| Austrian Winter Peas | 0.91 | 1.13 | 0.85 | 0.19 | 0.008 | 0.008 |
| Lentils | 0.91 | 1.13 | 0.85 | 0.19 | 0.008 | 0.008 |
| Wrinkled Seed Peas | 0.91 | 1.13 | 0.85 | 0.19 | 0.008 | 0.008 |
| Barley | 0.89 | 0.98 | 0.59 | 0.22 | 0.007 | 0.014 |
| Oats | 0.89 | 0.91 | 0.89 | 0.25 | 0.007 | 0.008 |
| Rye | 0.88 | 1.09 | 0.88 | 0.22 | 0.005 | 0.011 |
| Millet | 0.90 | 1.43 | 0.14 | 0.22 | 0.007 | 0.009 |
| Rice | 0.89 | 0.95 | 2.46 | 0.16 | 0.007 | 0.009 |

Table A- 214: Nitrogen in Crop Residues Retained on Soils Producing Non-Major Crops (Gg N)

| Crop | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Peanuts for Nuts | 64 | 63 | 61 | 71 | 61 | 69 | 71 | 77 | 63 | 65 | 79 | 65 | 70 | 64 |
| Dry Edible Beans | 16 | 16 | 15 | 13 | 16 | 14 | 13 | 15 | 14 | 15 | 15 | 15 | 16 | 13 |
| Dry Edible Peas | 9 | 11 | 10 | 10 | 10 | 11 | 14 | 15 | 8 | 8 | 14 | 17 | 15 | 11 |
| Austrian Winter Peas | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| Lentils | 9 | 9 | 10 | 10 | 9 | 9 | 10 | 11 | 10 | 10 | 9 | 11 | 12 | 10 |
| Wrinkled Seed Peas | 9 | 9 | 8 | 8 | 8 | 8 | 9 | 8 | 8 | 8 | 8 | 9 | 8 | 8 |
| Barley | 112 | 96 | 86 | 68 | 63 | 76 | 76 | 59 | 51 | 59 | 66 | 63 | 51 | 45 |
| Oats | 55 | 29 | 28 | 24 | 23 | 27 | 23 | 23 | 20 | 20 | 20 | 20 | 19 | 15 |
| Rye | 9 | 9 | 9 | 8 | 8 | 9 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| Millet | 7 | 7 | 3 | 7 | 2 | 5 | 6 | 5 | 4 | 6 | 6 | 4 | 5 | 4 |
| Rice | 80 | 87 | 94 | 103 | 101 | 97 | 109 | 106 | 95 | 96 | 99 | 105 | 114 | 91 |
| **Total** | **378** | **343** | **331** | **330** | **311** | **333** | **347** | **336** | **290** | **304** | **333** | **324** | **327** | **279** |

### *Step 1e: Additional Activity Data for Indirect $N_2O$ Emissions from Managed Soils of all Land-Use Types*

A portion of the N that is applied or deposited as synthetic fertilizer, livestock manure, sewage sludge, and other organic amendments volatilizes as $NH_3$ and $NO_x$. In turn, this N is returned to soils through atmospheric deposition, thereby increasing mineral N availability and enhancing $N_2O$ production. Additional N is lost from soils through leaching as water percolates through a soil profile and through runoff with overland water flow. N losses from leaching and runoff enter groundwater and waterways, from which a portion is emitted as $N_2O$. However, N leaching is assumed to be an insignificant source of indirect $N_2O$ in cropland and grassland systems where the amount of precipitation plus irrigation does not exceed 80 percent of the potential evapotranspiration. These areas are typically semi-arid to arid, and nitrate

leaching to groundwater is a relatively uncommon event; moreover IPCC (2006) recommends limiting the amount of nitrate leaching assumed to be a source of indirect $N_2O$ emissions based on precipitation, irrigation and potential evapotranspiration.

The activity data for synthetic fertilizer, livestock manure, other organic amendments, residue N inputs, sewage sludge N, and other N inputs are the same as those used in the calculation of direct emissions from agricultural mineral soils, and may be found in Table A- 207 through Table A- 211, Table A- 214, and Table A- 212. The activity data for computing direct and indirect $N_2O$ emissions from settlements and forest lands are described in the Land Use, Land-Use Change, and Forestry chapter.

Using the DAYCENT model, volatilization and leaching/surface run-off of N from soils is computed internally for major crop types and non-federal grasslands. DAYCENT simulates the processes leading to these losses of N based on environmental conditions (i.e., weather patterns and soil characteristics), management impacts (e.g., plowing, irrigation, harvest), and soil N availability. Note that the DAYCENT model accounts for losses of N from all anthropogenic activity, not just the inputs of N from mineral fertilization and organic amendments, which are addressed in the Tier 1 methodology. Similarly, the N available for producing indirect emissions resulting from grassland management as well as deposited PRP manure is also estimated by DAYCENT. Estimated leaching losses of N from DAYCENT are not used in the indirect $N_2O$ calculation if the amount of precipitation plus irrigation did not exceed 80 percent of the potential evapotranspiration. Volatilized losses of N are summed for each day in the annual cycle to provide an estimate of the amount of N subject to indirect $N_2O$ emissions. In addition, the daily losses of N through leaching and runoff in overland flow are summed for the annual cycle. Uncertainty in the estimates is derived from uncertainties in the activity data for the N inputs (i.e., fertilizer and organic amendments; see Step 1a for further information).

The Tier 1 method is used to estimate N losses from mineral soils due to volatilization and leaching/runoff for non-major crop types, forestland, settlements, sewage sludge applications, and PRP manure on federal grasslands not accounted for by DAYCENT simulations. To estimate volatilized losses, synthetic fertilizers, manure, sewage sludge, and other organic N inputs are multiplied by the fraction subject to gaseous losses using the respective default values of 0.1 kg N/kg N added as mineral fertilizers and 0.2 kg N/kg N added as manure (IPCC 2006). Uncertainty in the volatilized N ranges from 0.03-0.3 kg $NH_3$-N+NOx-N/kg N for synthetic fertilizer and 0.05-0.5 kg $NH_3$-N+NOx-N/kg N for organic amendments (IPCC 2006). Leaching/runoff losses of N are estimated by summing the N additions from synthetic and other organic fertilizers, manure, sewage sludge, and above- and below-ground crop residues, and then multiplying by the default fraction subject to leaching/runoff losses of 0.3 kg N/kg N applied, with an uncertainty from 0.1–0.8 kg $NO_3$-N/kg N (IPCC 2006). However, N leaching is assumed to be an insignificant source of indirect $N_2O$ emissions if the amount of precipitation plus irrigation did not exceed 80 percent of the potential evapotranspiration. PDFs are derived for each of the N inputs in the same manner as direct $N_2O$ emissions, discussed in Steps 1a and 1c.

Volatilized N is summed for losses from major crop types, minor crop types, grasslands, settlements, and forest lands. Similarly, the annual amounts of N lost from soil profiles through leaching and surface runoff are summed to obtain the total losses for this pathway.

### Step 2: Estimate Soil Organic C Stock Changes and Direct $N_2O$ Emissions from Mineral Soils

In this step, soil organic C stock changes and $N_2O$ emissions are estimated for major crop types, non-major crop types, federal and non-federal grasslands. Three methods are used to estimate soil organic C stock changes and direct $N_2O$ emissions from mineral soils. The DAYCENT process-based model is used for major crop types and non-federal grasslands. A Tier 2 method is used to estimate soil organic C stock changes for non-major crop types and land use change other than conversions between cropland and grassland. A Tier 1 methodology is used to estimate $N_2O$ emissions from crops considered non-major types, which are grown on a considerably smaller portion of land than the major types, as well as PRP manure N deposition on federal grasslands. Soil organic C stock changes and $N_2O$ emissions are not estimated for federal grasslands (other than the effect of PRP manure N), but are under evaluation as a planned improvement and may be estimated in future inventories.

### *Step 2a: Estimate Soil Organic C Stock Changes and $N_2O$ Emissions for Major Crops and Non-Federal Grassland with the Tier 3 DAYCENT Model*

Major crops include corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton, which represent approximately 90 percent of total principle cropland in the United States as defined by the U.S. Department of Agriculture (USDA 2003). Overall, the DAYCENT simulations included approximately 86 percent of total cropland area, and all non-federal grasslands.

The methodology description is divided into two sub-steps. First, the model is used to establish the initial conditions and C stocks for 1979, which is the last year before the NRI survey is initiated. In the second sub-step, DAYCENT is used to estimate changes in soil organic C stocks and direct $N_2O$ emissions based on the land-use and management histories recorded in the NRI (USDA-NRCS 2009), including the reporting period starting in 1990.

*Simulate Initial Conditions (Pre-NRI Conditions):* DAYCENT model initialization involves two steps, with the goal of estimating the most accurate stock for the pre-NRI history, and the distribution of organic C among the pools represented in the model (e.g., Structural, Metabolic, Active, Slow, and Passive). Each pool has a different turnover rate (representing the heterogeneous nature of soil organic matter), and the amount of C in each pool at any point in time influences the forward trajectory of the total soil organic C storage. There is currently no national set of soil C measurements that can be used for establishing initial conditions in the model. Sensitivity analysis of the soil organic C algorithms showed that the rate of change of soil organic matter is relatively insensitive to the *amount* of total soil organic C but is highly sensitive to the relative *distribution* of C among different pools (Parton et al. 1987). By simulating the historical land use prior to the inventory period, initial pool distributions are estimated in an unbiased way.

The first step involves running the model to a steady-state condition (e.g., equilibrium) under native vegetation, historical climate data based on the NARR product (1980-2007), and the soil physical attributes for the NRI points. Native vegetation is represented at the MLRA level for pre-settlement time periods in the United States. The model simulates 5,000 years in the pre-settlement era in order to achieve a steady-state condition.

The second step is to simulate the period of time from European settlement and expansion of agriculture to the beginning of the NRI survey, representing the influence of historic land-use change and management, particularly the conversion of native vegetation to agricultural uses. This encompasses a varying time period from land conversion (depending on historical settlement patterns) to 1979. The information on historical cropping practices used for DAYCENT simulations has been gathered from a variety of sources, ranging from the historical accounts of farming practices reported in the literature (e.g., Miner 1998) to national level databases (e.g., NASS 2004). A detailed description of the data sources and assumptions used in constructing the base history scenarios of agricultural practices can be found in Williams and Paustian (2005).

*NRI History Simulations:* After model initialization, DAYCENT is used to simulate the NRI land use and management histories from 1979 through 2007.[83] The simulations address the influence of soil management on direct $N_2O$ emissions, soil organic C stock changes and losses of N from the profile through leaching/runoff and volatilization. The NRI histories identify the land use and land use change histories for the NRI survey locations, as well as cropping patterns and irrigation history (see Step 1a for description of the NRI data). The input data for the model simulations also include the NARR weather dataset and SSURGO soils data, synthetic N fertilizer rates, managed manure amendments to cropland and grassland, manure deposition on grasslands (i.e., PRP), tillage histories and EVI data (See Step 1b for description of the inputs). The total number of DAYCENT simulations is over 12 million with a 100 repeated simulations (i.e., iterations) for each NRI point location in a Monte Carlo Analysis. The simulation system incorporates a dedicated MySQL database server and a 30-node parallel processing computer cluster. Input/output operations are managed by a set of run executive programs written in PERL.

The simulations for the NRI history are integrated with the uncertainty analysis. The assessment framework for this analysis is illustrated in Figure A-14. Evaluating uncertainty is an integral part of the analysis, and includes three

[83] The estimated soil C stock change in 2007 is currently assumed to represent the changes between 2008 and 2011. New estimates will be available in the future to extend the time series of land use and management data.

components: (1) uncertainty in the main activity data inputs affecting soil C and $N_2O$ emissions (input uncertainty); (2) uncertainty in the model formulation and parameterization (structural uncertainty); and (3) uncertainty in the land-use and management system areas (scaling uncertainty) (Ogle et al. 2010, Del Grosso et al. 2010). For component 1, input uncertainty is evaluated for fertilization management, manure applications, and tillage, which are primary management activity data that are supplemental to the NRI observations and have significant influence on soil organic C dynamics and $N_2O$ emissions. As described in Step 1b, PDFs are derived from surveys at the county scale for the inputs in most cases. In addition, uncertainty is included for predictions of EVI data that are needed to fill-data gaps and extend the time series (see Enhance Vegetation Index in Step 1b). To represent uncertainty in these inputs, a Monte-Carlo Analysis is used with 100 iterations for each NRI point; random draws are made from PDFs for fertilizer, manure application, tillage, and EVI predictions. As described above, an adjustment factor is also selected from PDFs with normal densities to represent the dependence between manure amendments and N fertilizer application rates.

Figure A-14: Framework for the DAYCENT Simulations Integrating Process-based Model with a Monte Carlo Analysis

**To be provided:**

**Figure A-13: Framework for the DAYCENT Simulations Integrating Process-based Model with a Monte Carlo Analysis**

The second component deals with uncertainty inherent in model formulation and parameterization. This component is generally the largest source of uncertainty in the model-based inventory analysis, accounting for more than 80 percent of the overall uncertainty in the final estimates (Ogle et al. 2010, Del Grosso et al. 2010). An empirically-based procedure is applied to develop a structural uncertainty estimator from the relationship between modeled results and field measurements from agricultural experiments and NRI soil monitoring network locations (Ogle et al. 2007; Spencer et al. 2011). For soil organic C, the DAYCENT model is initialized for 47 long-term field experiments with over 800 treatments and the NRI soil monitoring network, representing a variety of management conditions (e.g., variation in crop rotation, tillage, fertilization rates, and manure amendments). There are 11 experimental sites available to evaluate structural uncertainty in the $N_2O$ emission predictions from DAYCENT (Del Grosso et al. 2010). The inputs to the model are essentially known in the simulations for the long-term experiments, and, therefore, the analysis is designed to evaluate uncertainties associated with the model structure (i.e., model algorithms and parameterization).

The relationship between modeled soil organic C stocks and field measurements are statistically analyzed using linear-mixed effect modeling techniques. Additional fixed effects are included in the mixed effect model if they explained significant variation in the relationship between modeled and measured stocks (i.e., if they met an alpha level of 0.05 for significance). Several variables are tested including: land-use class; type of tillage; cropping system; geographic location; climate; soil texture; time since the management change; original land cover (i.e., forest or grassland); grain harvest as predicted by the model compared to the experimental values; and variation in fertilizer and residue management. The final model includes variables for organic matter amendments, fertilizer rates, inclusion of hay/pasture in cropping rotations, use of no-till, and inclusion of bare fallow in the rotation, which are significant at an alpha level of 0.05. These fixed effects are used to make an adjustment to modeled values due to biases that are creating significant mismatches between the modeled and measured stocks. For soil $N_2O$, simulated DAYCENT emissions are a highly significant predictor of the measurements, with a p-value of $<0.01$. Several other variables are considered in the statistical model to evaluate if DAYCENT exhibits bias under certain conditions related to climate, soil types, and management practices. The type of crop or grassland is significant at an alpha level of 0.05, demonstrating that DAYCENT tends to over-estimate emissions for small grains systems and grassland, but is accurate in predicting the $N_2O$ emissions for other crops. Random effects are included in the model to capture the dependence in time series and data collected from the same site, which are needed to estimate appropriate standard deviations for parameter coefficients.

A Monte Carlo approach is used to apply the uncertainty estimator (Ogle et al. 2010). Parameter values for the statistical equation (i.e., fixed effects) are selected from their joint probability distribution, as well as random error associated with fine-scale estimates at NRI points, and the residual or unexplained error associated with the linear mixed-

effect model. The estimate and associated management information is then used as input into the equation, and adjusted values are computed for each C stock and $N_2O$ emissions estimate. The variance of the adjusted estimates is computed from the 100 simulated values from the Monte Carlo analysis.

The third element is the uncertainty associated with scaling the DAYCENT results for each NRI point to the entire land base, using the expansion factors provided with the NRI survey dataset. The expansion factors represent the number of hectares associated with the land-use and management history for a particular point. This uncertainty is determined by computing the variances of a set of replicated weights for the expansion factor.

For the land base that is simulated with the DAYCENT model, soil organic C stock changes are provided in Table A-215, and soil $N_2O$ emissions are provided in Table A-216.

Table A-215: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Land Base Simulated with the Tier 3 DAYCENT Model-Based Approach (Tg $CO_2$ Eq.)

| | Cropland Remaining Cropland | | Land Converted to Cropland | | Grassland Remaining Grassland | | Land Converted to Grassland | |
|---|---|---|---|---|---|---|---|---|
| Year | Estimate | 95% CI | Estimate | 95% CI | Estimate | 95% CI | Estimate | 95% CI |
| 1990 | (55.19) | (111.72) to 1.33 | (4.43) | (5.06) to (3.80) | (55.10) | (57.18) to (53.01) | (15.75) | (18.43) to (13.07) |
| 1991 | (57.50) | (90.49) to (24.51) | (4.30) | (4.93) to (3.68) | (28.04) | (29.87) to (26.21) | (15.06) | (17.58) to (12.54) |
| 1992 | (68.05) | (99.81) to (36.28) | (4.75) | (5.38) to (4.13) | (9.84) | (10.82) to (8.85) | (13.83) | (16.23) to (11.44) |
| 1993 | (64.25) | (95.93) to (32.56) | (8.66) | (9.34) to (7.98) | (1.48) | (3.29) to 0.33 | (13.52) | (16.09) to (10.94) |
| 1994 | (62.38) | (94.48) to (30.29) | (12.61) | (13.42) to (11.80) | (66.74) | (68.28) to (65.20) | (17.87) | (20.62) to (15.12) |
| 1995 | (47.58) | (83.91) to (11.25) | (3.84) | (4.51) to (3.17) | (29.45) | (30.78) to (28.13) | (18.21) | (20.80) to (15.61) |
| 1996 | (54.99) | (83.65) to (26.32) | (4.55) | (5.24) to (3.85) | 4.25 | 3.0 to 5.50 | (15.19) | (17.78) to (12.60) |
| 1997 | (54.08) | (81.53) to (26.63) | (4.21) | (4.94) to (3.48) | (20.44) | (21.73) to (19.14) | (19.90) | (22.64) to (17.16) |
| 1998 | (44.34) | (77.06) to (11.61) | (10.77) | (11.60) to (9.94) | 1.46 | 0.43 to 2.49 | (17.33) | (20.33) to (14.33) |
| 1999 | (29.72) | (58.21) to (1.23) | (3.30) | (4.02) to (2.59) | (18.92) | (19.78) to (18.06) | (23.95) | (26.64) to (21.26) |
| 2000 | (54.83) | (85.86) to (23.80) | (4.41) | (5.15) to (3.67) | (55.15) | (56.04) to (54.26) | (23.11) | (26.26) to (19.97) |
| 2001 | (37.57) | (68.05) to (7.08) | (2.53) | (3.24) to (1.83) | (27.34) | (28.17) to (26.51) | (24.03) | (27.01) to (21.05) |
| 2002 | (36.14) | (67.43) to (4.85) | (1.97) | (2.68) to (1.25) | (46.81) | (47.62) to (46.0) | (22.72) | (25.70) to (19.73) |
| 2003 | (42.32) | (69.67) to (14.98) | (0.84) | (1.54) to (0.13) | (11.65) | (12.50) to (10.79) | (20.69) | (23.50) to (17.89) |
| 2004 | (42.32) | (69.67) to (14.98) | (0.84) | (1.54) to (0.13) | (11.49) | (12.34) to (10.64) | (20.51) | (23.31) to (17.70) |
| 2005 | (42.32) | (69.67) to (14.98) | (0.84) | (1.54) to (0.13) | (11.32) | (12.17) to (10.47) | (20.31) | (23.11) to (17.50) |
| 2006 | (42.32) | (69.67) to (14.98) | (0.84) | (1.54) to (0.13) | (11.14) | (11.99) to (10.29) | (20.10) | (22.90) to (17.30) |
| 2007 | (42.32) | (69.67) to (14.98) | (0.84) | (1.54) to (0.13) | (10.97) | (11.82) to (10.12) | (19.90) | (22.70) to (17.09) |
| 2008 | (42.32) | (69.67) to (14.98) | (0.84) | (1.54) to (0.13) | (10.79) | (11.65) to (9.94) | (19.69) | (22.49) to (16.89) |
| 2009 | (42.32) | (69.67) to (14.98) | (0.84) | (1.54) to (0.13) | (10.62) | (11.47) to (9.77) | (19.48) | (22.29) to (16.68) |
| 2010 | (42.32) | (69.67) to (14.98) | (0.84) | (1.54) to (0.13) | (10.62) | (11.47) to (9.77) | (19.48) | (22.29) to (16.68) |
| 2011 | (42.32) | (69.67) to (14.98) | (0.84) | (1.54) to (0.13) | (10.62) | (11.47) to (9.77) | (19.48) | (22.29) to (16.68) |

Table A-216: Annual $N_2O$ Emissions (95% Confidence Interval) for the Land Base Simulated with the Tier 3 DAYCENT Model-Based Approach (Tg $CO_2$ Eq.)

| | Major Crops | | Non-Federal Grasslands | |
|---|---|---|---|---|
| Year | Estimate | 95% CI | Estimate | 95% CI |
| 1990 | 100.1 | 90.8 to 113.2 | 55.2 | 49.7 to 64.62 |
| 1991 | 110.2 | 100.44 to 123.75 | 59.1 | 53.31 to 68.96 |
| 1992 | 109.2 | 99.84 to 123.6 | 54.5 | 49.29 to 63.48 |
| 1993 | 109.7 | 100.43 to 123.59 | 55.0 | 49.78 to 63.79 |
| 1994 | 109.8 | 101.59 to 121.25 | 55.2 | 49.86 to 64.19 |
| 1995 | 111.2 | 102.59 to 123.31 | 54.6 | 49.36 to 63.56 |
| 1996 | 117.7 | 108.44 to 130.77 | 56.4 | 50.98 to 65.66 |
| 1997 | 120.5 | 111.04 to 133.83 | 58.1 | 52.51 to 67.6 |
| 1998 | 106.6 | 98.48 to 118.36 | 57.7 | 52.05 to 67.24 |
| 1999 | 109.4 | 100.8 to 120.99 | 48.7 | 44.06 to 56.56 |
| 2000 | 105.8 | 97.45 to 117.57 | 54.5 | 49.11 to 63.56 |

| | | | | |
|---|---|---|---|---|
| 2001 | 113.6 | 104.25 to 126.61 | 52.2 | 47.16 to 60.85 |
| 2002 | 112.8 | 103.74 to 125.65 | 52.7 | 47.52 to 61.39 |
| 2003 | 109.1 | 100.12 to 121.61 | 51.3 | 46.38 to 59.54 |
| 2004 | 112.5 | 104.09 to 124.37 | 58.8 | 53.07 to 68.64 |
| 2005 | 112.6 | 103.36 to 125.38 | 54.7 | 49.58 to 63.48 |
| 2006 | 115.5 | 106.37 to 128.56 | 54.9 | 49.69 to 63.81 |
| 2007 | 118.6 | 108.8 to 132.52 | 59.0 | 53.22 to 68.94 |
| 2008 | 116.5 | 106.76 to 130.5 | 59.1 | 53.21 to 69 |
| 2009 | 115.0 | 105.34 to 129.03 | 58.9 | 53.07 to 68.85 |
| 2010 | 116.9 | 107.1 to 130.81 | 58.8 | 52.94 to 68.71 |
| 2011 | 117.2 | 107.39 to 131.1 | 58.6 | 52.8 to 68.57 |

In DAYCENT, the model cannot distinguish among the original sources of N after the N enters the plant and soil system to determine which management activity led to specific $N_2O$ emissions. This means, for example, that $N_2O$ emissions from applied synthetic fertilizer cannot be separated from emissions due to other N inputs, such as crop residues. It is desirable, however, to report emissions associated with specific N inputs. Thus, for each NRI point, the N inputs in a simulation are determined for anthropogenic practices discussed in IPCC (2006), including synthetic mineral N fertilization, organic amendments, and crop residue N added to soils (including N-fixing crops). The percentage of N input for anthropogenic practices is divided by the total N input, and this proportion is used to determine the amount of $N_2O$ emissions assigned to each of the practices.[84] For example, if 70 percent of the mineral N made available in the soil is due to mineral fertilization, then 70 percent of the $N_2O$ emissions are assigned to this practice. The remainder of soil $N_2O$ emissions is reported under "other N inputs," which includes mineralization due to decomposition of soil organic matter and litter, as well as asymbiotic N fixation from the atmosphere. Asymbiotic N fixation by soil bacteria is a minor source of N, typically not exceeding 10 percent of total N inputs to agroecosystems. Mineralization of soil organic matter is a more significant source of N, but is still typically less than half of the amount of N made available in the cropland soils compared to fertilization, manure amendments, and symbiotic fixation. Mineralization of soil organic matter accounts for the majority of available N in grassland soils. Accounting for the influence of "other N inputs" is necessary in order to meet the recommendation of reporting all emissions from managed lands (IPCC 2006). While this method allows for attribution of $N_2O$ emissions to the individual N inputs to the soils, it is important to realize that sources such as synthetic fertilization may have a larger impact on $N_2O$ emissions than would be suggested by the associated level of N input for this source (Delgado et al. 2009). Further research will be needed to improve upon this attribution method, however. The results of subdividing the $N_2O$ emissions based on N inputs are provided in and Table A- 218.

[84] This method is a simplification of reality to allow partitioning of $N_2O$ emissions, as it assumes that all N inputs have an identical chance of being converted to $N_2O$. This is unlikely to be the case, but DAYCENT does not track $N_2O$ emissions by source of mineral N so this approximation is the only approach that can be used currently for partitioning $N_2O$ emissions by source of N input. Moreover, this approach is similar to the IPCC Tier 1 method (IPCC 2006), which uses the same direct emissions factor for most N sources (e.g., PRP). Further research and model development may allow for other approaches in the future.

Table A- 217: Direct $N_2O$ Emissions from Cropland Soils (Tg $CO_2$ Eq.)

| Activity | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mineral Soils** | **116.7** | **129.5** | **127.6** | **133.7** | **134.1** | **130.2** | **133.5** | **132.7** | **138.1** | **140.1** | **136.1** | **133.4** | **135.3** | **135.0** |
| **Major Crops** | **100.2** | **111.3** | **105.9** | **113.7** | **112.8** | **109.2** | **112.6** | **112.7** | **115.6** | **118.7** | **116.6** | **115.1** | **116.9** | **117.2** |
| Synthetic Fertilizer | 40.5 | 45.6 | 44.3 | 44.4 | 45.4 | 44.3 | 44.6 | 45.9 | 46.8 | 50.1 | 48.2 | 46.8 | 48.5 | 48.7 |
| Managed Manure | 4.6 | 4.6 | 5.2 | 5.4 | 5.5 | 5.1 | 5.1 | 5.3 | 5.3 | 5.7 | 5.7 | 5.7 | 5.7 | 5.7 |
| Residue N[a] | 3.1 | 3.6 | 3.2 | 3.6 | 3.2 | 3.4 | 3.8 | 3.5 | 3.4 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| Mineralization and Asymbiotic Fixation | 52.0 | 57.6 | 53.2 | 60.3 | 58.8 | 56.4 | 59.1 | 58.0 | 60.1 | 59.4 | 59.3 | 59.1 | 59.3 | 59.3 |
| **Non-Major Crops** | **16.5** | **18.2** | **21.7** | **20.0** | **21.3** | **20.9** | **21.0** | **20.1** | **22.5** | **21.4** | **19.4** | **18.2** | **18.4** | **17.8** |
| Synthetic Fertilizer | 5.2 | 5.4 | 7.2 | 5.8 | 6.8 | 7.2 | 7.9 | 6.2 | 7.9 | 6.9 | 5.2 | 4.4 | 4.5 | 4.4 |
| Managed Manure and Other Organic Commercial Fertilizer | 9.5 | 11.1 | 12.9 | 12.7 | 13.0 | 12.1 | 11.4 | 12.2 | 13.1 | 12.9 | 12.7 | 12.2 | 12.2 | 12.0 |
| Residue N | 1.8 | 1.7 | 1.6 | 1.6 | 1.5 | 1.6 | 1.7 | 1.6 | 1.4 | 1.5 | 1.6 | 1.6 | 1.6 | 1.4 |
| **Organic Soils** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** |
| **Total*** | **119.6** | **132.4** | **130.6** | **136.6** | **137.0** | **133.1** | **136.4** | **135.6** | **141.0** | **143.0** | **139.0** | **136.3** | **138.2** | **137.9** |

+ Less than 0.05 Tg $CO_2$ Eq.

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Note: Quality control measures are still underway for Croplands, and estimates will be finalized after the expert review.

Table A- 218: Direct $N_2O$ Emissions from Grasslands (Tg $CO_2$ Eq.)

| | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **DAYCENT** | **55.2** | **54.6** | **54.5** | **52.2** | **52.7** | **51.3** | **58.8** | **54.7** | **54.9** | **59.0** | **59.1** | **58.9** | **58.9** | **58.9** |
| Synthetic Fertilizer | 2.3 | 2.4 | 2.6 | 2.6 | 2.7 | 2.5 | 2.5 | 2.5 | 2.7 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| PRP Manure | 9.1 | 10.0 | 8.5 | 8.8 | 8.4 | 9.1 | 9.3 | 9.3 | 8.5 | 10.1 | 10.2 | 10.2 | 10.2 | 10.2 |
| Managed Manure | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Residue N[a] | 2.4 | 2.7 | 2.2 | 2.4 | 2.4 | 2.4 | 2.8 | 2.7 | 2.7 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |
| Mineralization and Asymbiotic Fixation | 41.3 | 39.4 | 41.1 | 38.3 | 39.0 | 37.2 | 44.1 | 40.1 | 40.8 | 43.4 | 43.4 | 43.3 | 43.3 | 43.3 |
| **Tier 1** | **18.1** | **19.5** | **19.7** | **18.0** | **19.9** | **17.4** | **16.0** | **16.7** | **20.1** | **14.3** | **13.7** | **13.5** | **13.2** | **12.0** |
| PRP Manure | 17.9 | 19.1 | 19.3 | 17.6 | 19.5 | 17.0 | 15.5 | 16.2 | 19.6 | 13.8 | 13.2 | 12.9 | 12.6 | 12.0 |
| Sewage Sludge | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | + |
| **Total** | **73.4** | **74.1** | **74.2** | **70.3** | **72.6** | **68.7** | **74.8** | **71.5** | **75.0** | **73.3** | **72.8** | **72.4** | **72.1** | **70.9** |

+ Less than 0.05 Tg $CO_2$ Eq.

[a] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Note: Quality control measures are still underway for Grasslands, and estimates will be finalized after the expert review.

### *Step 2b: Soil $N_2O$ Emissions from Agricultural Lands on Mineral Soils Approximated with the Tier 1 Approach*

To estimate direct $N_2O$ emissions from N additions to non-major crops, the amount of N in applied synthetic fertilizer, manure and other commercial organic fertilizers (i.e., dried blood, tankage, compost, and other) is added to N inputs from crop residues, and the resulting annual totals are multiplied by the IPCC default emission factor of 0.01 kg $N_2O$-N/kg N (IPCC 2006). The uncertainty is determined based on simple error propagation methods (IPCC 2006). The uncertainty in the default emission factor ranges from 0.3–3.0 kg $N_2O$-N/kg N (IPCC 2006). For flooded rice soils, the IPCC default emission factor is 0.003 kg $N_2O$-N/kg N and the uncertainty range is 0.000–0.006 kg $N_2O$-N/kg N (IPCC 2006). Uncertainty in activity data is ± 20 percent for fertilizer additions (Mosier 2004).[85] Uncertainties in the emission factor and fertilizer additions are combined with uncertainty in the equations used to calculate residue N additions from above- and below-ground biomass dry matter and N concentration to derive overall uncertainty.

The Tier 1 method is also used to estimate emissions from manure N deposited by livestock on federal lands (i.e., PRP manure N), and from sewage sludge application to grasslands. These two sources of N inputs to soils are multiplied by the IPCC (2006) default emission factors (0.01 kg $N_2O$-N/kg N for sludge and horse, sheep, and goat manure, and 0.02 kg $N_2O$-N/kg N for cattle, swine, and poultry manure) to estimate $N_2O$ emissions. This emission estimate is summed with the DAYCENT simulated emissions to provide the national total for direct $N_2O$ emissions from grasslands (Table A- 218). The uncertainty is determined based on the Tier 1 error propagation methods provided by the IPCC (2006) with uncertainty in the default emission factor ranging from 0.007 to 0.06 kg $N_2O$-N/kg N (IPCC 2006).

### *Step 2c: Estimate Soil Organic C Stock Changes in Agricultural Lands on Mineral Soils with the Tier 2 Approach*

Mineral soil organic C stock values are derived for non-major crop rotations and land converted from non-agricultural land uses to cropland or grassland in 1982, 1992, 1997, 2002 and 2007, based on the land-use and management activity data in conjunction with appropriate reference C stocks, land-use change, management, input, and wetland restoration factors. Each input to the inventory calculations for the Tier 2 approach has some level of uncertainty that is quantified in PDFs, including the land-use and management activity data, reference C stocks, and management factors. A Monte Carlo Analysis is used to quantify uncertainty in soil organic C stock changes for the inventory period based on uncertainty in the inputs. Input values are randomly selected from PDFs in an iterative process to estimate SOC change for 50,000 times and produce a 95 percent confidence interval for the inventory results.

*Derive Mineral Soil Organic C Stock Change Factors:* Stock change factors representative of U.S. conditions are estimated from published studies (Ogle et al. 2003, Ogle et al. 2006). The numerical factors quantify the impact of changing land use and management on SOC storage in mineral soils, including tillage practices, cropping rotation or intensification, and land conversions between cultivated and native conditions (including set-asides in the Conservation Reserve Program). Studies from the United States and Canada are used in this analysis under the assumption that they would best represent management impacts for the Inventory.

The IPCC inventory methodology for agricultural soils divides climate into eight distinct zones based upon average annual temperature, average annual precipitation, and the length of the dry season (IPCC 2006) (Table A-219). Six of these climate zones occur in the conterminous United States and Hawaii (Eve et al. 2001).

[85] Note that due to lack of data, uncertainties in managed manure N production, PRP manure N production, other commercial organic fertilizer amendments, indirect losses of N in the DAYCENT simulations, and sewage sludge amendments to soils are currently treated as certain; these sources of uncertainty will be included in future Inventories.

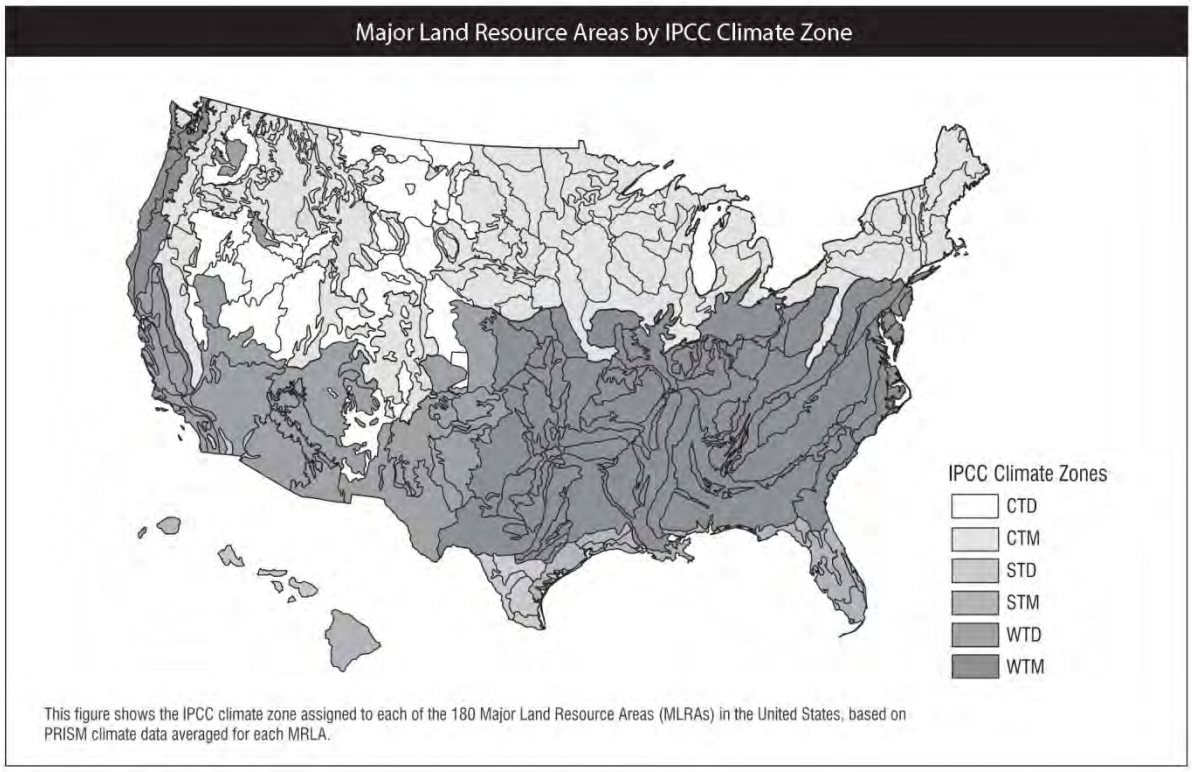
Table A-219: Characteristics of the IPCC Climate Zones that Occur in the United States

| Climate Zone | Annual Average Temperature (˚C) | Average Annual Precipitation (mm) | Length of Dry Season (months) |
|---|---|---|---|
| Cold Temperate, Dry | < 10 | < Potential Evapotranspiration | NA |
| Cold Temperate, Moist | < 10 | ≥ Potential Evapotranspiration | NA |
| Warm Temperate, Dry | 10 – 20 | < 600 | NA |
| Warm Temperate, Moist | 10 – 20 | ≥ Potential Evapotranspiration | NA |
| Sub-Tropical, Dry* | > 20 | < 1,000 | Usually long |
| Sub-Tropical, Moist (w/short dry season)[a] | > 20 | 1,000 – 2,000 | < 5 |

[a] The climate characteristics listed in the table for these zones are those that correspond to the tropical dry and tropical moist zones of the IPCC. They have been renamed "sub-tropical" here.

Mean climate (1961-1990) variables from the PRISM data set (Daly et al. 1994) are used to classify climate zones. Mean annual precipitation and annual temperature data are averaged (weighted by area) for each of the 4×4 km grid cells occurring within a MLRA region. These averages are used to assign a climate zone to each MLRA according to the IPCC climate classification (Figure A-15). MLRAs represent geographic units with relatively similar soils, climate, water resources, and land uses; and there are approximately 180 MLRAs in the United States (NRCS 1981).

Figure A-15: Major Land Resource Areas by IPCC Climate Zone




Soils are classified into one of seven classes based upon texture, morphology, and ability to store organic matter (IPCC 2006). Six of the categories are mineral types and one is organic (i.e., Histosol). Reference C stocks, representing estimates from conventionally managed cropland, are computed for each of the mineral soil types across the various climate zones, based on pedon (i.e., soil) data from the National Soil Survey Characterization Database (NRCS 1997) (Table A-220). These stocks are used in conjunction with management factors to compute the change in SOC stocks that

result from management and land-use activity. PDFs, which represent the variability in the stock estimates, are constructed as normal densities based on the mean and variance from the pedon data. Pedon locations are clumped in various parts of the country, which reduces the statistical independence of individual pedon estimates. To account for this lack of independence, samples from each climate by soil zone are tested for spatial autocorrelation using the Moran's I test, and variance terms are inflated by 10 percent for all zones with significant p-values.

Table A-220: U.S. Soil Groupings Based on the IPCC Categories and Dominant Taxonomic Soil, and Reference Carbon Stocks (Metric Tons C/ha)

| | | Reference Carbon Stock in Climate Regions | | | | | |
|---|---|---|---|---|---|---|---|
| **IPCC Inventory Soil Categories** | **USDA Taxonomic Soil Orders** | **Cold Temperate, Dry** | **Cold Temperate, Moist** | **Warm Temperate, Dry** | **Warm Temperate, Moist** | **Sub-Tropical, Dry** | **Sub-Tropical, Moist** |
| High Clay Activity Mineral Soils | Vertisols, Mollisols, Inceptisols, Aridisols, and high base status Alfisols | 42 (n = 133) | 65 (n = 526) | 37 (n = 203) | 51 (n = 424) | 42 (n = 26) | 57 (n = 12) |
| Low Clay Activity Mineral Soils | Ultisols, Oxisols, acidic Alfisols, and many Entisols | 45 (n = 37) | 52 (n = 113) | 25 (n = 86) | 40 (n = 300) | 39 (n = 13) | 47 (n = 7) |
| Sandy Soils | Any soils with greater than 70 percent sand and less than 8 percent clay (often Entisols) | 24 (n = 5) | 40 (n = 43) | 16 (n = 19) | 30 (n = 102) | 33 (n = 186) | 50 (n = 18) |
| Volcanic Soils | Andisols | 124 (n = 12) | 114 (n = 2) | 124 (n = 12) | 124 (n = 12) | 124 (n = 12) | 128 (n = 9) |
| Spodic Soils | Spodosols | 86 (n=20) | 74 (n = 13) | 86 (n=20) | 107 (n = 7) | 86 (n=20) | 86 (n=20) |
| Aquic Soils | Soils with Aquic suborder | 86 (n = 4) | 89 (n = 161) | 48 (n = 26) | 51 (n = 300) | 63 (n = 503) | 48 (n = 12) |
| Organic Soils[a] | Histosols | NA | NA | NA | NA | NA | NA |

[a] C stocks are not needed for organic soils.
Notes: C stocks are for the top 30 cm of the soil profile, and are estimated from pedon data available in the National Soil Survey Characterization database (NRCS 1997); sample size provided in parentheses (i.e., 'n' values refer to sample size).

To estimate the land use, management and input factors, studies had to report SOC stocks (or information to compute stocks), depth of sampling, and the number of years since a management change to be included in the analysis. The data are analyzed using linear mixed-effect modeling, accounting for both fixed and random effects. Fixed effects included depth, number of years since a management change, climate, and the type of management change (e.g., reduced tillage vs. no-till). For depth increments, the data are not aggregated for the C stock measurements; each depth increment (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) is included as a separate point in the dataset. Similarly, time series data are not aggregated in these datasets. Linear regression models assume that the underlying data are independent observations, but this is not the case with data from the same experimental site, or plot in a time series. These data are more related to each other than data from other sites (i.e., not independent). Consequently, random effects are needed to account for the dependence in time series data and the dependence among data points representing different depth increments from the same study. Factors are estimated for the effect of management practices at 20 years for the top 30 cm of the soil (Table A-221). Variance is calculated for each of the U.S. factor values, and used to construct PDFs with a normal density. In the IPCC method, specific factor values are given for improved grassland, high input cropland with organic amendments, and for wetland rice, each of which influences C stock changes in soils. Specifically, higher stocks are associated with increased productivity and C inputs (relative to native grassland) on improved grassland with both medium and high input.[86] Organic amendments in annual cropping systems also increase SOC stocks due to greater C inputs, while high SOC stocks in rice cultivation are associated with reduced decomposition due to periodic flooding. There are insufficient field studies to derive factor values for these systems from the published literature, and, thus, estimates from IPCC (2006) are used under the assumption that they would best approximate the impacts, given the lack of sufficient data to derive

[86] Improved grasslands are identified in the 2007 *National Resources Inventory* as grasslands that are irrigated or seeded with legumes, in addition to those reclassified as improved with manure amendments.

U.S.-specific factors. A measure of uncertainty is provided for these factors in IPCC (2006), which is used to construct PDFs.

Table A-221: Soil Organic Carbon Stock Change Factors for the United States and the IPCC Default Values Associated with Management Impacts on Mineral Soils

| | IPCC default | U.S. Factor Warm Moist Climate | Warm Dry Climate | Cool Moist Climate | Cool Dry Climate |
|---|---|---|---|---|---|
| Land-Use Change Factors | | | | | |
| Cultivated[a] | 1 | 1 | 1 | 1 | 1 |
| General Uncult.[a,b] (n=251) | 1.4 | 1.42±0.06 | 1.37±0.05 | 1.24±0.06 | 1.20±0.06 |
| Set-Aside[a] (n=142) | 1.25 | 1.31±0.06 | 1.26±0.04 | 1.14±0.06 | 1.10±0.05 |
| Improved Grassland Factors[c] | | | | | |
| Medium Input | 1.1 | 1.14±0.06 | 1.14±0.06 | 1.14±0.06 | 1.14±0.06 |
| High Input | Na | 1.11±0.04 | 1.11±0.04 | 1.11±0.04 | 1.11±0.04 |
| Wetland Rice Production Factor[b] | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Tillage Factors | | | | | |
| Conv. Till | 1 | 1 | 1 | 1 | 1 |
| Red. Till (n=93) | 1.05 | 1.08±0.03 | 1.01±0.03 | 1.08±0.03 | 1.01±0.03 |
| No-till (n=212) | 1.1 | 1.13±0.02 | 1.05±0.03 | 1.13±0.02 | 1.05±0.03 |
| Cropland Input Factors | | | | | |
| Low (n=85) | 0.9 | 0.94±0.01 | 0.94±0.01 | 0.94±0.01 | 0.94±0.01 |
| Medium | 1 | 1 | 1 | 1 | 1 |
| High (n=22) | 1.1 | 1.07±0.02 | 1.07±0.02 | 1.07±0.02 | 1.07±0.02 |
| High with amendment[b] | 1.2 | 1.38±0.06 | 1.34±0.08 | 1.38±0.06 | 1.34±0.08 |

Note: The "n" values refer to sample size.
[a] Factors in the IPCC documentation (IPCC 2006) are converted to represent changes in SOC storage from a cultivated condition rather than a native condition.
[b] U.S.-specific factors are not estimated for land improvements, rice production, or high input with amendment because of few studies addressing the impact of legume mixtures, irrigation, or manure applications for crop and grassland in the United States, or the impact of wetland rice production in the US. Factors provided in IPCC (2006) are used as the best estimates of these impacts.

Wetland restoration management also influences SOC storage in mineral soils, because restoration leads to higher water tables and inundation of the soil for at least part of the year. A stock change factor is estimated assessing the difference in SOC storage between restored and unrestored wetlands enrolled in the Conservation Reserve Program (Euliss and Gleason 2002), which represents an initial increase of C in the restored soils over the first 10 years (Table A-222). A PDF with a normal density is constructed from these data based on results from a linear regression model. Following the initial increase of C, natural erosion and deposition leads to additional accretion of C in these wetlands. The mass accumulation rate of organic C is estimated using annual sedimentation rates (cm/yr) in combination with percent organic C, and soil bulk density (g/cm$^3$) (Euliss and Gleason 2002). Procedures for calculation of mass accumulation rate are described in Dean and Gorham (1998); the resulting rate and variance are used to construct a PDF with a normal density (Table A-222).

Table A-222: Factor Estimate for the Initial and Subsequent Increase in Organic Soil C Following Wetland Restoration of Conservation Reserve Program

| Variable | Value |
|---|---|
| Factor (Initial Increase—First 10 Years) | 1.22±0.18 |
| Mass Accumulation (After Initial 10 Years) | 0.79±0.05 Mg C/ha-yr |

Note: Mass accumulation rate represents additional gains in C for mineral soils after the first 10 years (Euliss and Gleason 2002).

*Estimate Annual Changes in Mineral Soil Organic C Stocks:* In accordance with IPCC methodology, annual changes in mineral soil C are calculated by subtracting the beginning stock from the ending stock and then dividing by 20.[87] For this analysis, the base inventory estimate for 1990 through 1992 is the annual average of 1992 stock minus

[87] The difference in C stocks is divided by 20 because the stock change factors represent change over a 20-year time period.

the 1982 stock. The annual average change between 1993 and 1997 is the difference between the 1997 and 1992 C stocks. The annual average change between 1998 and 2002 is the difference between the 1998 and 2002 C stocks. The annual average change between 2003 and 2011 is the difference between the 2003 and 2007. Using the Monte Carlo approach, SOC stock changes for mineral soils are estimated 50,000 times between 1982 and 1992, 1993 and 1997, 1998 and 2002, and 2003 and 2007. From the final distribution of 50,000 values, a 95 percent confidence interval is generated based on the simulated values at the 2.5 and 97.5 percentiles in the distribution (Ogle et al. 2003). Soil organic C stock changes are provided in Table A-223.

Table A-223: Annual Change in Soil Organic Carbon Stocks (95% Confidence Interval) for the Land Base Estimated with the Tier 2 Analysis using U.S. Factor Values and Reference Carbon Stocks (Tg $CO_2$ Eq./yr)

| | Cropland Remaining Cropland | | Land Converted to Cropland | | Grassland Remaining Grassland* | | Land Converted to Grassland* | |
|---|---|---|---|---|---|---|---|---|
| Year | Estimate | 95% CI | Estimate | 95% CI | Estimate | 95% CI | Estimate | 95% CI |
| **Mineral Soils** | | | | | | | | |
| 1990-1992 | (6.49) | (4.1) to (9.2) | 4.81 | 2.7 to 7.2 | (0.19) | (0.03) to (0.4) | (3.50) | (2.2) to (5.0) |
| 1993-1997 | (7.64) | (4.8) to (10.7) | 4.69 | 2.5 to 7.1 | (0.08) | (<0.01) to 0.18 | (3.56) | (2.2) to (5.1) |
| 1998-2002 | (6.93) | (4.4) to (9.7) | 3.72 | 1.9 to 5.7 | (0.01) | (0.08) to 0.06 | (3.60) | (2.2) to (5.2) |
| 2003-2011 | (2.83) | (0.9) to (5.1) | 1.55 | 0.8 to 2.4 | 0.10 | 0.01 to 0.21 | (2.50) | (1.4) to (3.7) |
| **Organic Soils** | | | | | | | | |
| 1990-1992 | 26.29 | 17.4 to 38.2 | 2.16 | 1.3 to 3.3 | 3.39 | 1.8 to 5.6 | 0.43 | 0.2 to 0.8 |
| 1993-1997 | 25.67 | 16.9 to 37.5 | 2.51 | 1.5 to 3.8 | 3.01 | 1.6 to 5.0 | 0.73 | 0.4 to 1.3 |
| 1998-2002 | 25.66 | 16.9 to 37.5 | 2.54 | 1.4 to 4.0 | 2.61 | 1.4 to 4.3 | 0.86 | 0.4 to 1.5 |
| 2003-2011 | 26.80 | 17.7 to 39.0 | 1.13 | 0.3 to 2.2 | 2.78 | 1.5 to 4.6 | 0.79 | 0.4 to 1.4 |

### *Step 2d: Estimate Additional Changes in Soil Organic C Stocks Due to CRP Enrollment after 2007 and Sewage Sludge Amendments*

There are two additional land use and management activities in U.S. agricultural lands that are not estimated in Steps 2a and 2b. The first activity involves the application of sewage sludge to agricultural lands. Minimal data exist on where and how much sewage sludge is applied to U.S. agricultural soils, but national estimates of mineral soil land area receiving sewage sludge can be approximated based on sewage sludge N production data, and the assumption that amendments are applied at a rate equivalent to the assimilative capacity from Kellogg et al. (2000). It is assumed that sewage sludge for agricultural land application is applied to grassland because of the high heavy metal content and other pollutants found in human waste, which limits its application to crops. The impact of organic amendments on SOC is calculated as 0.38 metric tonnes C/ha-yr. This rate is based on the IPCC default method and country-specific factors (see Table A-225), by calculating the effect of converting nominal, medium-input grassland to high input improved grassland. The assumptions are that reference C stock are 50 metric tonnes C/ha, which represents a mid-range value of reference C stocks for the cropland soils in the United States[88], that the land use factor for grassland of 1.4 and 1.11 for high input improved grassland are representative of typical conditions, and that the change in stocks are occurring over a 20 year (default value) time period (i.e., $[50 \times 1.4 \times 1.11 - 50 \times 1.4] / 20 = 0.38$). A nominal ±50 percent uncertainty is attached to these estimates due to limited information on application and the rate of change in soil C stock change with sewage sludge amendments. The influence of sewage sludge on soil organic C stocks are available in Table A-225.

The second activity is the change in enrollment for the Conservation Reserve Program after 2007 for mineral soils. Relative to the enrollment in 2007, the total area in the Conservation Reserve Program has decreased from 2008 to 2011 (USDA-FSA 2011). An average annual change in SOC of 0.5 metric tonnes C/ha-yr is used to estimate the effect of the enrollment changes. This rate is based on the IPCC default method and country-specific factors (see To estimate the

[88] Reference C stocks are based on cropland soils for the Tier 2 method applied in this Inventory.

land use, management and input factors, studies had to report SOC stocks (or information to compute stocks), depth of sampling, and the number of years since a management change to be included in the analysis. The data are analyzed using linear mixed-effect modeling, accounting for both fixed and random effects. Fixed effects included depth, number of years since a management change, climate, and the type of management change (e.g., reduced tillage vs. no-till). For depth increments, the data are not aggregated for the C stock measurements; each depth increment (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) is included as a separate point in the dataset. Similarly, time series data are not aggregated in these datasets. Linear regression models assume that the underlying data are independent observations, but this is not the case with data from the same experimental site, or plot in a time series. These data are more related to each other than data from other sites (i.e., not independent). Consequently, random effects are needed to account for the dependence in time series data and the dependence among data points representing different depth increments from the same study. Factors are estimated for the effect of management practices at 20 years for the top 30 cm of the soil (**Table A-221). Variance is calculated for** each of the U.S. factor values, and used to construct PDFs with a normal density. In the IPCC method, specific factor values are given for improved grassland, high input cropland with organic amendments, and for wetland rice, each of which influences C stock changes in soils. Specifically, higher stocks are associated with increased productivity and C inputs (relative to native grassland) on improved grassland with both medium and high input. Organic amendments in annual cropping systems also increase SOC stocks due to greater C inputs, while high SOC stocks in rice cultivation are associated with reduced decomposition due to periodic flooding. There are insufficient field studies to derive factor values for these systems from the published literature, and, thus, estimates from IPCC (2006) are used under the assumption that they would best approximate the impacts, given the lack of sufficient data to derive U.S.-specific factors. A measure of uncertainty is provided for these factors in IPCC (2006), which is used to construct PDFs.

Table A-221) by estimating the impact of setting aside a medium input cropping system in the Conservation Reserve Program. The assumptions are that reference C stock are 50 metric tonnes C/ha, which represents a mid-range value for the dominant cropland soils in the United States, and the average country-specific factor is 1.2 for setting-aside cropland from production, with the change in stocks occurring over a 20 year (default value) time period equal to 0.5 (i.e., $[50 \times 1.2 - 50] / 20 = 0.5$). A nominal ±50 percent uncertainty is attached to these estimates due to limited information about the enrollment trends at subregional scales, which creates uncertainty in the rate of soil C stock change (stock change factors for set-aside lands vary by climate region). Estimates and uncertainties are available in Table A-229.

### Step 3: Estimate Soil Organic C Stock Changes and Direct $N_2O$ Emissions from Organic Soils

In this step, soil organic C losses and $N_2O$ emissions are estimated for organic soils that are drained for agricultural production.

#### *Step 3a: Direct $N_2O$ Emissions Due to Drainage and Cultivation of Organic Cropland Soils*

To estimate annual $N_2O$ emissions from drainage and cultivation of organic soils, the area of cultivated organic soils in temperate regions is multiplied by the IPCC (2006) default emission factor for temperate soils and the corresponding area in sub-tropical regions is multiplied by the average (12 kg $N_2O$-N/ha cultivated) of IPCC (2006) default emission factors for temperate (8 kg $N_2O$-N/ha cultivated) and tropical (16 kg $N_2O$-N/ha cultivated) organic soils. The uncertainty is determined based on simple error propagation methods (IPCC 2006), including uncertainty in the default emission factor ranging from 2–24 kg $N_2O$-N/ha (IPCC 2006).

#### *Step 3b: Soil Organic C Stock Changes Due to Drainage of Organic Soils in Cropland and Grassland*

Change in soil organic C stocks due to drainage of cropland and grassland soils are estimated for 1982, 1992, 1997, 2002 and 2007, based on the land-use and management activity data in conjunction with appropriate loss rate emission factors. Each input to the inventory for the Tier 2 approach has some level of uncertainty that is quantified in PDFs. A Monte Carlo Analysis is used to quantify uncertainty in soil organic C stock changes for the inventory period based on uncertainty in the inputs. Input values are randomly selected from PDFs in an iterative process to estimate SOC change for 50,000 times and produce a 95 percent confidence interval for the inventory results.

*Derive Organic Soil Emission Factors:* Organic Soil emission factors representative of U.S. conditions have been estimated from published studies (Ogle et al. 2003), based on subsidence studies in the United States and Canada (Table A-225). PDFs are constructed as normal densities based on the mean C loss rates and associated variances.

*Estimate Annual C Emissions from Organic Soils:* Losses of C are estimated by applying the Monte Carlo approach to 1992, 1997, 2002 and 2007 land-use data from the NRI. The results for 1992 are applied to the years 1990 through 1992, results for 1997 are applied to the years 1993 through 1997, results for 2002 are applied to the years 1998 through 2002, and results for 2007 are applied to the years 2003 through 2011. Losses of soil organic C from drainage of cropland and grassland soils are provided in Table A- 226.

### Step 4: Estimate Indirect $N_2O$ Emissions for All Land-Use Types

In this step, $N_2O$ emissions are estimated for the two indirect emission pathways ($N_2O$ emissions due to volatilization, and $N_2O$ emissions due to leaching and runoff of N), which are summed to yield total indirect $N_2O$ emissions from croplands, grasslands, forest lands, and settlements.

#### *Step 4a: Indirect Soil $N_2O$ Emissions Due to Volatilization*

Indirect emissions from volatilization of N inputs from synthetic and commercial organic fertilizers, and PRP manure, are calculated according to the amount of mineral N that is transported in gaseous forms from the soil profile and later emitted as soil $N_2O$ following atmospheric deposition. See Step 1e for additional information about the methods used to compute N losses due to volatilization. The estimated N volatilized for all land-use and livestock activities is multiplied by the IPCC default emission factor of 0.01 kg $N_2O$-N/kg N (IPCC 2006) to estimate total $N_2O$ emissions from volatilization. The uncertainty is estimated using simple error propagation methods (IPCC 2006), by combining uncertainties in the amount of N volatilized, with uncertainty in the default emission factor ranging from 0.002–0.05 kg $N_2O$-N/kg N (IPCC 2006). The estimates and uncertainties are available in Table A- 226.

#### *Step 4b: Indirect Soil $N_2O$ Emissions Due to Leaching and Runoff*

The amount of mineral N from synthetic fertilizers, commercial organic fertilizers, PRP manure, crop residue, N mineralization, asymbiotic fixation that is transported from the soil profile in aqueous form is used to calculate indirect emissions from (1) leaching of mineral N from soils and (2) losses in runoff of water associated with overland flow. See Step 1e for additional information about the methods used to compute N losses from soils due to leaching and runoff in overland water flows.

The total amount of N transported from soil profiles through leaching and surface runoff is multiplied by the IPCC default emission factor of 0.0075 kg $N_2O$-N/kg N (IPCC 2006) to estimate emissions for this source. The emission estimates are available in Table A-228. The uncertainty is estimated based on simple error propagation methods (IPCC 2006), including uncertainty in the default emission factor ranging from 0.0005 to 0.025 kg $N_2O$-N/kg N (IPCC 2006).

### Step 5: Estimate Total Soil Organic C Stock Changes and $N_2O$ Emissions for U.S. Soils

#### *Step 5a: Estimate Total Soil $N_2O$ Emissions*

Total emissions are estimated by adding total direct emissions (from major crop types and non-major crop types on mineral cropland soils, drainage and cultivation of organic soils, and grassland management) to indirect emissions for all land use and management activities. Uncertainties in the final estimate are combined using simple error propagation methods (IPCC 2006), and expressed as a 95 percent confidence interval. Estimates and uncertainties are provided in Table A- 224.

Direct and indirect emissions of soil $N_2O$ vary regionally in both croplands and grasslands as a function of N inputs, weather, and soil type. The highest total $N_2O$ emissions from major crops occur in Iowa, Illinois, Nebraska, Texas, and Kansas where N inputs associated with corn rotations are high or where large land areas are cropped (Table A- 230).

On a per area unit basis, direct $N_2O$ emissions are also high in many of the Mississippi River Basin states where there are also high N input to corn and soybean crops (Figure A- 16). Indirect emissions tend to be high on an area basis in the central and eastern United States because relatively high rainfall facilitates N losses from leaching and runoff and in some western states where irrigation can contribute to leaching and runoff (Figure A- 17).

Direct and indirect emissions from grasslands are typically lower than those from croplands (Table A- 230, Figure A- 18, and Figure A- 19) because N inputs tend to be lower, particularly from synthetic fertilizer. Texas is by far the highest emitter for this category, followed by Montana, Nebraska, South Dakota, Kansas, and Oklahoma. On a per area unit basis, emissions are lower in the western United States because grasslands in the East and Central regions are more intensively managed (legume seeding, fertilization) while western rangelands receive few, if any, N inputs. Also, rainfall is limited in most of the western United States, and grasslands are not typically irrigated so minimal leaching and runoff of N occurs in these grasslands.

Figure A- 16: Major Crops, Average Annual Direct $N_2O$ Emissions, Estimated Using the DAYCENT Model, 1990-2011 (Metric Tons $CO_2$ Eq./ha/year)

**To be provided:**

**Figure A-15: Major Crops, Average Annual Direct N2O Emissions, Estimated Using the DAYCENT Model, 1990-2011 (Mg CO2 Eq./ha/year)**

Figure A- 17: Major Crops, Average Annual N Losses Leading to Indirect $N_2O$ Emissions, Estimated Using the DAYCENT Model, 1990-2011 (kg N/ha/year)

**To be provided:**

**Figure A-16: Major Crops, Average Annual N Losses Leading to Indirect N2O Emissions, Estimated Using the DAYCENT Model, 1990-2011 (kg N/ha/year)**

Figure A- 18: Grasslands, Average Annual Direct $N_2O$ Emissions, Estimated Using the DAYCENT Model, 1990-2011 (Metric Tons $CO_2$ Eq./ha/year)

**To be provided:**

**Figure A-17: Grasslands, Average Annual Direct N2O Emissions, Estimated Using the DAYCENT Model, 1990-2011 (Mg CO2 Eq./ha/year)**

Figure A- 19: Grasslands, Average Annual N Losses Leading to Indirect $N_2O$ Emissions, Estimated Using the DAYCENT Model, 1990-2011 (kg N/ha/year)

**To be provided:**

**Figure A-18: Grasslands, Average Annual N Losses Leading to Indirect N2O Emissions, Estimated Using the DAYCENT Model, 1990-2011 (kg N/ha/year)**

### *Step 5b: Estimate Total Soil Organic Stock Change*

The sum of total $CO_2$ emissions and removals from the Tier 3 DAYCENT Model Approach, Tier 2 IPCC Methods and additional land-use and management considerations are provided in Table A-229. The total change in soil organic C stocks (as seen in the Land Use, Land-Use Change, and Forestry chapter) as well as per hectare rate of change varies among the states (Figure A-17 and Figure A-18). On a per hectare basis, the highest rates of C accumulation occur in the Northeast, Midwest, northern Great Plains, and Northwest. The states with highest total amounts of C sequestration are Iowa, Illinois, Idaho, Missouri, Montana, Oklahoma, and Oregon (Table A- 231). For organic soils, emission rates are highest in the regions that contain the majority of the drained organic soils, including California, Florida, Michigan, Minnesota, and New York. On a per hectare basis, the emission rate patterns are very similar to the total emissions in each state, with the highest rates in those regions with warmer climates and a larger proportion of the drained organic soil managed for crop production.

Figure A-20: Net C Stock Change, per Hectare, for Mineral Soils Under Agricultural Management, 2011

**To be provided:**

**Figure A-19: Net C Stock Change, per Hectare, for Mineral Soils Under Agricultural Management, 2011**

Figure A-21: Net C Stock Change, per Hectare, for Organic Soils Under Agricultural Management, 2011

**To be provided:**

**Figure A-20: Net C Stock Change, per Hectare, for Organic Soils Under Agricultural Management, 2011**

Table A- 224: Assumptions and Calculations to Estimate the Contribution to Soil Organic Carbon Stocks from Application of Sewage Sludge to Mineral Soils

| | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sewage Sludge N Applied to Agricultural Land (Mg N)[a] | 52,198 | 55,658 | 59,250 | 62,977 | 65,966 | 69,001 | 72,081 | 75,195 | 78,353 | 80,932 | 83,523 | 86,124 | 88,736 | 91,358 | 93,991 | 98,081 | 100,887 | 103,682 | 106,468 | 109,245 | 109,245 | 109,245 |
| Assimilative Capacity (Mg N/ha)[b] | 0.120 | 0.120 | 0.120 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 | 0.122 |
| Area covered by Available Sewage Sludge N (ha)[c] | 434,985 | 463,816 | 493,746 | 516,202 | 540,707 | 565,583 | 590,828 | 616,357 | 642,240 | 663,381 | 684,612 | 705,932 | 727,341 | 748,836 | 770,418 | 803,942 | 826,940 | 849,851 | 872,686 | 895,452 | 895,452 | 895,452 |
| Average Annual Rate of C storage (Mg C/ha-yr)[d] | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 |
| **Contribution to Soil C ($TgCO_2$/yr)[e,f]** | **(0.61)** | **(0.65)** | **(0.69)** | **(0.72)** | **(0.75)** | **(0.79)** | **(0.82)** | **(0.86)** | **(0.89)** | **(0.92)** | **(0.95)** | **(0.98)** | **(1.01)** | **(1.04)** | **(1.07)** | **(1.12)** | **(1.15)** | **(1.18)** | **(1.22)** | **(1.25)** | **(1.25)** | **(1.25)** |

Values in parentheses indicate net C storage.

[a] N applied to soils described in Step 1d.

[b] Assimilative Capacity is the national average amount of manure-derived N that can be applied on cropland without buildup of nutrients in the soil (Kellogg et al., 2000).

[c] Area covered by sewage sludge N available for application to soils is the available N applied at the assimilative capacity rate. The 1992 assimilative capacity rate was applied to 1990 – 1992 and the 1997 rate was applied to 1993-2009.

[d] Annual rate of C storage based on national average increase in C storage for grazing lands that is attributed to organic matter amendments (0.38 Mg/ha-yr)

[e] Contribution to Soil C is estimated as the product of the area covered by the available sewage sludge N and the average annual C storage attributed to an organic matter amendment.

[f] Some small, undetermined fraction of this applied N is probably not applied to agricultural soils, but instead is applied to forests, home gardens, and other lands.

Table A-225: Carbon Loss Rates for Organic Soils Under Agricultural Management in the United States, and IPCC Default Rates (Metric Ton C/ha-yr)

| | Cropland | | Grassland | |
|---|---|---|---|---|
| **Region** | **IPCC** | **U.S. Revised** | **IPCC** | **U.S. Revised** |
| Cold Temperate, Dry & Cold Temperate, Moist | 1 | 11.2±2.5 | 0.25 | 2.8±0.5[a] |
| Warm Temperate, Dry & Warm Temperate, Moist | 10 | 14.0±2.5 | 2.5 | 3.5±0.8[a] |
| Sub-Tropical, Dry & Sub-Tropical, Moist | 1 | 11.2±2.5 | 0.25 | 2.8±0.5[a] |

[a] There are not enough data available to estimate a U.S. value for C losses from grassland. Consequently, estimates are 25 percent of the values for cropland, which is an assumption that is used for the IPCC default organic soil C losses on grassland.

Table A- 226: Indirect N2O Emissions from Volatilization (Tg CO2 Eq.)

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Croplands | 13.2 | 14.6 | 14.6 | 14.8 | 15.0 | 14.8 | 14.8 | 14.6 | 14.9 | 14.3 | 15.1 | 14.7 | 15.5 | 15.0 | 14.6 | 14.3 | 14.4 | 14.4 |
| Settlements | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Forest Land | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Grasslands | 7.3 | 8.0 | 7.8 | 7.8 | 7.8 | 7.4 | 7.3 | 7.3 | 7.3 | 7.5 | 7.8 | 7.8 | 7.5 | 7.8 | 7.7 | 7.7 | 7.6 | 7.5 |
| **Total** | **20.7** | **22.8** | **22.6** | **22.8** | **22.9** | **22.5** | **22.3** | **22.2** | **22.4** | **22.1** | **23.2** | **22.8** | **23.3** | **23.0** | **22.5** | **22.2** | **22.3** | **22.1** |

Note: Quality control measures are still underway for Croplands and Grasslands, and estimates will be finalized after the expert review.

Table A- 227: Indirect N2O Emissions from Leaching and Runoff (Tg CO2 Eq.)

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Croplands | 27.0 | 29.4 | 26.9 | 22.4 | 24.4 | 27.4 | 18.5 | 23.6 | 19.6 | 16.7 | 27.8 | 18.7 | 17.7 | 33.6 | 32.6 | 31.9 | 32.6 | 32.7 |
| Settlements | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Forest Land | + | + | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Grasslands | 4.5 | 5.3 | 5.6 | 4.8 | 5.1 | 4.6 | 4.5 | 4.3 | 4.4 | 4.2 | 3.7 | 4.3 | 4.8 | 3.8 | 3.6 | 3.6 | 3.5 | 3.2 |
| **Total** | **31.8** | **35.0** | **32.9** | **27.5** | **29.9** | **32.5** | **23.5** | **28.4** | **24.5** | **21.4** | **32.0** | **23.6** | **23.0** | **37.9** | **36.7** | **36.0** | **36.6** | **36.4** |

Note: Quality control measures are still underway for the Croplands and Grasslands, and estimates will be finalized after the expert review.

Table A-228: Total $N_2O$ Emissions from Agricultural Soil Management (Tg $CO_2$ Eq.)

| Activity | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Total Direct** | **192.9** | **206.5** | **219.1** | **220.1** | **207.6** | **200.6** | **204.8** | **206.9** | **209.6** | **201.8** | **211.3** | **207.1** | **216.0** | **216.3** | **211.7** | **208.6** | **210.3** | **208.8** |
| **Direct Emissions from Mineral** | | | | | | | | | | | | | | | | | | |
| **Cropland Soils** | **116.7** | **129.5** | **138.2** | **140.7** | **126.5** | **131.2** | **127.6** | **133.7** | **134.1** | **130.2** | **133.5** | **132.7** | **138.1** | **140.1** | **136.1** | **133.4** | **135.3** | **135.0** |
| Synthetic Fertilizer | 45.7 | 50.9 | 56.4 | 57.4 | 50.4 | 53.0 | 51.5 | 50.1 | 52.1 | 51.5 | 52.4 | 52.2 | 54.7 | 57.0 | 53.3 | 51.2 | 53.0 | 53.1 |
| Organic Amendment[a] | 14.0 | 15.7 | 16.3 | 17.0 | 16.2 | 17.9 | 18.1 | 18.0 | 18.5 | 17.2 | 16.5 | 17.5 | 18.5 | 18.7 | 18.4 | 18.0 | 18.0 | 17.8 |
| Residue N[b] | 4.9 | 5.2 | 5.4 | 5.4 | 4.9 | 5.2 | 4.8 | 5.2 | 4.8 | 5.0 | 5.5 | 5.1 | 4.8 | 5.0 | 5.1 | 5.0 | 5.1 | 4.8 |
| Mineralization and Asymbiotic Fixation | 52.0 | 57.6 | 60.1 | 60.8 | 54.9 | 55.0 | 53.2 | 60.3 | 58.8 | 56.4 | 59.1 | 58.0 | 60.1 | 59.4 | 59.3 | 59.1 | 59.3 | 59.3 |
| **Direct Emissions from Drained Organic** | | | | | | | | | | | | | | | | | | |
| **Cropland Soils** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** | **2.9** |
| **Direct Emissions from Grasslands*** | **73.4** | **74.1** | **78.0** | **76.6** | **78.2** | **66.5** | **74.2** | **70.3** | **72.6** | **68.7** | **74.8** | **71.5** | **75.0** | **73.3** | **72.8** | **72.4** | **72.1** | **70.9** |
| Synthetic Mineral Fertilizer | 2.3 | 2.4 | 2.6 | 2.5 | 2.5 | 2.5 | 2.6 | 2.6 | 2.7 | 2.5 | 2.5 | 2.5 | 2.7 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| PRP Manure* | 26.9 | 29.1 | 30.5 | 28.1 | 29.1 | 26.7 | 27.8 | 26.5 | 27.9 | 26.1 | 24.9 | 25.6 | 28.1 | 23.9 | 23.4 | 23.1 | 22.8 | 22.1 |
| Managed Manure | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Sewage Sludge | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | + |
| Residue[b] | 2.4 | 2.7 | 3.0 | 2.7 | 2.9 | 2.1 | 2.2 | 2.4 | 2.4 | 2.4 | 2.8 | 2.7 | 2.7 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |
| Mineralization and Asymbiotic Fixation | 41.3 | 39.4 | 41.4 | 42.8 | 43.2 | 34.7 | 41.1 | 38.3 | 39.0 | 37.2 | 44.1 | 40.1 | 40.8 | 43.4 | 43.4 | 43.3 | 43.3 | 43.3 |
| **Total Indirect** | **52.4** | **57.8** | **55.5** | **50.3** | **52.9** | **55.0** | **45.8** | **50.6** | **46.8** | **43.5** | **55.2** | **46.4** | **46.3** | **60.9** | **59.2** | **58.1** | **58.9** | **58.4** |
| Volatilization | 20.7 | 22.8 | 22.6 | 22.8 | 22.9 | 22.5 | 22.3 | 22.2 | 22.4 | 22.1 | 23.2 | 22.8 | 23.3 | 23.0 | 22.5 | 22.2 | 22.3 | 22.1 |
| Leaching/Runoff | 31.8 | 35.0 | 32.9 | 27.5 | 29.9 | 32.5 | 23.5 | 28.4 | 24.5 | 21.4 | 32.0 | 23.6 | 23.0 | 37.9 | 36.7 | 36.0 | 36.6 | 36.4 |
| **Total Emissions** | **245.3** | **264.3** | **274.5** | **270.4** | **260.5** | **255.5** | **250.5** | **257.5** | **256.4** | **245.2** | **266.5** | **253.5** | **262.3** | **277.1** | **270.9** | **266.8** | **269.2** | **267.2** |

Note: Quality control measures are still underway for Cropland and Grassland, and estimates will be finalized after the expert review.
+ Less than 0.05 Tg $CO_2$ Eq.
[a] Organic amendment inputs include managed manure amendments, daily spread manure and other commercial organic fertilizer (i.e., dried blood, tankage, compost, and other).
[b] Residue N inputs include unharvested fixed N from legumes as well as crop residue N.

Table A-229: Annual Soil C Stock Change in *Cropland Remaining Cropland* (CRC), *Land Converted to Cropland* (LCC), *Grassland Remaining Grassland* (GRG), and *Land Converted to Grassland* (LCG), in U.S. Agricultural Soils (Tg $CO_2$ Eq.)

| | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Net emissions based on Tier 3 DAYCENT-based analysis (Step 2)** | | | | | | | | | | | | | | | | | | | | | | |
| CRC | (55.2) | (57.5) | (68.0) | (64.2) | (62.4) | (47.6) | (55.0) | (54.1) | (44.3) | (29.7) | (54.8) | (37.6) | (36.1) | (42.3) | (42.3) | (42.3) | (42.3) | (42.3) | (42.3) | (42.3) | (42.3) | (42.3) |
| LCC | (4.4) | (4.3) | (4.8) | (8.7) | (12.6) | (3.8) | (4.5) | (4.2) | (10.8) | (3.3) | (4.4) | (2.5) | (2.0) | (0.8) | (0.8) | (0.8) | (0.8) | (0.8) | (0.8) | (0.8) | (0.8) | (0.8) |
| GRG | (55.1) | (28.0) | (9.8) | (1.5) | (66.7) | (29.5) | 4.2 | (20.4) | 1.5 | (18.9) | (55.1) | (27.3) | (46.8) | (11.6) | (11.5) | (11.3) | (11.1) | (11.0) | (10.8) | (10.6) | (10.6) | (10.6) |
| LCG | (15.7) | (15.1) | (13.8) | (13.5) | (17.9) | (18.2) | (15.2) | (19.9) | (17.3) | (24.0) | (23.1) | (24.0) | (22.7) | (20.7) | (20.5) | (20.3) | (20.1) | (19.9) | (19.7) | (19.5) | (19.5) | (19.5) |
| **Net emissions based on the IPCC Tier 2 analysis (Step 3)** | | | | | | | | | | | | | | | | | | | | | | |
| Mineral Soils | Mineral Soils | | | | | | | | | | | | | | | | | | | | | |

| | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CRC | (6.5) | (6.5) | (6.5) | (7.6) | (7.6) | (7.6) | (7.6) | (7.6) | (6.9) | (6.9) | (6.9) | (6.9) | (6.9) | (2.8) | (2.8) | (2.8) | (2.8) | (2.8) | (2.8) | (2.8) | (2.8) | (2.8) |
| LCC | 4.8 | 4.8 | 4.8 | 4.7 | 4.7 | 4.7 | 4.7 | 4.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| GRG | (0.2) | (0.2) | (0.2) | (0.1) | (0.1) | (0.1) | (0.1) | (0.1) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| LCG | (3.5) | (3.5) | (3.5) | (3.6) | (3.6) | (3.6) | (3.6) | (3.6) | (3.6) | (3.6) | (3.6) | (3.6) | (3.6) | (2.5) | (2.5) | (2.5) | (2.5) | (2.5) | (2.5) | (2.5) | (2.5) | (2.5) |
| Organic Soils | | Organic Soils | | | | | | | | | | | | | | | | | | | | |
| CRC | 26.3 | 26.3 | 26.3 | 25.7 | 25.7 | 25.7 | 25.7 | 25.7 | 25.7 | 25.7 | 25.7 | 25.7 | 25.7 | 26.8 | 26.8 | 26.8 | 26.8 | 26.8 | 26.8 | 26.8 | 26.8 | 26.8 |
| LCC | 2.2 | 2.2 | 2.2 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| GRG | 3.4 | 3.4 | 3.4 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |
| LCG | 0.4 | 0.4 | 0.4 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| **Additional changes in net emissions from mineral soils based on application of sewage sludge to agricultural land (Step 4)** | | | | | | | | | | | | | | | | | | | | | | |
| GRG | (0.6) | (0.6) | (0.7) | (0.7) | (0.8) | (0.8) | (0.8) | (0.9) | (0.9) | (0.9) | (1.0) | (1.0) | (1.0) | (1.0) | (1.1) | (1.1) | (1.2) | (1.2) | (1.2) | (1.2) | (1.2) | (1.2) |
| **Additional changes in net emissions from mineral soils based on additional enrollment of CRP land (Step 4)** | | | | | | | | | | | | | | | | | | | | | | |
| CRC | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1.4 | 2.0 | 3.6 | 3.7 |
| **Total Stock Changes by Land Use/Land-Use Change Category (Step 5)** | | | | | | | | | | | | | | | | | | | | | | |
| CRC | (35.4) | (37.7) | (48.2) | (46.2) | (44.4) | (29.6) | (37.0) | (36.1) | (25.6) | (11.0) | (36.1) | (18.8) | (17.4) | (18.4) | (18.4) | (18.4) | (18.4) | (18.4) | (16.9) | (16.3) | (14.7) | (14.6) |
| LCC | 2.5 | 2.7 | 2.2 | (1.5) | (5.4) | 3.4 | 2.6 | 3.0 | (4.5) | 3.0 | 1.8 | 3.7 | 4.3 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 |
| GRG | (52.5) | (25.5) | (7.3) | 0.7 | (64.6) | (27.3) | 6.4 | (18.4) | 3.2 | (17.2) | (53.5) | (25.7) | (45.2) | (9.8) | (9.7) | (9.6) | (9.4) | (9.3) | (9.1) | (9.0) | (9.0) | (9.0) |
| LCG | (18.8) | (18.1) | (16.9) | (16.3) | (20.7) | (21.0) | (18.0) | (22.7) | (20.1) | (26.7) | (25.9) | (26.8) | (25.5) | (22.4) | (22.2) | (22.0) | (21.8) | (21.6) | (21.4) | (21.2) | (21.2) | (21.2) |
| **Total*** | **(104.2)** | **(78.6)** | **(70.3)** | **(63.3)** | **(135.0)** | **(74.5)** | **(46.0)** | **(74.2)** | **(47.0)** | **(52.0)** | **(113.6)** | **(67.6)** | **(83.8)** | **(48.7)** | **(48.4)** | **(48.1)** | **(47.7)** | **(47.4)** | **(45.6)** | **(44.7)** | **(43.1)** | **(43.0)** |

Note: Quality control measures are still underway for the Cropland and Grassland, and estimates will be finalized after the expert review.

Table A- 230: Total 2011 $N_2O$ Emissions (Direct and Indirect) from Agricultural Soil Management by State (Tg $CO_2$ Eq.)

| State | Croplands[1] | Grasslands[2] | Settlements[3] | Forest Lands[4] | Total | Lower Bound | Upper Bound[2] |
|---|---|---|---|---|---|---|---|
| AL | 1.19 | 1.23 | 0.03 | n.e. | 2.45 | 1.59 | 4.13 |
| AR | 3.99 | 1.52 | 0.02 | n.e. | 5.53 | 3.98 | 9.21 |
| AZ | 0.53 | 1.84 | 0.01 | n.e. | 2.38 | 1.31 | 4.30 |
| CA | 6.31 | 1.90 | 0.19 | n.e. | 8.40 | 6.11 | 14.47 |
| CO | 4.84 | 3.43 | 0.02 | n.e. | 8.30 | 5.58 | 14.84 |
| CT | 0.88 | 0.03 | 0.02 | n.e. | 0.93 | 0.41 | 2.51 |
| DE | 0.66 | 0.02 | 0.01 | n.e. | 0.68 | 0.27 | 1.75 |
| FL | 2.58 | 1.36 | 0.23 | n.e. | 4.17 | 2.91 | 6.61 |
| GA | 1.58 | 0.96 | 0.01 | n.e. | 2.54 | 1.59 | 4.47 |
| HI5 | 0.00 | n.e. | n.e. | n.e. | 0.03 | 0.01 | 0.11 |
| IA | 15.35 | 2.07 | 0.07 | n.e. | 17.49 | 11.88 | 27.59 |
| ID | 2.92 | 1.42 | 0.02 | n.e. | 4.36 | 3.33 | 6.91 |
| IL | 12.84 | 0.81 | 0.12 | n.e. | 13.77 | 9.74 | 20.66 |
| IN | 7.34 | 0.55 | 0.08 | n.e. | 7.97 | 3.46 | 12.69 |
| KS | 11.20 | 4.05 | 0.07 | n.e. | 15.32 | 10.99 | 24.02 |
| KY | 2.71 | 1.88 | 0.03 | n.e. | 4.63 | 2.99 | 7.38 |
| LA | 2.45 | 0.67 | 0.04 | n.e. | 3.16 | 2.32 | 4.84 |
| MA | 0.56 | 0.03 | 0.04 | n.e. | 0.63 | 0.22 | 1.63 |
| MD | 1.15 | 0.17 | 0.05 | n.e. | 1.37 | 0.87 | 2.52 |
| ME | 0.62 | 0.05 | 0.01 | n.e. | 0.69 | 0.27 | 1.70 |
| MI | 4.19 | 0.57 | 0.08 | n.e. | 4.85 | 3.67 | 9.45 |
| MN | 8.76 | 1.30 | 0.04 | n.e. | 10.09 | 7.66 | 14.67 |
| MO | 7.24 | 3.40 | 0.07 | n.e. | 10.71 | 7.64 | 16.56 |
| MS | 2.87 | 0.77 | 0.03 | n.e. | 3.67 | 2.67 | 5.72 |
| MT | 3.62 | 5.72 | 0.01 | n.e. | 9.36 | 6.10 | 14.15 |
| NC | 1.87 | 0.74 | 0.05 | n.e. | 2.66 | 1.74 | 5.03 |
| ND | 6.28 | 1.60 | 0.03 | n.e. | 7.91 | 5.86 | 11.27 |
| NE | 15.24 | 3.94 | 0.07 | n.e. | 19.25 | 9.12 | 38.44 |
| NH | 0.53 | 0.02 | 0.01 | n.e. | 0.56 | 0.14 | 1.55 |
| NJ | 0.69 | 0.04 | 0.08 | n.e. | 0.81 | 0.38 | 4.82 |
| NM | 1.17 | 4.41 | 0.01 | n.e. | 5.59 | 3.00 | 9.49 |
| NV | 0.72 | 0.83 | 0.01 | n.e. | 1.56 | 1.07 | 2.83 |
| NY | 2.91 | 0.56 | 0.07 | n.e. | 3.54 | 2.49 | 5.95 |
| OH | 7.38 | 0.74 | 0.11 | n.e. | 8.24 | 6.06 | 12.29 |
| OK | 3.98 | 4.30 | 0.03 | n.e. | 8.31 | 5.54 | 13.26 |
| OR | 1.71 | 2.04 | 0.01 | n.e. | 3.76 | 2.73 | 5.64 |
| PA | 2.33 | 0.60 | 0.06 | n.e. | 2.99 | 2.05 | 5.32 |
| RI | 0.50 | 0.01 | 0.01 | n.e. | 0.51 | 0.26 | 1.46 |
| SC | 1.12 | 0.37 | 0.03 | n.e. | 1.52 | 1.02 | 2.82 |
| SD | 6.36 | 4.32 | 0.02 | n.e. | 10.70 | 6.02 | 16.90 |
| TN | 2.09 | 1.75 | 0.05 | n.e. | 3.90 | 2.39 | 6.50 |
| TX | 9.38 | 10.53 | 0.09 | n.e. | 20.00 | 10.14 | 32.85 |
| UT | 1.15 | 1.02 | 0.01 | n.e. | 2.18 | 1.50 | 3.63 |
| VA | 1.33 | 1.35 | 0.06 | n.e. | 2.74 | 1.62 | 4.73 |
| VT | 0.78 | 0.09 | 0.00 | n.e. | 0.88 | 0.46 | 1.96 |
| WA | 3.02 | 1.22 | 0.03 | n.e. | 4.26 | 3.36 | 6.20 |
| WI | 0.86 | 0.30 | 0.01 | n.e. | 1.17 | 0.71 | 2.28 |
| WV | 4.61 | 1.33 | 0.01 | n.e. | 5.95 | 4.31 | 10.21 |
| WY | 2.03 | 3.15 | 0.04 | n.e. | 5.22 | 3.40 | 2.18 |

[1] Emissions from non-manure organic N inputs for minor crops were not estimated (n.e.) at the state level.
[2] Emissions from sewage sludge applied to grasslands and were not estimated (n.e.) at the state level
[3] Emissions from sewage sludge applied to settlements were not estimated (n.e.) at the state level.
[4] Forestland emissions were not estimated (n.e.) at the state level.
[5] $N_2O$ emissions are not reported for Hawaii except from cropland organic soils.
Note: Quality control measures are still underway for Cropland and Grassland, and estimates will be finalized after the expert review.

Table A- 231: Soil C Stock Change for Mineral and Organic Soils during 2011 within individual states (Tg $CO_2$ Eq.))

| State | Mineral Soil | Organic Soil | Total |
|---|---|---|---|
| AL | (0.45) | - | (0.45) |
| AR | (0.46) | - | (0.46) |
| AZ | (0.84) | - | (0.84) |

| | | | |
|---|---|---|---|
| CA | (0.43) | 2.29 | 1.86 |
| CO | (0.41) | 0.00 | (0.40) |
| CT | (0.06) | - | (0.06) |
| DE | 0.01 | - | 0.01 |
| FL | 0.15 | 10.84 | 10.99 |
| GA | (0.11) | - | (0.11) |
| HI | - | 0.25 | 0.25 |
| IA | (4.64) | 0.75 | (3.89) |
| ID | (1.55) | 0.11 | (1.45) |
| IL | (5.11) | 0.54 | (4.57) |
| IN | (1.75) | 2.93 | 1.18 |
| KS | (1.60) | - | (1.60) |
| KY | (1.51) | - | (1.51) |
| LA | (1.27) | 0.07 | (1.20) |
| MA | (0.03) | 0.03 | 0.00 |
| MD | (0.18) | 0.03 | (0.15) |
| ME | (0.14) | - | (0.14) |
| MI | (1.94) | 2.72 | 0.78 |
| MN | (2.68) | 7.30 | 4.62 |
| MO | (9.09) | - | (9.09) |
| MS | (0.77) | 0.00 | (0.77) |
| MT | (6.09) | 0.11 | (5.98) |
| NC | (0.19) | 2.25 | 2.07 |
| ND | (6.26) | - | (6.26) |
| NE | (1.64) | - | (1.64) |
| NH | (0.04) | 0.01 | (0.03) |
| NJ | (0.10) | 0.01 | (0.09) |
| NM | (1.14) | - | (1.14) |
| NV | (0.24) | 0.00 | (0.24) |
| NY | (1.84) | 0.61 | (1.23) |
| OH | (2.97) | 0.42 | (2.55) |
| OK | (6.11) | - | (6.11) |
| OR | (2.16) | 0.12 | (2.04) |
| PA | (1.80) | 0.01 | (1.79) |
| RI | (0.01) | 0.00 | (0.01) |
| SC | (0.01) | 0.04 | 0.02 |
| SD | (5.77) | - | (5.77) |
| TN | (1.67) | - | (1.67) |
| TX | 5.33 | - | 5.33 |
| UT | 0.03 | - | 0.03 |
| VA | (0.44) | 0.02 | (0.42) |
| VT | (0.25) | 0.00 | (0.24) |
| WA | (2.16) | 0.26 | (1.90) |
| WI | (2.45) | 2.88 | 0.43 |
| WV | (0.41) | - | (0.41) |
| WY | 0.25 | 0.01 | 0.26 |

Note: Parentheses indicate net C accumulation. Estimates do not include soil C stock change associated with CRP enrollment after 2007 or sewage sludge application to soils, which were only estimated at the national scale. The sum of state results will not match the national results because state results are generated in a separate programming package, the sewage sludge and CRP enrollment after 2007 are not included, and differences arise due to rounding of values in this table.

Note: Quality control measures are still underway for Cropland and Grassland, and estimates will be finalized after the expert review.

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# 3.13. Methodology for Estimating Net Carbon Stock Changes in Forest Lands Remaining Forest Lands

This sub-annex expands on the methodology used to calculate net changes in carbon (C) stocks in forest ecosystems and in harvested wood products. Some of the details of C conversion factors and procedures for calculating net $CO_2$ flux for forests are provided below; full details of selected topics may be found in the cited references.

### Carbon Stocks and Net Changes in Forest Ecosystem Carbon Stocks

At least two forest inventories exist for most forest land in the United States. C stocks are estimated based on data from each inventory, at the level of permanent inventory plots. C per hectare (for a sample location) is multiplied by the total number of hectares that the plot represents, and then totals are summed for an area of interest, such as the state of Maine. Net annual C stock changes are calculated by taking the difference between the inventories and dividing by the number of years between the inventories for a selected state or sub-state area.

#### *Forest inventory data*

The estimates of forest C stocks are based on data derived from forest inventory surveys. Forest inventory data were obtained from the USDA Forest Service, Forest Inventory and Analysis (FIA) program (Frayer and Furnival 1999, USDA Forest Service 2012a, USDA Forest Service 2012b). FIA data include remote sensing information and collection of measurements in the field at sample locations called plots. Tree measurements include diameter and species. On a subset of plots, additional measurements or samples are taken of down dead wood, litter, and soil C. However, the technical advances needed to estimate C stocks from these data is still under development (e.g., forest floor, Woodall et al. 2012). The field protocols are thoroughly documented and available for download from the USDA Forest Service (2012c). Bechtold and Patterson (2005) provide the estimation procedures for standard forest inventory results. The data are freely available for download at USDA Forest Service (2011b) as the Forest Inventory and Analysis Database (FIADB) Version 5.1 (USDA Forest Service 2012b, Woudenberg et al. 2010); these data are the primary sources of forest inventory used to estimate forest C stocks.

Forest surveys have begun in the U.S. territories and in Hawaii. Meanwhile this inventory assumes that these areas account for a net C change of zero. Survey data are available for the temperate oceanic ecoregion of Alaska (southeast and south central). Inventory data are publicly available for 6 million hectares of forest land, and these inventoried lands, comprising 12 percent of the total forest land in Alaska, contribute to the forest carbon stocks presented here.

Agroforestry systems are also not currently accounted for in the U.S. inventory, since they are not explicitly inventoried by either of the two primary national natural resource inventory programs: the FIA program of the USDA Forest Service and the National Resources Inventory (NRI) of the USDA Natural Resources Conservation Service (Perry et al. 2005). The majority of these tree-based practices do not meet the size and definitions for forests within each of these resource inventories. The size characteristics that exclude them from inventories also allow these systems to provide their many services without taking the land out of agricultural production, making them an appealing C sequestration option. Agroforestry in the United States has been defined as "intensive land-use management that optimizes the benefits (physical, biological, ecological, economic, social) from bio-physical interactions created when trees and/or shrubs are deliberately combined with crops and/or livestock" (Gold et al. 2000). In the United States, there are six categories of agroforestry practices: riparian forest buffers, windbreaks, alley cropping, silvopasture, forest farming and special applications.[89] These practices are used to address many issues facing agricultural lands, such as economic diversification, habitat fragmentation, and water quality. While providing these services and regardless of intent, these tree-based plantings will also reduce atmospheric $CO_2$. This occurs directly through $CO_2$ sequestration into woody biomass, and indirectly through enhancement of agricultural production, trapping wind-blown and surface runoff sediments, and/or reducing $CO_2$ emissions through fuel-use savings (Quam et al. 1992). The effects of these individual practices can potentially be quite large when taken into account within a whole-farm or within an aggregating larger entity (i.e., state-level) (Quam et al. 1992, Schoeneberger 2006). One estimate of the sequestration potential through agroforestry practices in the United States is 90.3 Mt C/year by 2025 (Nair and Nair 2003).

[89] More information on agroforestry practices can be found online at <http://www.unl.edu/nac>.

***Summing state-level C stocks to calculate United States net C flux in forest ecosystems***

The overall approach for determining forest C stocks and stock change is essentially based on methodology and algorithms coded into the computer tool described in Smith et al. (2010). A change in methods for the present inventory involves a modification of the down dead wood estimates to incorporate population estimates of down woody material measured on a subset of the inventory plots (Domke et al , Woodall and Monleon 2008, Woodall et al. In Review) ). The carbon calculation tool focuses on estimating forest C stocks based on data from two or more forest surveys conducted several years apart for each state or sub-state. There are generally two or more surveys available for download for each state. C stocks are calculated separately for each state based on available inventories conducted since 1990 and for the inventory closest to, but prior to, 1990 if such data are available and consistent with these methods. This approach ensures that the period 1990 (the base year) to present can be adequately represented. Surveys conducted prior to and in the early to mid-1990s focused on land capable of supporting timber production (timberland).[90] As a result, information on less productive forest land or lands reserved from harvest was limited. Inventory field crews periodically measured all the plots in a state at a frequency of every 5 to 14 years. Generally, forests in states with fast-growing (and therefore rapidly changing) forests tended to be surveyed more often than states with slower-growing (and therefore slowly changing) forests. Older surveys for some states, particularly in the West, also have National Forest System (NFS) lands or reserved lands that were surveyed at different times than productive, privately-owned forest land in the state. Periodic data for each state thus became available at irregular intervals and determining the year of data collection associated with the survey can sometimes be difficult.

Table A-232: Source of Unique Forest Inventory and Average Year of Field Survey Used to Estimate Statewide Carbon Stocks

| State/Substate | Source of Inventory Data, Report/Inventory Year | Average Year Assigned to Inventory |
|---|---|---|
| Alabama | FIADB 5.1, 1982 | 1982 |
| | FIADB 5.1, 1990 | 1990 |
| | FIADB 5.1, 2000 | 1999 |
| | FIADB 5.1, 2005 | 2003 |
| | FIADB 5.1, 2011 | 2008 |
| Alaska, non-reserved Southcentral | FIADB 4.0, 2003 | 2001 |
| | FIADB 5.1, 2010 | 2008 |
| Alaska, non-reserved Southeast | FIADB 4.0, 2003 | 1997 |
| | FIADB 5.1, 2010 | 2008 |
| Alaska, reserved Southcentral | FIADB 5.1, 2010 | 2007 |
| Alaska, reserved Southeast | FIADB 5.1, 2010 | 2006 |
| Arizona, NFS non-woodlands | 1987 RPA | 1985 |
| | FIADB 5.1, 1999 | 1996 |
| | FIADB 5.1, 2009 | 2005 |
| Arizona, NFS woodlands | 1987 RPA | 1984 |

[90] Forest land is defined as land at least 120 feet wide and 1 acre in size with at least 10 percent cover (or equivalent stocking by live trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated. Forest land includes transition zones, such as areas between forest and nonforest lands that have at least 10 percent cover (or equivalent stocking) with live trees and forest areas adjacent to urban and built-up lands. Roadside, streamside, and shelterbelt strips of trees must have a crown width of at least 120 feet and continuous length of at least 363 feet to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas are classified as forest if they are less than 120 feet wide or an acre in size. Tree-covered areas in agricultural production settings, such as fruit orchards, or tree-covered areas in urban settings, such as city parks, are not considered forest land (Smith et al. 2009). Timberland is the most productive type of forest land, which is on unreserved land and is producing or capable of producing crops of industrial wood. Productivity is at a minimum rate of 20 cubic feet of industrial wood per acre per year (Woudenberg and Farrenkopf 1995). There are about 203 million hectares of timberland in the conterminous United States, which represents 81 percent of all forest lands over the same area (Smith et al. 2009).

| | | |
|---|---|---|
| | FIADB 5.1, 1999 | 1996 |
| | FIADB 5.1, 2009 | 2005 |
| Arizona, non-NFS non-woodlands | FIADB 5.1, 1985 | 1986 |
| | FIADB 5.1, 1999 | 1996 |
| | FIADB 5.1, 2009 | 2006 |
| Arizona, non-NFS woodlands | FIADB 5.1, 1999 | 1990 |
| | FIADB 5.1, 2009 | 2006 |
| Arkansas | FIADB 5.1, 1988 | 1988 |
| | FIADB 5.1, 1995 | 1996 |
| | FIADB 5.1, 2005 | 2003 |
| | FIADB 5.1, 2010 | 2008 |
| California, NFS | IDB, 1990s | 1997 |
| | FIADB 5.1, 2010 | 2006 |
| California, non-NFS | IDB, 1990s | 1993 |
| | FIADB 5.1, 2010 | 2006 |
| Colorado, NFS non-woodlands | 1997 RPA | 1981 |
| | FIADB 5.1, 2009 | 2006 |
| Colorado, NFS woodlands | FIADB 5.1, 2009 | 2006 |
| Colorado, non-NFS non-woodlands | Westwide, 1983 | 1980 |
| | FIADB 5.1, 2009 | 2006 |
| Colorado, non-NFS woodlands | Westwide, 1983 | 1983 |
| | FIADB 5.1, 2009 | 2006 |
| Connecticut | FIADB 5.1, 1985 | 1985 |
| | FIADB 5.1, 1998 | 1998 |
| | FIADB 5.1, 2007 | 2006 |
| | FIADB 5.1, 2011 | 2010 |
| Delaware | FIADB 5.1, 1986 | 1986 |
| | FIADB 5.1, 1999 | 1999 |
| | FIADB 5.1, 2008 | 2007 |
| Florida | FIADB 5.1, 1987 | 1987 |
| | FIADB 5.1, 1995 | 1995 |
| | FIADB 5.1, 2007 | 2005 |
| Georgia | FIADB 5.1, 1989 | 1989 |
| | FIADB 5.1, 1997 | 1997 |
| | FIADB 5.1, 2004 | 2002 |
| | FIADB 5.1, 2009 | 2007 |
| Idaho, Caribou-Targhee NF | Westwide, 1991 | 1992 |
| | FIADB 5.1, 2009 | 2007 |
| Idaho, Kootenai NF | 1987 RPA | 1988 |
| | FIADB 5.1, 1991 | 1995 |
| | FIADB 5.1, 2009 | 2007 |
| Idaho, Payette NF | 1987 RPA | 1982 |
| | FIADB 5.1, 2009 | 2007 |
| Idaho, Salmon-Challis NF | 1987 RPA | 1978 |
| | FIADB 5.1, 2009 | 2007 |
| Idaho, Sawtooth NF | Westwide, 1991 | 1983 |
| | FIADB 5.1, 1991 | 1996 |
| | FIADB 5.1, 2009 | 2007 |

| | | |
|---|---|---|
| Idaho, non-NFS non-woodlands | FIADB 5.1, 1991 | 1990 |
| | FIADB 5.1, 2009 | 2007 |
| Idaho, non-NFS woodlands | FIADB 5.1, 1991 | 1982 |
| | FIADB 5.1, 2009 | 2007 |
| Idaho, other NFS | Westwide, 1991 | 1988 |
| | FIADB 5.1, 1991 | 2000 |
| | FIADB 5.1, 2009 | 2007 |
| Illinois | FIADB 5.1, 1985 | 1985 |
| | FIADB 5.1, 1998 | 1998 |
| | FIADB 5.1, 2005 | 2004 |
| | FIADB 5.1, 2010 | 2008 |
| Indiana | FIADB 5.1, 1986 | 1986 |
| | FIADB 5.1, 1998 | 1998 |
| | FIADB 5.1, 2003 | 2001 |
| | FIADB 5.1, 2008 | 2007 |
| | FIADB 5.1, 2011 | 2009 |
| Iowa | FIADB 5.1, 1990 | 1990 |
| | FIADB 5.1, 2003 | 2002 |
| | FIADB 5.1, 2008 | 2006 |
| | FIADB 5.1, 2011 | 2009 |
| Kansas | FIADB 5.1, 1981 | 1981 |
| | FIADB 5.1, 1994 | 1994 |
| | FIADB 5.1, 2005 | 2003 |
| | FIADB 5.1, 2010 | 2009 |
| Kentucky | FIADB 5.1, 1988 | 1987 |
| | FIADB 5.1, 2004 | 2002 |
| | FIADB 5.1, 2009 | 2008 |
| Louisiana | FIADB 5.1, 1984 | 1984 |
| | FIADB 5.1, 1991 | 1991 |
| | FIADB 5.1, 2005 | 2004 |
| Maine | Eastwide, 1982 | 1983 |
| | FIADB 5.1, 1995 | 1995 |
| | FIADB 5.1, 2003 | 2002 |
| | FIADB 5.1, 2008 | 2007 |
| | FIADB 5.1, 2011 | 2010 |
| Maryland | FIADB 5.1, 1986 | 1986 |
| | FIADB 5.1, 1999 | 2000 |
| | FIADB 5.1, 2008 | 2007 |
| Massachusetts | FIADB 5.1, 1985 | 1985 |
| | FIADB 5.1, 1998 | 1998 |
| | FIADB 5.1, 2007 | 2006 |
| | FIADB 5.1, 2011 | 2010 |
| Michigan | FIADB 5.1, 1980 | 1980 |
| | FIADB 5.1, 1993 | 1993 |
| | FIADB 5.1, 2004 | 2003 |
| | FIADB 5.1, 2009 | 2007 |
| Minnesota | FIADB 5.1, 1990 | 1989 |
| | FIADB 5.1, 2003 | 2001 |
| | FIADB 5.1, 2008 | 2006 |

| | | |
|---|---|---|
| | FIADB 5.1, 2011 | 2009 |
| Mississippi | FIADB 5.1, 1987 | 1987 |
| | FIADB 5.1, 1994 | 1994 |
| | FIADB 5.1, 2006 | 2007 |
| Missouri | FIADB 5.1, 1989 | 1988 |
| | FIADB 5.1, 2003 | 2002 |
| | FIADB 5.1, 2008 | 2006 |
| | FIADB 5.1, 2011 | 2009 |
| Montana, NFS | 1987 RPA | 1988 |
| | FIADB 5.1, 1989 | 1996 |
| | FIADB 5.1, 2009 | 2007 |
| Montana, non-NFS non-reserved | FIADB 5.1, 1989 | 1989 |
| | FIADB 5.1, 2009 | 2006 |
| Montana, non-NFS reserved | 1997 RPA | 1990 |
| | FIADB 5.1, 2009 | 2007 |
| Nebraska | FIADB 5.1, 1983 | 1983 |
| | FIADB 5.1, 1994 | 1995 |
| | FIADB 5.1, 2005 | 2004 |
| | FIADB 5.1, 2010 | 2008 |
| Nevada, NFS non-woodlands | 1987 RPA | 1974 |
| | FIADB 5.1, 1989 | 1997 |
| | FIADB 5.1, 2005 | 2005 |
| Nevada, NFS woodlands | 1987 RPA | 1978 |
| | FIADB 5.1, 1989 | 1997 |
| | FIADB 5.1, 2005 | 2005 |
| Nevada, non-NFS non-woodlands | 1997 RPA | 1985 |
| | FIADB 5.1, 2005 | 2005 |
| Nevada, non-NFS woodlands | FIADB 5.1, 1989 | 1980 |
| | FIADB 5.1, 2005 | 2005 |
| New Hampshire | FIADB 5.1, 1983 | 1983 |
| | FIADB 5.1, 1997 | 1997 |
| | FIADB 5.1, 2007 | 2005 |
| | FIADB 5.1, 2011 | 2010 |
| New Jersey | FIADB 5.1, 1987 | 1987 |
| | FIADB 5.1, 1999 | 1999 |
| | FIADB 5.1, 2008 | 2007 |
| New Mexico, NFS non-woodlands | 1987 RPA | 1986 |
| | FIADB 5.1, 1999 | 1997 |
| New Mexico, NFS woodlands | 1987 RPA | 1986 |
| | FIADB 5.1, 1999 | 1997 |
| New Mexico, non-NFS non-woodlands | FIADB 5.1, 1987 | 1987 |
| | FIADB 5.1, 1999 | 1999 |
| New Mexico, non-NFS woodlands | FIADB 5.1, 1999 | 1989 |
| New York, non-reserved | Eastwide, 1980 | 1981 |
| | FIADB 5.1, 1993 | 1993 |
| | FIADB 5.1, 2007 | 2005 |
| | FIADB 5.1, 2010 | 2009 |
| New York, reserved | 1987 RPA | 1988 |

| | | |
|---|---|---|
| | FIADB 5.1, 2007 | 2005 |
| | FIADB 5.1, 2010 | 2009 |
| North Carolina | FIADB 5.1, 1984 | 1984 |
| | FIADB 5.1, 1990 | 1990 |
| | FIADB 5.1, 2002 | 2001 |
| | FIADB 5.1, 2007 | 2006 |
| North Dakota | FIADB 5.1, 1980 | 1979 |
| | FIADB 5.1, 1995 | 1995 |
| | FIADB 5.1, 2005 | 2003 |
| | FIADB 5.1, 2010 | 2009 |
| Ohio | FIADB 5.1, 1991 | 1991 |
| | FIADB 5.1, 2006 | 2005 |
| | FIADB 5.1, 2011 | 2010 |
| Oklahoma, Central & West | FIADB 5.1, 2011 | 2011 |
| Oklahoma, East | FIADB 5.1, 1986 | 1986 |
| | FIADB 5.1, 1993 | 1993 |
| | FIADB 5.1, 2008 | 2008 |
| Oregon, NFS East | IDB, 1990s | 1995 |
| | FIADB 5.1, 2010 | 2006 |
| Oregon, NFS West | IDB, 1990s | 1996 |
| | FIADB 5.1, 2010 | 2006 |
| Oregon, non-NFS East | Westwide, 1992 | 1991 |
| | IDB, 1990s | 1999 |
| | FIADB 5.1, 2010 | 2006 |
| Oregon, non-NFS West | Westwide, 1992 | 1989 |
| | IDB, 1990s | 1997 |
| | FIADB 5.1, 2010 | 2006 |
| Pennsylvania | FIADB 5.1, 1989 | 1990 |
| | FIADB 5.1, 2004 | 2003 |
| | FIADB 5.1, 2009 | 2008 |
| Rhode Island | FIADB 5.1, 1985 | 1985 |
| | FIADB 5.1, 1998 | 1999 |
| | FIADB 5.1, 2007 | 2006 |
| | FIADB 5.1, 2011 | 2010 |
| South Carolina | FIADB 5.1, 1986 | 1986 |
| | FIADB 5.1, 1993 | 1993 |
| | FIADB 5.1, 2001 | 2001 |
| | FIADB 5.1, 2006 | 2005 |
| | FIADB 5.1, 2011 | 2009 |
| South Dakota, NFS | 1997 RPA | 1986 |
| | FIADB 5.1, 1995 | 1999 |
| | FIADB 5.1, 2005 | 2004 |
| | FIADB 5.1, 2010 | 2009 |
| South Dakota, non-NFS | 1987 RPA | 1986 |
| | FIADB 5.1, 1995 | 1995 |
| | FIADB 5.1, 2005 | 2004 |
| | FIADB 5.1, 2010 | 2008 |
| Tennessee | FIADB 5.1, 1989 | 1989 |
| | FIADB 5.1, 1999 | 1998 |

| | | |
|---|---|---|
| | FIADB 5.1, 2004 | 2003 |
| | FIADB 5.1, 2009 | 2008 |
| Texas, Central & West | FIADB 5.1, 2010 | 2008 |
| Texas, East | FIADB 5.1, 1986 | 1986 |
| | FIADB 5.1, 1992 | 1992 |
| | FIADB 5.1, 2003 | 2003 |
| | FIADB 5.1, 2008 | 2006 |
| | FIADB 5.1, 2011 | 2009 |
| Utah, non-woodlands | FIADB 5.1, 1993 | 1993 |
| | FIADB 5.1, 2009 | 2005 |
| Utah, woodlands | FIADB 5.1, 1993 | 1994 |
| | FIADB 5.1, 2009 | 2005 |
| Vermont | FIADB 5.1, 1983 | 1983 |
| | FIADB 5.1, 1997 | 1997 |
| | FIADB 5.1, 2007 | 2006 |
| | FIADB 5.1, 2011 | 2010 |
| Virginia | FIADB 5.1, 1985 | 1985 |
| | FIADB 5.1, 1992 | 1991 |
| | FIADB 5.1, 2001 | 2000 |
| | FIADB 5.1, 2007 | 2005 |
| | FIADB 5.1, 2011 | 2010 |
| Washington, NFS East | IDB, 1990s | 1996 |
| | FIADB 5.1, 2010 | 2007 |
| Washington, NFS West | IDB, 1990s | 1996 |
| | FIADB 5.1, 2010 | 2007 |
| Washington, non-NFS East | IDB, 1990s | 1992 |
| | FIADB 5.1, 2010 | 2007 |
| Washington, non-NFS West | IDB, 1990s | 1990 |
| | FIADB 5.1, 2010 | 2007 |
| West Virginia | FIADB 5.1, 1989 | 1988 |
| | FIADB 5.1, 2000 | 2001 |
| | FIADB 5.1, 2008 | 2007 |
| | FIADB 5.1, 2011 | 2010 |
| Wisconsin | FIADB 5.1, 1983 | 1982 |
| | FIADB 5.1, 1996 | 1995 |
| | FIADB 5.1, 2004 | 2002 |
| | FIADB 5.1, 2009 | 2007 |
| Wyoming, NFS | 1997 RPA | 1982 |
| | FIADB 5.1, 2000 | 2000 |
| Wyoming, non-NFS non-reserved non-woodlands | FIADB 5.1, 1984 | 1984 |
| | FIADB 5.1, 2000 | 2002 |
| Wyoming, non-NFS non-reserved woodlands | FIADB 5.1, 1984 | 1984 |
| | FIADB 5.1, 2000 | 2002 |
| Wyoming, non-NFS reserved | 1997 RPA | 1985 |
| | FIADB 5.1, 2000 | 2000 |

[a] Substate areas (Smith et al. 2010) include National Forests (NFS), all forest ownerships except National Forest (non-NFS), woodlands (forest land dominated by woodland species, such as pinyon and juniper, where stocking cannot be determined (USDA Forest Service 2012c)), non-woodlands (used for clarity to emphasize that woodlands are classified separately), reserved (forest land withdrawn from timber utilization through statute, administrative regulation, or designation, Smith et al. (2009)), and non-reserved (forest land that is not reserved, used for clarity). Some National Forests are listed individually by name, e.g., Payette NF. Oregon and Washington were divided into eastern and western forests (east or west of the crest of the Cascade

Mountains). Oklahoma and Texas are divided into East versus Central & West according to forest inventory survey units (USDA Forest Service 2012d). Alaska is represented by a portion of forest land, in the southcentral and southeast part of the state.

[b] FIADB 5.1 is the current, publicly available, format of FIA inventory data, and these files were downloaded from the Internet 20 August 2012 (USDA Forest Service 2012b). IDB (Integrated Database) data are a compilation of periodic inventory data from the 1990s for California, Oregon, and Washington (Waddell and Hiserote 2005). Eastwide (Hansen et al. 1992) and Westwide (Woudenberg and Farrenkopf 1995) inventory data are formats that predate the FIADB data. RPA data are periodic national summaries. The year is the nominal, or reporting, year associated with each dataset.

c Average year is based on average measurement year of forest land survey plots and rounded to the nearest integer year.

A national plot design and annualized sampling (USDA Forest Service 2012a) was introduced by FIA with most new surveys beginning after 1998. These surveys include sampling of all forest land including reserved and lower productivity lands. Most states have annualized inventory data available as of August 2012. Annualized sampling means that a portion of plots throughout the state is sampled each year, with the goal of measuring all plots once every 5 to 10 years, depending on the region of the United States. The full unique set of data with all measured plots, such that each plot has been measured one time, is called a cycle. Sampling is designed such that partial inventory cycles provide usable, unbiased samples of forest inventory, but with higher sampling errors than the full cycle. After all plots have been measured once, the sequence continues with remeasurement of the first year's plots, starting the next new cycle. Most Eastern states have completed one or two cycles of the annualized inventories and are providing annual updates to the state's forest inventory with each year's remeasurements, such that one plot's measurements are included in subsequent year's annual updates. Thus, annually updated estimates of forest C stocks are accurate, but estimates of stock change cannot utilize the annually updated inventory measurements directly, as there is redundancy in the data used to generate the annual updates of C stock. For example, a typical annual inventory update for an eastern state will include new data from remeasurement on 20 percent of plots; data from the remaining 80 percent of plots is identical to that included in the previous year's annual update. The interpretation and use of the sequence of annual inventory updates can affect trends in annualized stock and stock change. In general, the C stock and stock change calculations use annual inventory summaries (updates) with unique sets of plot-level data (that is, without redundant sets); the most-recent annual update is the exception because it is included in stock change calculations if at least half of the plots in a state include new measurements. Table A-232 lists the specific surveys used in this report, and this list can be compared with the full set of summaries available for download (USDA Forest Service 2012b).

For each pool in each state in each year, C stocks are estimated by linear interpolation between survey years. Similarly, fluxes, or net stock changes, are estimated for each pool in each state by dividing the difference between two successive stocks by the number of intervening years between surveys. Thus, the number of separate stock change estimates for each state or sub-state is one less than the number of available inventories. Annual estimates of stock and net change since the most recent survey are based on linear extrapolation. C stock and flux estimates for each pool are summed over all forest land in all states as identified in  to form estimates for the United States. Summed net annual stock change and stock are presented in Table A-232 and Table A-233 , respectively. Table A-234 also provides an estimate of forest area based on the interpolation and extrapolation procedure described above. Estimated net stock change of non-soil forest ecosystem carbon for each of the states is shown in Table A-235, which also includes estimated forest area and total non-soil forest carbon stock. The state-level forest areas and carbon stocks are from the most recent inventory available (USDA Forest Service 2011a), and the estimate for net stock change is the 10-year mean of the 2002 through 2011 estimates from the carbon calculator (Smith et al. 2010).

Table A-233: Net Annual Changes in Carbon Stocks (Tg C $yr^{-1}$) in Forest and Harvested Wood Pools, 1990–2011

| Year | Total Net Flux | Forest Total | Live, aboveground | Live, belowground | Dead Wood | Litter | Soil Organic Carbon | Harvested Wood Total | Products in Use | SWDS |
|---|---|---|---|---|---|---|---|---|---|---|
| 1990 | (190.0) | (154.1) | (98.1) | (19.2) | (8.9) | (6.8) | (21.1) | (35.9) | (17.7) | (18.3) |
| 1991 | (187.7) | (153.9) | (98.0) | (19.2) | (9.1) | (6.7) | (20.9) | (33.8) | (14.9) | (18.8) |
| 1992 | (186.1) | (152.4) | (99.0) | (19.4) | (9.2) | (6.8) | (18.1) | (33.8) | (16.3) | (17.4) |
| 1993 | (186.7) | (153.8) | (104.9) | (20.6) | (9.9) | (5.9) | (12.5) | (32.9) | (15.0) | (17.9) |
| 1994 | (193.5) | (160.1) | (108.0) | (21.2) | (10.0) | (5.3) | (15.6) | (33.4) | (15.9) | (17.5) |
| 1995 | (195.2) | (162.9) | (111.1) | (21.9) | (9.3) | (3.8) | (16.8) | (32.3) | (15.1) | (17.2) |
| 1996 | (196.5) | (165.9) | (112.3) | (22.1) | (15.3) | (4.2) | (12.0) | (30.6) | (14.1) | (16.5) |
| 1997 | (187.6) | (155.6) | (113.1) | (22.3) | (13.5) | (4.1) | (2.5) | (32.0) | (14.7) | (17.3) |
| 1998 | (172.2) | (141.1) | (108.0) | (21.3) | (13.5) | 0.0 | 1.7 | (31.1) | (13.4) | (17.7) |
| 1999 | (154.7) | (122.2) | (103.9) | (20.5) | (13.0) | 3.6 | 11.6 | (32.5) | (14.1) | (18.4) |
| 2000 | (148.4) | (117.6) | (102.5) | (20.2) | (13.2) | 5.5 | 12.9 | (30.8) | (12.8) | (18.0) |
| 2001 | (176.4) | (150.9) | (111.6) | (22.0) | (13.6) | 0.2 | (3.9) | (25.5) | (8.7) | (16.8) |
| 2002 | (212.1) | (185.3) | (114.3) | (22.5) | (14.9) | (6.4) | (27.2) | (26.8) | (9.6) | (17.2) |
| 2003 | (241.6) | (215.7) | (120.5) | (23.7) | (13.9) | (10.7) | (46.9) | (25.9) | (9.7) | (16.2) |
| 2004 | (251.7) | (222.9) | (122.3) | (24.1) | (13.3) | (12.5) | (50.9) | (28.7) | (12.4) | (16.3) |
| 2005 | (246.8) | (218.1) | (119.0) | (23.4) | (12.9) | (13.5) | (49.2) | (28.7) | (12.4) | (16.3) |
| 2006 | (238.0) | (208.4) | (114.6) | (22.6) | (13.9) | (14.2) | (43.1) | (29.6) | (12.3) | (17.3) |
| 2007 | (234.5) | (206.5) | (110.2) | (21.8) | (14.3) | (14.9) | (45.3) | (28.1) | (10.7) | (17.4) |
| 2008 | (227.3) | (206.5) | (110.2) | (21.8) | (14.3) | (14.9) | (45.4) | (20.8) | (3.7) | (17.1) |
| 2009 | (221.3) | (206.5) | (110.2) | (21.8) | (14.3) | (14.9) | (45.4) | (14.8) | 1.8 | (16.6) |
| 2010 | (223.0) | (206.8) | (110.2) | (21.8) | (14.6) | (14.9) | (45.4) | (16.2) | 0.3 | (16.5) |
| 2011 | (227.3) | (207.8) | (110.2) | (21.8) | (15.6) | (14.9) | (45.4) | (19.5) | (2.7) | (16.8) |

Table A-234: Carbon Stocks (Tg C) in Forest and Harvested Wood Pools, 1990–2012

| | | Forest | | | | | | Harvested Wood | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Total Carbon Stock | Total | Live, aboveground | Live, belowground | Dead Wood | Litter | Soil Organic Carbon | Total | Products in Use | SWDS | Forest Area (1000 ha) |
| 1990 | 40,637 | 38,777 | 12,284 | 2,432 | 2,161 | 4,816 | 17,084 | 1,859 | 1,231 | 628 | 271,794 |
| 1991 | 40,827 | 38,931 | 12,383 | 2,451 | 2,170 | 4,823 | 17,105 | 1,895 | 1,249 | 646 | 272,435 |
| 1992 | 41,014 | 39,085 | 12,481 | 2,470 | 2,179 | 4,830 | 17,126 | 1,929 | 1,264 | 665 | 273,084 |
| 1993 | 41,200 | 39,238 | 12,580 | 2,489 | 2,188 | 4,836 | 17,144 | 1,963 | 1,280 | 683 | 273,709 |
| 1994 | 41,387 | 39,391 | 12,684 | 2,510 | 2,198 | 4,842 | 17,157 | 1,996 | 1,295 | 701 | 274,291 |
| 1995 | 41,581 | 39,552 | 12,792 | 2,531 | 2,208 | 4,848 | 17,172 | 2,029 | 1,311 | 718 | 274,868 |
| 1996 | 41,776 | 39,714 | 12,904 | 2,553 | 2,217 | 4,851 | 17,189 | 2,061 | 1,326 | 735 | 275,439 |
| 1997 | 41,972 | 39,880 | 13,016 | 2,575 | 2,233 | 4,856 | 17,201 | 2,092 | 1,340 | 752 | 275,956 |
| 1998 | 42,160 | 40,036 | 13,129 | 2,597 | 2,246 | 4,860 | 17,204 | 2,124 | 1,355 | 769 | 276,416 |
| 1999 | 42,332 | 40,177 | 13,237 | 2,619 | 2,260 | 4,860 | 17,202 | 2,155 | 1,368 | 787 | 276,871 |
| 2000 | 42,487 | 40,299 | 13,341 | 2,639 | 2,273 | 4,856 | 17,190 | 2,187 | 1,382 | 805 | 277,214 |
| 2001 | 42,635 | 40,417 | 13,443 | 2,660 | 2,286 | 4,851 | 17,178 | 2,218 | 1,395 | 823 | 277,504 |
| 2002 | 42,812 | 40,568 | 13,555 | 2,682 | 2,300 | 4,850 | 17,181 | 2,244 | 1,404 | 840 | 277,862 |
| 2003 | 43,024 | 40,753 | 13,669 | 2,704 | 2,314 | 4,857 | 17,209 | 2,271 | 1,413 | 857 | 278,367 |
| 2004 | 43,265 | 40,969 | 13,790 | 2,728 | 2,328 | 4,867 | 17,255 | 2,296 | 1,423 | 873 | 279,050 |
| 2005 | 43,517 | 41,192 | 13,912 | 2,752 | 2,342 | 4,880 | 17,306 | 2,325 | 1,436 | 890 | 279,781 |
| 2006 | 43,764 | 41,410 | 14,031 | 2,775 | 2,354 | 4,893 | 17,356 | 2,354 | 1,448 | 906 | 280,490 |
| 2007 | 44,002 | 41,618 | 14,146 | 2,798 | 2,368 | 4,908 | 17,399 | 2,383 | 1,460 | 923 | 281,090 |
| 2008 | 44,236 | 41,825 | 14,256 | 2,820 | 2,383 | 4,923 | 17,444 | 2,411 | 1,471 | 941 | 281,694 |
| 2009 | 44,463 | 42,031 | 14,366 | 2,842 | 2,397 | 4,937 | 17,489 | 2,432 | 1,474 | 958 | 282,300 |
| 2010 | 44,684 | 42,238 | 14,476 | 2,863 | 2,411 | 4,952 | 17,535 | 2,447 | 1,472 | 974 | 282,905 |
| 2011 | 44,907 | 42,444 | 14,586 | 2,885 | 2,426 | 4,967 | 17,580 | 2,463 | 1,472 | 991 | 283,510 |
| 2012 | 45,135 | 42,652 | 14,696 | 2,907 | 2,441 | 4,982 | 17,625 | 2,483 | 1,475 | 1,008 | 284,115 |

Table A-235: State-level forest area, carbon stock, and net annual stock change. Estimates are forest ecosystem carbon and do not include harvested wood

| State | Mean year of field data collection | Forest area (1000 ha) | Nonsoil C stock (Tg C) | Mean net annual nonsoil stock change 2002–2011 (Tg C/yr) |
|---|---|---|---|---|
| Alabama | 2008 | 9,258 | 674 | (6.5) |
| Alaska | 2007 | 6,176 | 993 | (5.8) |
| Arizona | 2006 | 7,572 | 396 | 0.5 |
| Arkansas | 2009 | 7,590 | 572 | (4.2) |
| California | 2006 | 13,288 | 1,772 | (6.3) |
| Colorado | 2006 | 9,294 | 754 | (1.5) |
| Connecticut | 2010 | 693 | 83 | (0.8) |
| Delaware | 2008 | 138 | 15 | (0.2) |
| Florida | 2008 | 7,018 | 445 | (2.8) |
| Georgia | 2009 | 10,023 | 732 | (6.0) |
| Idaho | 2007 | 8,656 | 923 | 0.5 |
| Illinois | 2009 | 1,962 | 164 | (2.9) |
| Indiana | 2009 | 1,955 | 182 | (2.5) |
| Iowa | 2009 | 1,220 | 88 | (1.7) |
| Kansas | 2010 | 1,013 | 62 | (1.3) |
| Kentucky | 2010 | 5,047 | 444 | (4.3) |
| Louisiana | 2006 | 5,884 | 423 | (2.7) |
| Maine | 2010 | 7,147 | 615 | (2.4) |
| Maryland | 2009 | 1,004 | 119 | (1.4) |
| Massachusetts | 2010 | 1,224 | 146 | (1.3) |
| Michigan | 2009 | 8,145 | 684 | (6.7) |
| Minnesota | 2009 | 7,030 | 441 | (4.7) |
| Mississippi | 2008 | 7,908 | 569 | (7.9) |
| Missouri | 2009 | 6,261 | 460 | (6.5) |
| Montana | 2007 | 10,356 | 992 | (8.4) |
| Nebraska | 2009 | 638 | 38 | (1.0) |
| Nevada | 2005 | 4,520 | 193 | (1.2) |
| New Hampshire | 2010 | 1,956 | 218 | (1.4) |
| New Jersey | 2009 | 794 | 76 | (0.7) |
| New Mexico | 1994 | 6,753 | 385 | (0.4) |
| New York | 2009 | 7,634 | 841 | (7.4) |
| North Carolina | 2008 | 7,522 | 661 | (3.4) |
| North Dakota | 2010 | 308 | 15 | (0.1) |
| Ohio | 2010 | 3,273 | 329 | (4.2) |
| Oklahoma | 2010 | 5,118 | 237 | (1.4) |
| Oregon | 2006 | 12,139 | 1,748 | (3.7) |
| Pennsylvania | 2009 | 6,784 | 734 | (7.0) |
| Rhode Island | 2010 | 145 | 16 | (0.3) |
| South Carolina | 2009 | 5,310 | 418 | (5.8) |
| South Dakota | 2009 | 773 | 42 | (0.6) |
| Tennessee | 2010 | 5,642 | 572 | (4.4) |
| Texas | 2008 | 25,248 | 896 | (1.4) |
| Utah | 2005 | 7,396 | 428 | (4.6) |
| Vermont | 2010 | 1,858 | 221 | (1.4) |
| Virginia | 2010 | 6,437 | 616 | (4.7) |
| Washington | 2007 | 9,060 | 1,574 | (6.8) |
| West Virginia | 2010 | 4,919 | 547 | (7.6) |
| Wisconsin | 2009 | 6,872 | 501 | (5.7) |
| Wyoming | 2001 | 4,633 | 413 | (1.1) |

Table A-236 shows average C density values for forest ecosystem C pools according to region and forest types based on forest lands in this Inventory. These values were calculated by applying plot-level C estimation procedures as

described below to the most recent inventory per state as available 20 August 2012 (USDA Forest Service 2012b). C density values reflect the most recent survey for each state as available in the FIADB, not potential maximum C storage. C densities are affected by the distribution of stand sizes within a forest type, which can range from regenerating to mature stands. A large proportion of young stands in a particular forest type are likely to reduce the regional average for C density.

Table A-236: Average carbon density (Mg C/ha) by carbon pool and forest area (1000 ha) according to region and forest type, based on the most recent inventory survey available for each state from FIA, corresponding to an average year of 2008

| Region (States) Forest Types | Above-ground Biomass | Below-ground Biomass | Dead Wood | Litter | Soil Organic Carbon | Forest Area |
|---|---|---|---|---|---|---|
| | Carbon Density (Mg C/ha) | | | | | (1,000 ha) |
| **Northeast** | | | | | | |
| (CT,DE,MA,MD,ME,NH,NJ,NY,OH,PA,RI,VT,WV) | | | | | | |
| White/Red/Jack Pine | 78.1 | 16.1 | 6.8 | 13.8 | 78.1 | 1,645 |
| Spruce/Fir | 39.1 | 8.2 | 7.4 | 30.7 | 98.0 | 3,046 |
| Oak/Pine | 70.8 | 14.0 | 5.6 | 27.9 | 66.9 | 1,203 |
| Oak/Hickory | 77.9 | 14.7 | 6.3 | 8.2 | 53.1 | 13,053 |
| Elm/Ash/Cottonwood | 55.3 | 10.4 | 5.4 | 7.1 | 111.7 | 1,467 |
| Maple/Beech/Birch | 70.9 | 13.6 | 6.7 | 27.3 | 69.6 | 13,710 |
| Aspen/Birch | 41.5 | 8.1 | 5.8 | 8.6 | 87.4 | 1,591 |
| Minor Types and Nonstocked | 45.4 | 8.9 | 5.7 | 11.0 | 73.8 | 1,854 |
| All | 67.9 | 13.1 | 6.4 | 18.0 | 69.0 | 37,569 |
| **Northern Lake States** | | | | | | |
| (MI,MN,WI) | | | | | | |
| White/Red/Jack Pine | 45.9 | 9.6 | 5.5 | 12.4 | 120.8 | 1,872 |
| Spruce/Fir | 29.1 | 6.1 | 5.4 | 33.3 | 261.8 | 3,172 |
| Oak/Hickory | 54.2 | 10.2 | 7.0 | 8.0 | 97.1 | 3,978 |
| Elm/Ash/Cottonwood | 42.0 | 8.0 | 5.2 | 7.6 | 179.9 | 2,248 |
| Maple/Beech/Birch | 58.6 | 11.2 | 6.5 | 27.7 | 134.3 | 4,418 |
| Aspen/Birch | 31.6 | 6.1 | 6.0 | 8.3 | 146.1 | 5,201 |
| Minor Types and Nonstocked | 28.5 | 5.6 | 6.0 | 17.8 | 121.0 | 1,157 |
| All | 42.8 | 8.3 | 6.1 | 16.5 | 151.5 | 22,046 |
| **Northern Prairie States** | | | | | | |
| (IA,IL,IN,KS,MO,ND,NE,SD) | | | | | | |
| Ponderosa Pine | 33.1 | 6.9 | 4.2 | 14.4 | 48.5 | 556 |
| Oak/Pine | 39.9 | 7.7 | 4.3 | 25.9 | 40.8 | 566 |
| Oak/Hickory | 52.8 | 9.9 | 5.8 | 7.9 | 49.6 | 9,548 |
| Elm/Ash/Cottonwood | 55.4 | 10.3 | 6.3 | 6.9 | 83.1 | 2,057 |
| Minor Types and Nonstocked | 30.7 | 6.0 | 5.0 | 17.7 | 60.3 | 1,401 |
| All | 49.7 | 9.4 | 5.7 | 9.7 | 55.2 | 14,129 |
| **South Central** | | | | | | |
| (AL,AR,KY,LA,MS,OK,TN,TX) | | | | | | |
| Loblolly/Shortleaf Pine | 48.2 | 9.9 | 7.4 | 9.6 | 41.9 | 13,638 |
| Pinyon/Juniper | 12.1 | 2.3 | 4.0 | 12.2 | 37.7 | 4,030 |
| Oak/Pine | 44.2 | 8.6 | 6.5 | 9.3 | 41.7 | 5,140 |
| Oak/Hickory | 47.9 | 9.0 | 7.4 | 6.4 | 38.6 | 25,210 |
| Oak/Gum/Cypress | 64.2 | 12.2 | 7.5 | 6.5 | 52.8 | 5,196 |
| Elm/Ash/Cottonwood | 38.6 | 7.2 | 6.1 | 5.9 | 49.9 | 4,049 |
| Woodland Hardwoods | 9.6 | 1.5 | 1.9 | 5.0 | 65.0 | 9,457 |
| Minor Types and Nonstocked | 27.8 | 5.4 | 6.6 | 6.7 | 54.3 | 4,975 |
| All | 39.9 | 7.6 | 6.3 | 7.4 | 45.6 | 71,694 |
| **Southeast** | | | | | | |
| (FL,GA,NC,SC,VA) | | | | | | |
| Longleaf/Slash Pine | 40.7 | 8.4 | 5.0 | 9.9 | 110.0 | 4,175 |
| Loblolly/Shortleaf Pine | 52.4 | 10.8 | 4.3 | 9.7 | 72.9 | 9,261 |
| Oak/Pine | 50.5 | 9.9 | 4.0 | 9.4 | 61.4 | 4,095 |
| Oak/Hickory | 64.6 | 12.2 | 5.3 | 6.5 | 45.3 | 11,803 |
| Oak/Gum/Cypress | 64.0 | 12.4 | 5.4 | 6.5 | 158.0 | 4,648 |
| Elm/Ash/Cottonwood | 48.7 | 9.2 | 3.9 | 5.6 | 95.7 | 884 |
| Minor Types and Nonstocked | 32.1 | 6.1 | 7.1 | 5.8 | 110.6 | 1,445 |
| All | 55.4 | 10.9 | 4.9 | 8.0 | 79.8 | 36,311 |
| **Coastal Alaska** | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| (approximately 12 percent of forest land in Alaska) | | | | | | |
| Spruce/Fir | 14.0 | 2.7 | 7.8 | 33.6 | 62.1 | 402 |
| Fir/Spruce/Mountain Hemlock | 63.0 | 13.2 | 16.6 | 43.1 | 62.1 | 2,252 |
| Hemlock/Sitka Spruce | 116.7 | 24.6 | 27.4 | 50.5 | 116.3 | 2,843 |
| Aspen/Birch | 27.5 | 5.1 | 8.3 | 10.7 | 42.5 | 284 |
| Minor Types and Nonstocked | 30.1 | 5.8 | 7.3 | 22.5 | 75.0 | 395 |
| All | 80.8 | 16.9 | 20.0 | 43.1 | 87.0 | 6,176 |
| **Pacific Northwest, Westside** | | | | | | |
| (Western OR and WA) | | | | | | |
| Douglas-fir | 139.1 | 29.2 | 29.2 | 32.2 | 94.8 | 5,944 |
| Fir/Spruce/Mountain Hemlock | 128.2 | 27.0 | 30.2 | 38.4 | 62.1 | 1,184 |
| Hemlock/Sitka Spruce | 168.7 | 35.6 | 36.7 | 37.8 | 116.3 | 1,575 |
| Alder/Maple | 77.5 | 15.1 | 15.9 | 7.6 | 115.2 | 1,175 |
| Minor Types and Nonstocked | 56.0 | 11.0 | 16.0 | 13.2 | 85.6 | 1,237 |
| All | 126.4 | 26.3 | 27.5 | 28.9 | 95.5 | 11,115 |
| **Pacific Northwest, Eastside** | | | | | | |
| (Eastern OR and WA) | | | | | | |
| Douglas-fir | 62.6 | 13.0 | 16.7 | 36.3 | 94.8 | 2,047 |
| Ponderosa Pine | 40.8 | 8.4 | 9.3 | 22.5 | 50.7 | 2,793 |
| Fir/Spruce/Mountain Hemlock | 74.4 | 15.7 | 23.9 | 37.9 | 62.1 | 1,772 |
| Lodgepole Pine | 36.4 | 7.6 | 11.9 | 21.1 | 52.0 | 1,018 |
| Western Larch | 68.5 | 14.3 | 18.6 | 36.0 | 45.1 | 204 |
| Other Western Softwoods | 11.7 | 2.2 | 3.3 | 36.2 | 78.8 | 1,200 |
| Minor Types and Nonstocked | 27.6 | 5.4 | 14.5 | 24.3 | 80.9 | 1,049 |
| All | 46.4 | 9.6 | 13.6 | 30.0 | 68.2 | 10,083 |
| **Pacific Southwest** | | | | | | |
| (CA) | | | | | | |
| Pinyon/Juniper | 13.5 | 2.5 | 2.2 | 21.1 | 26.3 | 752 |
| Douglas-fir | 143.0 | 29.6 | 20.7 | 35.5 | 40.1 | 441 |
| Ponderosa Pine | 52.4 | 10.8 | 9.2 | 22.3 | 41.3 | 914 |
| Fir/Spruce/Mountain Hemlock | 110.4 | 23.3 | 27.3 | 38.3 | 51.9 | 819 |
| Redwood | 238.6 | 49.8 | 28.0 | 60.5 | 53.8 | 291 |
| Other Western Softwoods | 22.7 | 4.3 | 5.1 | 37.6 | 49.8 | 818 |
| California Mixed Conifer | 104.7 | 21.9 | 19.2 | 37.9 | 49.8 | 3,157 |
| Western Oak | 49.3 | 9.3 | 4.7 | 29.8 | 27.6 | 3,812 |
| Tanoak/Laurel | 122.2 | 24.0 | 10.6 | 28.1 | 27.6 | 827 |
| Minor Types and Nonstocked | 46.5 | 9.3 | 14.1 | 25.6 | 37.1 | 1,457 |
| All | 74.3 | 15.1 | 12.2 | 32.0 | 38.6 | 13,288 |
| **Rocky Mountain, North** | | | | | | |
| (ID,MT) | | | | | | |
| Douglas-fir | 51.5 | 10.8 | 12.5 | 37.0 | 38.8 | 5,587 |
| Ponderosa Pine | 31.2 | 6.4 | 7.9 | 22.9 | 34.3 | 1,865 |
| Fir/Spruce/Mountain Hemlock | 54.2 | 11.4 | 21.0 | 37.4 | 44.1 | 4,471 |
| Lodgepole Pine | 47.0 | 10.0 | 15.7 | 23.1 | 37.2 | 2,761 |
| Western Larch | 67.3 | 14.2 | 15.5 | 36.3 | 34.2 | 492 |
| Other Western Softwoods | 29.9 | 6.2 | 12.2 | 39.3 | 31.4 | 649 |
| Aspen/Birch | 23.0 | 4.3 | 14.6 | 26.8 | 56.6 | 533 |
| Minor Types and Nonstocked | 24.1 | 4.8 | 18.4 | 22.5 | 42.9 | 2,655 |
| All | 44.5 | 9.3 | 15.4 | 31.4 | 40.1 | 19,012 |
| **Rocky Mountain, South** | | | | | | |
| (AZ,CO,NM,NV,UT,WY) | | | | | | |
| Pinyon/Juniper | 15.6 | 3.1 | 1.8 | 21.1 | 19.7 | 18,738 |
| Douglas-fir | 49.7 | 10.5 | 12.2 | 38.1 | 30.9 | 1,797 |
| Ponderosa Pine | 35.5 | 7.4 | 7.2 | 23.6 | 24.1 | 3,570 |
| Fir/Spruce/Mountain Hemlock | 56.8 | 12.0 | 18.6 | 38.8 | 31.5 | 4,262 |
| Lodgepole Pine | 47.9 | 10.2 | 17.9 | 24.0 | 27.0 | 2,024 |
| Aspen/Birch | 40.7 | 7.7 | 10.2 | 28.5 | 58.8 | 2,555 |
| Woodland Hardwoods | 16.7 | 3.0 | 5.2 | 28.2 | 25.9 | 4,135 |
| Minor Types and Nonstocked | 12.9 | 2.4 | 9.1 | 22.6 | 25.4 | 3,088 |
| All | 26.4 | 5.3 | 6.8 | 25.4 | 25.8 | 40,168 |
| **United States (forest land included in Inventory)** | **50.9** | **10.1** | **8.4** | **17.5** | **62.1** | **281,591** |

Note: The forest area values in this table do not equal the forest area values reported in Table A-234, because the forest area values in this table are estimated using the most recent dataset per state, with an average year of 2008. The time series of forest area values reported in Table A-234, in contrast, is constructed following the CCT methods used to construct the carbon stock series. The forest area values reported in Table A-234 and Table A-236 would only be identical if all states were measured simultaneously or they all had identical rates of change.

The Inventory is derived primarily from the current FIADB 5.1 data (USDA Forest Service 2012b), but it also draws on older FIA survey data where necessary. The Resources Planning Act Assessment (RPA) database, which includes periodic summaries of state inventories, is one example. Information about the RPA data is available on the Internet (USDA Forest Service 2012a), and compilations of analytical estimates based on these databases are found in Waddell et al. (1989) and Smith et al. (2001). The basic difference between the RPA database and the FIADB is that the FIADB includes some informative additional details such as individual-tree data. Having only plot-level information (such as volume per hectare) limits the conversion to biomass. This does not constitute a substantial difference for the overall state-wide estimates, but it does affect plot-level precision (Smith et al. 2004). In the past, FIA made their data available in tree-level Eastwide (Hansen et al. 1992) or Westwide (Woudenberg and Farrenkopf 1995) formats, which included inventories for Eastern and Western states, respectively. The current Inventory estimates rely in part on older tree-level data that are not available on the current FIADB site. The Integrated Database (IDB) is a compilation of periodic forest inventory data from the 1990s for California, Oregon, and Washington (Waddell and Hiserote 2005). These data were identified by Heath et al. (2011) as the most appropriate non-FIADB sources for these three states.

An historical focus of the FIA program was to provide information on timber resources of the United States. For this reason, prior to 1998, some forest land, which were less productive or reserved (i.e., land where harvesting was prohibited by law), were less intensively surveyed. This generally meant that on these less productive lands, forest type and area were identified but data were not collected on individual tree measurements. The practical effect that this evolution in inventories has had on estimating forest C stocks from 1990 through the present is that some older surveys of lands do not have the individual-tree data or even stand-level characteristics such as stand age. Any data gaps identified in the surveys taken before 1998 were filled by assigning average C densities calculated from the more complete, later inventories from the respective states. The overall effect of this necessary approach to generate estimates for C stock is that no net change in C density occurs on those lands with gaps in past surveys. This approach to filling gaps in older data also extends to timberlands where individual-tree data as not available (e.g., standing dead trees).

#### *Estimating C stocks from forest inventory data*

For each inventory summary in each state, data are converted to C units or augmented by other ecological data. Most of the conversion factors and models used for inventory-based forest carbon estimates (Smith et al. 2010, Heath et al. 2011) were intitially developed as an offshoot of the forest carbon simulation model FORCARB (Heath et al. 2010) and are incorporated into a number of applications (Birdsey and Heath 1995, Birdsey and Heath 2001, Heath et al. 2003, Smith et al. 2004, Hoover and Rebain 2008). The conversion factors and model coefficients are usually categorized by region, and forest type. Classifications for both region and forest type are subject to change depending on the particular coefficient set. Thus, region and type are specifically defined for each set of estimates. Factors are applied to the survey data at the scale of FIA inventory plots. The results are estimates of C density (Mg per hectare) for the various forest pools. C density for live trees, standing dead trees, understory vegetation, down dead wood, litter, and soil organic matter are estimated. All non-soil pools except litter can be separated into aboveground and belowground components. The live tree and understory C pools are pooled as biomass in this inventory. Similarly, standing dead trees and down dead wood are pooled as dead wood in this inventory. C stocks and fluxes for *Forest Land Remaining Forest Land* are reported in pools following IPCC (2003).

#### *Live tree C pools*

Live tree C pools include aboveground and belowground (coarse root) biomass of live trees with diameter at diameter breast height (d.b.h.) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates are made for above- and below-ground biomass components. If inventory plots include data on individual trees, tree C is based on Woodall et al. (2011), which is also known as the component ratio method (CRM), and is a function of volume, species, and diameter. The value for sound volume provided in the tree table of the FIADB is the principal input to the CRM biomass calculation for each tree. The estimated volumes of wood and bark are converted to biomass based on density of each. Additional components of the trees such as tops, branches, and coarse roots, are estimated according to adjusted component estimates of Jenkins et al. (2003). Live trees with d.b.h of less than 12.7 cm do not have estimates of sound volume in the FIADB, and CRM biomass estimates follow a separate process. An additional component of foliage, which was not explicitly included in Woodall et al. (2011), was added to each tree following the same CRM method. C is calculated by

multiplying biomass by 0.5 because biomass is 50 percent of dry weight (IPCC/UNEP/OECD/IEA 1997). Further discussion and example calculations are provided in Woodall et al. 2011.

Some of the older forest inventory data in use for these estimates do not provide measurements of individual trees. Examples of these data include plots with incomplete or missing tree data (e.g., some of the non-timberland plots in older surveys) or the RPA plot-level summaries. The C estimates for these plots are based on average densities (metric tons C per hectare) obtained from plots of more recent surveys with similar stand characteristics and location. This applies to 5 percent of the forest land inventory-plot-to-carbon conversions within the 183 state-level surveys utilized here.

***Understory vegetation***

Understory vegetation is a minor component of biomass. Understory vegetation is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than one-inch d.b.h. In this inventory, it is assumed that 10 percent of understory C mass is belowground. This general root-to-shoot ratio (0.11) is near the lower range of temperate forest values provided in IPCC (2006) and was selected based on two general assumptions: ratios are likely to be lower for light-limited understory vegetation as compared with larger trees, and a greater proportion of all root mass will be less than 2 mm diameter.

Estimates of C density are based on information in Birdsey (1996), which was applied to FIA permanent plots. These were fit to the equation:

$$\text{Ratio} = e^{(A - B \times \ln(\text{live tree C density}))}$$

In this equation, "ratio" is the ratio of understory C density (Mg C/ha) to live tree C density (above- and below-ground) according to Jenkins et al. (2003) and expressed in Mg C/ha. An additional coefficient is provided as a maximum ratio; that is, any estimate predicted from the equation that is greater than the maximum ratio is set equal to the maximum ratio. A full set of coefficients is in Table A-237. Regions and forest types are the same classifications described in Smith et al. (2003). As an example, the basic calculation for understory C in aspen-birch forests in the Northeast is:

$$\text{Understory (Mg C/ha)} = (\text{live tree C density}) \times e^{(0.855 - 1.03 \times \ln(\text{tree C density}))}$$

This calculation is followed by three possible modifications. First, the maximum value for the ratio is set to 2.02 (see value in column "maximum ratio"); this also applies to stands with zero tree C, which is undefined in the above equation. Second, the minimum ratio is set to 0.005 (Birdsey 1996). Third, nonstocked and pinyon/juniper stands are set to coefficient A, which is a C density (Mg C/ha) for these types only.

Table A-237: Coefficients for estimating the ratio of carbon density of understory vegetation (above- and belowground, MgC/ha)[a] by region and forest type. The ratio is multiplied by tree carbon density on each plot to produce understory vegetation

| Region[b] | Forest Type[b] | A | B | Maximum ratio[c] |
|---|---|---|---|---|
| NE | Aspen-Birch | 0.855 | 1.032 | 2.023 |
| | MBB/Other Hardwood | 0.892 | 1.079 | 2.076 |
| | Oak-Hickory | 0.842 | 1.053 | 2.057 |
| | Oak-Pine | 1.960 | 1.235 | 4.203 |
| | Other Pine | 2.149 | 1.268 | 4.191 |
| | Spruce-Fir | 0.825 | 1.121 | 2.140 |
| | White-Red-Jack Pine | 1.000 | 1.116 | 2.098 |
| | Nonstocked | 2.020 | 2.020 | 2.060 |
| NLS | Aspen-Birch | 0.777 | 1.018 | 2.023 |
| | Lowland Hardwood | 0.650 | 0.997 | 2.037 |
| | Maple-Beech-Birch | 0.863 | 1.120 | 2.129 |
| | Oak-Hickory | 0.965 | 1.091 | 2.072 |
| | Pine | 0.740 | 1.014 | 2.046 |
| | Spruce-Fir | 1.656 | 1.318 | 2.136 |
| | Nonstocked | 1.928 | 1.928 | 2.117 |
| NPS | Conifer | 1.189 | 1.190 | 2.114 |
| | Lowland Hardwood | 1.370 | 1.177 | 2.055 |
| | Maple-Beech-Birch | 1.126 | 1.201 | 2.130 |
| | Oak-Hickory | 1.139 | 1.138 | 2.072 |
| | Oak-Pine | 2.014 | 1.215 | 4.185 |
| | Nonstocked | 2.052 | 2.052 | 2.072 |
| PSW | Douglas-fir | 2.084 | 1.201 | 4.626 |

| | | | | |
|---|---|---|---|---|
| | Fir-Spruce | 1.983 | 1.268 | 4.806 |
| | Hardwoods | 1.571 | 1.038 | 4.745 |
| | Other Conifer | 4.032 | 1.785 | 4.768 |
| | Pinyon-Juniper | 4.430 | 4.430 | 4.820 |
| | Redwood | 2.513 | 1.312 | 4.698 |
| | Nonstocked | 4.431 | 4.431 | 4.626 |
| PWE | Douglas-fir | 1.544 | 1.064 | 4.626 |
| | Fir-Spruce | 1.583 | 1.156 | 4.806 |
| | Hardwoods | 1.900 | 1.133 | 4.745 |
| | Lodgepole Pine | 1.790 | 1.257 | 4.823 |
| | Pinyon-Juniper | 2.708 | 2.708 | 4.820 |
| | Ponderosa Pine | 1.768 | 1.213 | 4.768 |
| | Nonstocked | 4.315 | 4.315 | 4.626 |
| PWW | Douglas-fir | 1.727 | 1.108 | 4.609 |
| | Fir-Spruce | 1.770 | 1.164 | 4.807 |
| | Other Conifer | 2.874 | 1.534 | 4.768 |
| | Other Hardwoods | 2.157 | 1.220 | 4.745 |
| | Red Alder | 2.094 | 1.230 | 4.745 |
| | Western Hemlock | 2.081 | 1.218 | 4.693 |
| | Nonstocked | 4.401 | 4.401 | 4.589 |
| RMN | Douglas-fir | 2.342 | 1.360 | 4.731 |
| | Fir-Spruce | 2.129 | 1.315 | 4.749 |
| | Hardwoods | 1.860 | 1.110 | 4.745 |
| | Lodgepole Pine | 2.571 | 1.500 | 4.773 |
| | Other Conifer | 2.614 | 1.518 | 4.821 |
| | Pinyon-Juniper | 2.708 | 2.708 | 4.820 |
| | Ponderosa Pine | 2.099 | 1.344 | 4.776 |
| | Nonstocked | 4.430 | 4.430 | 4.773 |
| RMS | Douglas-fir | 5.145 | 2.232 | 4.829 |
| | Fir-Spruce | 2.861 | 1.568 | 4.822 |
| | Hardwoods | 1.858 | 1.110 | 4.745 |
| | Lodgepole Pine | 3.305 | 1.737 | 4.797 |
| | Other Conifer | 2.134 | 1.382 | 4.821 |
| | Pinyon-Juniper | 2.757 | 2.757 | 4.820 |
| | Ponderosa Pine | 3.214 | 1.732 | 4.820 |
| | Nonstocked | 4.243 | 4.243 | 4.797 |
| SC | Bottomland Hardwood | 0.917 | 1.109 | 1.842 |
| | Misc. Conifer | 1.601 | 1.129 | 4.191 |
| | Natural Pine | 2.166 | 1.260 | 4.161 |
| | Oak-Pine | 1.903 | 1.190 | 4.173 |
| | Planted Pine | 1.489 | 1.037 | 4.124 |
| | Upland Hardwood | 2.089 | 1.235 | 4.170 |
| | Nonstocked | 4.044 | 4.044 | 4.170 |
| SE | Bottomland Hardwood | 0.834 | 1.089 | 1.842 |
| | Misc. Conifer | 1.601 | 1.129 | 4.191 |
| | Natural Pine | 1.752 | 1.155 | 4.178 |
| | Oak-Pine | 1.642 | 1.117 | 4.195 |
| | Planted Pine | 1.470 | 1.036 | 4.141 |
| | Upland Hardwood | 1.903 | 1.191 | 4.182 |
| | Nonstocked | 4.033 | 4.033 | 4.182 |

[a]Prediction of ratio of understory C to live tree C is based on the equation: Ratio=exp(A − B × ln(tree_carbon_tph)), where "ratio" is the ratio of understory C density to live tree (above-and below- ground) C density, and "tree_carbon_density" is live tree (above-and below- ground) C density in Mg C/ha.
[b] Regions and types as defined in Smith et al. (2003).
[c]Maximum ratio: any estimate predicted from the equation that is greater than the maximum ratio is set equal to the maximum ratio.

### *Dead Wood*

The standing dead tree C pools include aboveground and belowground (coarse root) mass and includes trees of at least 12.7 cm d.b.h. Calculations follow the basic CRM method applied to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss. In addition to the lack of foliage, two characteristics of standing dead trees that can significantly affect C mass are decay, which affects density and thus specific C content (Domke et al. 2011, Harmon et al. 2011), and structural loss such as branches and bark (Domke et al. 2011). Dry weight to C mass conversion is by multiplying by 0.5.

Some of the older forest inventory data in use for these estimates do not provide measurements of individual standing dead trees. In addition to the RPA data, which are plot-level summaries, some of the older surveys that otherwise include individual-tree data may not completely sample dead trees on non-timberlands and in some cases timberlands. The C estimates for these plots are based on average densities (metric tons C per hectare) obtained from plots of more recent surveys with similar stand characteristics and location. This applies to 25 percent of the forest land inventory-plot-to-carbon conversions within the 183 state-level surveys utilized here.

Down dead wood, inclusive of logging residue, are sampled on a subset of FIA plots. Despite a reduced sample intensity, a single down woody material population estimate (Domke et al. , Woodall et al. 2010, Woodall et al. In Review) per state is now incorporated into these empirical down dead wood estimates. Down dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. Down dead wood includes stumps and roots of harvested trees. Ratio estimates of down dead wood to live tree biomass were developed using FORCARB2 simulations and applied at the plot level (Smith et al. 2004). Estimates for down dead wood correspond to the region and forest type classifications described in Smith et al. (2003). A full set of ratios is provided in Table A-225. An additional component of down dead wood is a regional average estimate of logging residue based on Smith et al. (2006) applied at the plot level. These are based on a regional average C density at age zero and first order decay; initial densities and decay coefficients are provided in Table A-226. These amounts are added to explicitly account for down dead wood following harvest. The sum of these two components are then adjusted by the ratio of population totals; that is, the ratio of plot-based to modeled estimates. An example of this 3-part calculation for down dead wood in a 25-year-old naturally regenerated loblolly pine forest with 82.99 Mg C/ha in live trees (Jenkins et al. 2003) in Louisianais as follows:

First, an initial estimate from live tree C density and Table A-225 (SC, Natural Pine)

C density =82.99 × 0.068 = 5.67 (Mg C/ha)

Second, an average logging residue from age and Table A-226 (SC, softwood)C density = $5.5 \times e^{(-25/17.9)}$ = 1.37 (Mg C/ha)

Third, adjust the sum by the down dead wood ratio plot-to-model for Louisiana, which was 27.6/31.1 = 0.886

C density = (5.67 + 1.37) × 0.886 = 6.24 (Mg C/ha)

Table A-238: Ratio for estimating down dead wood by region and forest type. The ratio is multiplied by the live tree carbon density on a plot to produce down dead wood carbon density (MgC/ha)

| Region[a] | Forest type[a] | Ratio | Region (cont'd) | Forest type (cont'd) | Ratio (cont'd) |
|---|---|---|---|---|---|
| NE | Aspen-Birch | 0.078 | PWW | Douglas-fir | 0.100 |
| | MBB/Other Hardwood | 0.071 | | Fir-Spruce | 0.090 |
| | Oak-Hickory | 0.068 | | Other Conifer | 0.073 |
| | Oak-Pine | 0.061 | | Other Hardwoods | 0.062 |
| | Other Pine | 0.065 | | Red Alder | 0.095 |
| | Spruce-Fir | 0.092 | | Western Hemlock | 0.099 |
| | White-Red-Jack Pine | 0.055 | | Nonstocked | 0.020 |
| | Nonstocked | 0.019 | RMN | Douglas-fir | 0.062 |
| NLS | Aspen-Birch | 0.081 | | Fir-Spruce | 0.100 |
| | Lowland Hardwood | 0.061 | | Hardwoods | 0.112 |
| | Maple-Beech-Birch | 0.076 | | Lodgepole Pine | 0.058 |
| | Oak-Hickory | 0.077 | | Other Conifer | 0.060 |
| | Pine | 0.072 | | Pinyon-Juniper | 0.030 |
| | Spruce-Fir | 0.087 | | Ponderosa Pine | 0.087 |
| | Nonstocked | 0.027 | | Nonstocked | 0.018 |
| NPS | Conifer | 0.073 | RMS | Douglas-fir | 0.077 |
| | Lowland Hardwood | 0.069 | | Fir-Spruce | 0.079 |
| | Maple-Beech-Birch | 0.063 | | Hardwoods | 0.064 |
| | Oak-Hickory | 0.068 | | Lodgepole Pine | 0.098 |
| | Oak-Pine | 0.069 | | Other Conifer | 0.060 |
| | Nonstocked | 0.026 | | Pinyon-Juniper | 0.030 |
| PSW | Douglas-fir | 0.091 | | Ponderosa Pine | 0.082 |
| | Fir-Spruce | 0.109 | | Nonstocked | 0.020 |

| | | |
|---|---|---|
| | Hardwoods | 0.042 |
| | Other Conifer | 0.100 |
| | Pinyon-Juniper | 0.031 |
| | Redwood | 0.108 |
| | Nonstocked | 0.022 |
| PWE | Douglas-fir | 0.103 |
| | Fir-Spruce | 0.106 |
| | Hardwoods | 0.027 |
| | Lodgepole Pine | 0.093 |
| | Pinyon-Juniper | 0.032 |
| | Ponderosa Pine | 0.103 |
| | Nonstocked | 0.024 |
| SC | Bottomland Hardwood | 0.063 |
| | Misc. Conifer | 0.068 |
| | Natural Pine | 0.068 |
| | Oak-Pine | 0.072 |
| | Planted Pine | 0.077 |
| | Upland Hardwood | 0.067 |
| | Nonstocked | 0.013 |
| SE | Bottomland Hardwood | 0.064 |
| | Misc. Conifer | 0.081 |
| | Natural Pine | 0.081 |
| | Oak-Pine | 0.063 |
| | Planted Pine | 0.075 |
| | Upland Hardwood | 0.059 |
| | Nonstocked | 0.012 |

[a] Regions and types as defined in Smith et al. (2003).

Table A-239: Coefficients for estimating logging residue component of down dead wood.

| Region[a] | Forest Type Group[b] (softwood/hardwood) | Initial Carbon Density (Mg/ha) | Decay Coefficient |
|---|---|---|---|
| Alaska | hardwood | 6.9 | 12.1 |
| Alaska | softwood | 8.6 | 32.3 |
| NE | hardwood | 13.9 | 12.1 |
| NE | softwood | 12.1 | 17.9 |
| NLS | hardwood | 9.1 | 12.1 |
| NLS | softwood | 7.2 | 17.9 |
| NPS | hardwood | 9.6 | 12.1 |
| NPS | softwood | 6.4 | 17.9 |
| PSW | hardwood | 9.8 | 12.1 |
| PSW | softwood | 17.5 | 32.3 |
| PWE | hardwood | 3.3 | 12.1 |
| PWE | softwood | 9.5 | 32.3 |
| PWW | hardwood | 18.1 | 12.1 |
| PWW | softwood | 23.6 | 32.3 |
| RMN | hardwood | 7.2 | 43.5 |
| RMN | softwood | 9.0 | 18.1 |
| RMS | hardwood | 5.1 | 43.5 |
| RMS | softwood | 3.7 | 18.1 |
| SC | hardwood | 4.2 | 8.9 |
| SC | softwood | 5.5 | 17.9 |
| SE | hardwood | 6.4 | 8.9 |
| SE | softwood | 7.3 | 17.9 |

[a] Regions are defined in Smith et al. (2003) with the addition of coastal Alaska.
[b] Forest types are according to majority hardwood or softwood species.

### *Litter carbon*

C of the litter layer is currently sampled on a subset of the FIA plots. However, these data are not yet available electronically for general application to all inventories in Table A-1. Litter C is the pool of organic C (including material known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. Estimates therefore continue to be based on equations of Smith and Heath (2002) and applied at the plot level. The equations describe processes for decay or loss of forest floor following harvest and the net accumulation of new forest floor material following stand growth. For example, total forest floor C at a given number of years after a clearcut harvest for aspen-birch forests in the North is:

$$\text{Total forest floor C (Mg C/ha)} = (18.4 \times \text{years})/(53.7 + \text{years}) + 10.2 \times e^{(-\text{years} \div 9.2)}$$

See Table 4 of Smith and Heath (2002) for the complete set of coefficients. Note that these are direct estimates of C density; the 0.5 conversion does not apply to litter.

#### *Soil organic carbon*

Soil organic carbon (SOC) is currently sampled to a 20 cm depth on subsets of FIA plots, however, these data are not available for the entire United States. Thus, estimates of SOC are based on the national STATSGO spatial database (USDA 1991), and the general approach described by Amichev and Galbraith (2004). In their procedure, SOC was calculated for the conterminous United States using the STATSGO database, and data gaps were filled by representative values from similar soils. Links to region and forest type groups were developed with the assistance of the USDA Forest Service FIA Geospatial Service Center by overlaying FIA forest inventory plots on the soil C map.

### Carbon in Harvested Wood Products

Estimates of the harvested wood product (HWP) contribution to forest C sinks and emissions (hereafter called "HWP Contribution") are based on methods described in Skog (2008) using the WOODCARB II model. These methods are based on IPCC (2006) guidance for estimating HWP carbon. The 2006 IPCC Guidelines provide methods that allow Parties to report HWP Contribution using one of several different accounting approaches: production, stock change, and atmospheric flow, as well as a default method. The various approaches are described below. The approaches differ in how HWP Contribution is allocated based on production or consumption as well as what processes (atmospheric fluxes or stock changes) are emphasized.

- **Production approach**: Accounts for the net changes in carbon stocks in forests and in the wood products pool, but attributes both to the producing country.
- **Stock change approach**: Accounts for changes in the product pool within the boundaries of the consuming country.
- **Atmospheric flow approach**: Accounts for net emissions or removals of carbon to and from the atmosphere within national boundaries. C removal due to forest growth is accounted for in the producing country while C emissions to the atmosphere from oxidation of wood products are accounted for in the consuming country.
- **Default approach**: Assumes no change in C stocks in HWP. IPCC (2006) requests that such an assumption be justified if this is how a Party is choosing to report.

The United States uses the production accounting approach (as in previous years) to report HWP Contribution (Table A-243). Though reported U.S. HWP estimates are based on the production approach, estimates resulting from use of the two alternative approaches—the stock change and atmospheric flow approaches—are also presented for comparison (see Table A-244). Annual estimates of change are calculated by tracking the additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in solid waste disposal sites (SWDS).

Estimates of five HWP variables that can be used to calculate HWP contribution for the stock change and atmospheric flow approaches for imports and exports are provided in Table A-243. The HWP variables estimated are:

(1A) annual change of C in wood and paper products in use in the United States,

(1B) annual change of C in wood and paper products in SWDS in the United States,

(2A) annual change of C in wood and paper products in use in the United States and other countries where the wood came from trees harvested in the United States,

(2B) annual change of C in wood and paper products in SWDS in the United States and other countries where the wood came from trees harvested in the United States,

(3) C in imports of wood, pulp, and paper to the United States,

(4) C in exports of wood, pulp and paper from the United States, and

(5) C in annual harvest of wood from forests in the United States.

Table A-240: Harvested wood products from wood harvested in United States—Annual additions of carbon to stocks and total stocks under the production approach (Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere)

| Year | Net carbon additions per year (Tg C per year) | | | | | | | Total Carbon stocks (Tg C) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Total | Products in use | | | Products in SWDS | | | | | |
| | | Total | Solid wood products | Paper products | Total | Solid wood products | Paper products | Total | Products in use | Products in SWDS |
| 1990 | (35.9) | (17.7) | (14.4) | (3.3) | (18.3) | (9.9) | (8.3) | 1,859 | 1,231 | 628 |
| 1991 | (33.8) | (14.9) | (11.9) | (3.1) | (18.8) | (11.1) | (7.7) | 1,895 | 1,249 | 646 |
| 1992 | (33.8) | (16.3) | (12.6) | (3.7) | (17.4) | (9.5) | (7.9) | 1,929 | 1,264 | 665 |
| 1993 | (32.9) | (15.0) | (12.2) | (2.8) | (17.9) | (9.7) | (8.3) | 1,963 | 1,280 | 683 |
| 1994 | (33.4) | (15.9) | (12.1) | (3.8) | (17.5) | (9.8) | (7.7) | 1,996 | 1,295 | 701 |
| 1995 | (32.3) | (15.1) | (11.2) | (3.8) | (17.2) | (10.7) | (6.5) | 2,029 | 1,311 | 718 |
| 1996 | (30.6) | (14.1) | (11.5) | (2.6) | (16.5) | (10.6) | (6.0) | 2,061 | 1,326 | 735 |
| 1997 | (32.0) | (14.7) | (11.8) | (3.0) | (17.3) | (10.3) | (6.9) | 2,092 | 1,340 | 752 |
| 1998 | (31.1) | (13.4) | (11.4) | (2.0) | (17.7) | (10.2) | (7.5) | 2,124 | 1,355 | 769 |
| 1999 | (32.5) | (14.1) | (12.1) | (2.0) | (18.4) | (10.6) | (7.8) | 2,155 | 1,368 | 787 |
| 2000 | (30.8) | (12.8) | (11.9) | (1.0) | (18.0) | (10.7) | (7.3) | 2,187 | 1,382 | 805 |
| 2001 | (25.5) | (8.7) | (10.1) | 1.4 | (16.8) | (10.7) | (6.0) | 2,218 | 1,395 | 823 |
| 2002 | (26.8) | (9.6) | (10.7) | 1.1 | (17.2) | (11.1) | (6.1) | 2,244 | 1,404 | 840 |
| 2003 | (25.9) | (9.7) | (10.1) | 0.4 | (16.2) | (11.1) | (5.1) | 2,271 | 1,413 | 857 |
| 2004 | (28.7) | (12.4) | (11.6) | (0.8) | (16.3) | (11.3) | (5.0) | 2,296 | 1,423 | 873 |
| 2005 | (28.7) | (12.4) | (11.9) | (0.5) | (16.3) | (11.5) | (4.8) | 2,325 | 1,436 | 890 |
| 2006 | (29.4) | (12.1) | (10.4) | (1.7) | (17.3) | (11.6) | (5.7) | 2,354 | 1,448 | 906 |
| 2007 | (27.9) | (10.5) | (8.5) | (2.0) | (17.4) | (11.7) | (5.7) | 2,383 | 1,460 | 923 |
| 2008 | (20.8) | (3.7) | (2.9) | (0.9) | (17.1) | (11.4) | (5.7) | 2,411 | 1,471 | 941 |
| 2009 | (14.8) | 1.8 | 0.5 | 1.3 | (16.6) | (11.2) | (5.4) | 2,432 | 1,474 | 958 |
| 2010 | (16.2) | 0.3 | 0.2 | 0.2 | (16.5) | (11.3) | (5.3) | 2,447 | 1,472 | 974 |
| 2011 | (19.5) | (2.7) | (2.1) | (0.6) | (16.8) | (11.5) | (5.4) | 2,463 | 1,472 | 991 |
| 2012 | | | | | | | | 2,483 | 1,475 | 1,008 |

Table A-241: Comparison of Net Annual Change in Harvested Wood Products Carbon Stocks Using Alternative Accounting Approaches

| | HWP Contribution to LULUCF Emissions/ removals (Tg $CO_2$ Eq.) | | |
|---|---|---|---|
| Inventory Year | Stock Change Approach | Atmospheric Flow Approach | Production Approach |
| 1990 | (129.6) | (138.4) | (131.8) |
| 1991 | (116.3) | (131.4) | (123.8) |
| 1992 | (120.0) | (131.6) | (123.8) |
| 1993 | (126.8) | (127.8) | (120.7) |
| 1994 | (130.0) | (129.9) | (122.5) |
| 1995 | (126.0) | (128.0) | (118.4) |
| 1996 | (122.3) | (122.5) | (112.2) |
| 1997 | (131.4) | (127.4) | (117.3) |
| 1998 | (139.8) | (122.7) | (114.1) |
| 1999 | (149.4) | (127.3) | (119.1) |
| 2000 | (143.2) | (120.3) | (112.9) |
| 2001 | (128.3) | (100.3) | (93.4) |
| 2002 | (135.6) | (103.1) | (98.2) |
| 2003 | (134.6) | (99.2) | (94.8) |
| 2004 | (163.0) | (109.1) | (105.3) |
| 2005 | (161.4) | (109.0) | (105.4) |
| 2006 | (138.6) | (114.2) | (108.6) |
| 2007 | (115.4) | (112.1) | (103.0) |
| 2008 | (73.1) | (88.4) | (76.3) |
| 2009 | (42.4) | (69.8) | (54.3) |
| 2010 | (50.6) | (79.3) | (59.4) |
| 2011 | (57.4) | (95.4) | (71.7) |

Note: Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere).

Table A-242: Harvested Wood Products Sectoral Background Data for LULUCF—United States (production approach)

| Inventory year | 1A Annual Change in stock of HWP in use from consumption | 1B Annual Change in stock of HWP in SWDS from consumption | 2A Annual Change in stock of HWP in use produced from domestic harvest | 2B Annual Change in stock of HWP in SWDS produced from domestic harvest | 3 Annual Imports of wood, and paper products plus wood fuel, pulp, recovered paper, roundwood/ chips | 4 Annual Exports of wood, and paper products plus wood fuel, pulp, recovered paper, roundwood/ chips | 5 Annual Domestic Harvest | 6 Annual release of carbon to the atmosphere from HWP consumption (from fuelwood and products in use and products in SWDS) | 7 Annual release of carbon to the atmosphere from HWP (including firewood) where wood came from domestic harvest (from products in use and products in SWDS ) | 8 HWP Contribution to AFOLU $CO_2$ emissions/ removals |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\Delta C_{HWP\ IU\ DC}$ | $\Delta C_{HWP\ SWDS\ DC}$ | $\Delta C_{HWP\ IU\ DH}$ | $\Delta C_{HWP\ SWDS\ DH}$ | $P_{IM}$ | $P_{EX}$ | H | $\uparrow C_{HWP\ DC}$ | $\uparrow C_{HWP\ DH}$ | |
| | | | | | | | | | Gg C/yr | Gg $CO_2$/yr |
| 1990 | 17,044 | 18,308 | 17,659 | 18,278 | 12,680 | 15,078 | 142,297 | 104,547 | 106,359 | (131,772) |
| 1991 | 13,129 | 18,602 | 14,940 | 18,812 | 11,552 | 15,667 | 144,435 | 108,588 | 110,682 | (123,758) |
| 1992 | 15,718 | 17,006 | 16,334 | 17,427 | 12,856 | 16,032 | 139,389 | 103,489 | 105,627 | (123,791) |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1993 | 16,957 | 17,627 | 14,971 | 17,949 | 14,512 | 14,788 | 134,554 | 99,694 | 101,633 | (120,708) |
| 1994 | 18,221 | 17,221 | 15,930 | 17,479 | 15,685 | 15,665 | 134,750 | 99,328 | 101,342 | (122,498) |
| 1995 | 17,307 | 17,051 | 15,065 | 17,229 | 16,712 | 17,266 | 137,027 | 102,115 | 104,733 | (118,411) |
| 1996 | 17,018 | 16,348 | 14,092 | 16,513 | 16,691 | 16,733 | 134,477 | 101,069 | 103,872 | (112,219) |
| 1997 | 18,756 | 17,090 | 14,740 | 17,263 | 17,983 | 16,877 | 135,439 | 100,699 | 103,436 | (117,344) |
| 1998 | 19,654 | 17,769 | 13,376 | 17,735 | 18,994 | 15,057 | 135,021 | 101,536 | 103,911 | (114,071) |
| 1999 | 21,444 | 18,662 | 14,123 | 18,353 | 20,599 | 15,245 | 134,939 | 100,187 | 102,464 | (119,078) |
| 2000 | 20,000 | 18,508 | 12,828 | 17,962 | 21,858 | 16,185 | 134,458 | 101,623 | 103,667 | (112,898) |
| 2001 | 16,491 | 17,610 | 8,711 | 16,774 | 22,051 | 15,336 | 128,621 | 101,235 | 103,136 | (93,447) |
| 2002 | 17,414 | 18,235 | 9,570 | 17,207 | 23,210 | 15,744 | 127,567 | 99,384 | 100,791 | (98,179) |
| 2003 | 17,208 | 17,342 | 9,676 | 16,186 | 23,707 | 16,303 | 124,949 | 97,804 | 99,086 | (94,828) |
| 2004 | 21,781 | 17,673 | 12,429 | 16,298 | 26,447 | 16,948 | 130,460 | 100,505 | 101,733 | (105,332) |
| 2005 | 21,459 | 17,806 | 12,394 | 16,347 | 26,736 | 17,423 | 131,711 | 101,759 | 102,971 | (105,382) |
| 2006 | 19,001 | 18,594 | 12,124 | 17,290 | 25,443 | 18,836 | 127,064 | 96,075 | 97,649 | (107,853) |
| 2007 | 13,064 | 18,318 | 10,488 | 17,399 | 21,648 | 20,656 | 120,922 | 90,533 | 93,035 | (102,255) |
| 2008 | 2,405 | 17,520 | 3,713 | 17,088 | 16,980 | 21,157 | 108,339 | 84,237 | 87,538 | (76,271) |
| 2009 | (5,100) | 16,652 | (1,846) | 16,644 | 13,115 | 20,608 | 95,143 | 76,098 | 80,345 | (54,258) |
| 2010 | (2,528) | 16,337 | (338) | 16,543 | 14,157 | 21,988 | 98,196 | 76,556 | 81,992 | (59,417) |
| 2011 | (616) | 16,275 | 2,727 | 16,822 | 13,935 | 24,302 | 99,081 | 73,055 | 79,532 | (71,679) |

Note: $\uparrow C_{HWP\ DC} = H + P_{IM} - P_{EX} - \Delta C_{HWP\ IU\ DC} - \Delta C_{HWP\ SWDS\ DC}$ AND $\uparrow C_{HWP\ DH} = H - \Delta C_{HWP\ IU\ DH} - \Delta C_{HWP\ SWDS\ DH}$. Parentheses indicate net C sequestration (i.e., a net removal of C from the atmosphere)..

Annual estimates of variables 1A, 1B, 2A and 2B were calculated by tracking the additions to and removals from the pool of products held in end uses (e.g., products in uses such as housing or publications) and the pool of products held in SWDS. In the case of variables 2A and 2B, the pools include products exported and held in other countries and the pools in the United States exclude products made from wood harvested in other countries. Solidwood products added to pools include lumber and panels. End-use categories for solidwood include single and multifamily housing, alteration and repair of housing, and other end uses. There is one product category and one end-use category for paper. Additions to and removals from pools are tracked beginning in 1900, with the exception that additions of softwood lumber to housing begins in 1800. Solidwood and paper product production and trade data are from USDA Forest Service and other sources (Hair and Ulrich 1963; Hair 1958; USDC Bureau of Census 1976; Ulrich, 1985, 1989; Steer 1948; AF&PA 2006a, 2006b; Howard 2003).

The rate of removals from products in use and the rate of decay of products in SWDS are specified by first order (exponential) decay curves with given half-lives (time at which half of amount placed in use will have been discarded from use). Half-lives for products in use, determined after calibration of the model to meet two criteria, are shown in Table A-246. The first criterion is that the WOODCARB II model estimate of C in houses standing in 2001 needed to match an independent estimate of C in housing based on U.S. Census and USDA Forest Service survey data. The second criterion is that the WOODCARB II model estimate of wood and paper being discarded to SWDS needed to match EPA estimates of discards over the period 1990 to 2000. This calibration strongly influences the estimate of variable 1A, and to a lesser extent variable 2A. The calibration also determines the amounts going to SWDS. In addition ,WOODCARB II landfill decay rates have been validated by making sure that estimates of methane emissions from landfills based on EPA data are reasonable in comparison to methane estimates based on WOODCARB II landfill decay rates.

Decay parameters for products in SWDS are shown in Table A-244. Estimates of 1B and 2B also reflect the change over time in the fraction of products discarded to SWDS (versus burning or recycling) and the fraction of SWDS that are sanitary landfills versus dumps.

Variables 2A and 2B are used to estimate HWP contribution under the production accounting approach. A key assumption for estimating these variables is that products exported from the United States and held in pools in other countries have the same half lives for products in use, the same percentage of discarded products going to SWDS, and the same decay rates in SWDS. Summaries of net fluxes and stocks for harvested wood in products and SWDS are in Table A-233 and Table A-234. The decline in net additions to HWP carbon stocks continued through 2009 from the recent high point in 2006. This is due to sharp declines in U.S. production of solidwood and paper products in 2009 primarily due to the decline in housing construction. The low level of gross additions to solidwood and paper products in use in 2009 was exceeded by discards from uses. The result is a net reduction in the amount of HWP carbon that is held in products in use during 2009. For 2009 additions to landfills still exceeded emissions from landfills and the net additions to landfills have remained relatively stable. Overall, there were net carbon additions to HWP in use and in landfills combined.

Table A-243: Half life of solidwood and paper products in end uses

| Parameter | Value | Units |
|---|---|---|
| Half life of wood in single family housing 1920 and before | 78.0 | Years |
| Half life of wood in single family housing 1920–1939 | 78.0 | Years |
| Half life of wood in single family housing 1940–1959 | 80.0 | Years |
| Half life of wood in single family housing 1960–1979 | 81.9 | Years |
| Half life of wood in single family housing 1980 + | 83.9 | Years |
| Ratio of multifamily half live to single family half life | 0.61 | |
| Ratio of repair and alterations half life to single family half life | 0.30 | |
| Half life for other solidwood product in end uses | 38.0 | Years |
| Half life of paper in end uses | 2.54 | Years |

Source: Skog, K.E. (2008) " Sequestration of carbon in harvested wood products for the United States." *Forest Products Journal* 58:56–72.

Table A-244: Parameters determining decay of wood and paper in SWDS

| Parameter | Value | Units |
|---|---|---|
| Percentage of wood and paper in dumps that is subject to decay | 100 | Percent |
| Percentage of wood in landfills that is subject to decay | 23 | Percent |
| Percentage of paper in landfills that is subject to decay | 56 | Percent |
| Half life of wood in landfills / dumps (portion subject to decay) | 29 | Years |
| Half life of paper in landfills/ dumps (portion subject to decay) | 14.5 | Years |

Source: Skog, K.E. (2008) " Sequestration of carbon in harvested wood products for the United States." *Forest Products Journal* 58:56–72

### Uncertainty Analysis

The uncertainty analyses for total net flux of forest C (see uncertainty table in LULUCF chapter) are consistent with the IPCC-recommended Tier 2 methodology (IPCC 2006). Separate analyses are produced for forest ecosystem and HWP flux. The uncertainty estimates are from Monte Carlo simulations of the respective models and input data. Methods generally follow those described in Heath and Smith (2000), Smith and Heath (2000), and Skog et al. (2004). Uncertainties surrounding input data or model processes are quantified as probability distribution functions (PDFs), so that a series of sample values can be randomly selected from the distributions. Model simulations are repeated a large number of times to numerically simulate the effect of the random PDF selections on estimated total C flux. The separate results from the ecosystem and HWP simulations are pooled for total uncertainty (see uncertainty table in LULUCF chapter).

Uncertainty surrounding current net C flux in forest ecosystems is based on the value for 2010 as obtained from the Monte Carlo simulation. C stocks are based on forest condition level (plot-level) calculations, and, therefore, uncertainty analysis starts probabilistic sampling at the plot level. Uncertainty surrounding C density (Mg/ha) is defined for each of six C pools for each inventory plot. Live and standing dead tree C pools are generally assigned normal PDFs that represent total uncertainty of all trees measured on the plot, which varies according to species, number of trees, and per area representation. Error estimates for volume and the component ratio method of estimating biomass are not available, so an assumed 10 percent error on biomass from volume is applied to the volume portion of the estimate and error information in Jenkins et al. (2003) is applied to uncertainty about the additional components (e.g., top, leaves, and roots). Uniform PDFs with a range of ±90 percent of the average are used for those plots where C densities from similarly classified forest stands were applied.

Distributions for the remaining C pools are triangular or uniform, which partly reflects the lower level of information available about these estimates. The PDFs defined for these four pools were sampled as marginal distributions. Down dead wood, understory, and litter are assigned triangular distributions with the mean at the expected value for each plot and the minimum and mode at 10 percent of the expected value. The use of these PDFs skewed to the right reflects the assumption that a small proportion of plots will have relatively high C densities. Soil organic C is defined as a uniform PDF at ±50 percent of the mean. Sub-state or state total carbon stocks associated with each survey are the cumulative sum of random samples from the plot-level PDFs, which are then appropriately expanded to population estimates. These expected values for each carbon pool include uncertainty associated with sampling, which is also incorporated in the Monte Carlo simulation. Sampling errors are determined according to methods described for the FIADB (Bechtold and Patterson 2005), are normally distributed, and are assigned a slight positive correlation between successive surveys for Monte Carlo sampling. More recent annual inventories are assigned higher sampling correlation between successive surveys based on the proportion of plot data jointly included in each. Errors for older inventory data are not available, and these surveys are assigned values consistent with those obtained from the FIADB.

Uncertainty about net C flux in HWP is based on Skog et al. (2004) and Skog (2008). Latin hypercube sampling is the basis for the HWP Monte Carlo simulation. Estimates of the HWP variables and HWP Contribution under the production approach are subject to many sources of uncertainty. An estimate of uncertainty is provided that evaluated the effect of uncertainty in 13 sources, including production and trade data and parameters used to make the estimate. Uncertain data and parameters include data on production and trade and factors to convert them to C, the Census-based estimate of C in housing in 2001, the EPA estimate of wood and paper discarded to SWDS for 1990 to 2000, the limits on decay of wood and paper in SWDS, the decay rate (half-life) of wood and paper in SWDS, the proportion of products produced in the United States made with wood harvested in the United States, and the rate of storage of wood and paper C in other countries that came from United States harvest, compared to storage in the United States.

A total of ten thousand samples are drawn from the PDF input to separately determine uncertainties about forest ecosystem and HWP flux before they are combined for a quantitative estimate of total forest carbon uncertainty (see uncertainty table in LULUCF chapter). Again this year, true Monte Carlo sampling is used for the forest ecosystem estimates (in contrast to Latin hypercube sampling, which was used in some previous estimates), and a part of the QA/QC process includes verifying that the PDFs are adequately sampled.

### Emissions from Fires

#### *$CO_2$*

As stated in other sections, the forest inventory approach implicitly accounts for emissions due to disturbances. Net C stock change is estimated by subtracting consecutive C stock estimates. A disturbance removes C from the forest. The inventory data, on which net C stock estimates are based, already reflects the C loss because only C remaining in the forest is estimated. Estimating the $CO_2$ emissions from a disturbance such as fire and adding those emissions to the net $CO_2$ change in forests would result in double-counting the loss from fire because the inventory data already reflect the

loss. There is interest, however, in the size of the $CO_2$ emissions from disturbances such as fire. The IPCC (2003) methodology and IPCC (2006) default combustion factor for wildfire were employed to estimate emissions from forest fires.

The same methodology was used to estimate emissions from both wildfires and prescribed fires occurring in the lower 48 states. Wildfire area statistics are available, but they include non-forest land, such as shrublands and grasslands. It was thus necessary to develop a rudimentary estimate of the percent of area burned in forest by multiplying the reported area burned by a ratio of total forest land area to the total area considered to be under protection from fire. Data on total area of forest land were obtained from FIA (USDA Forest Service 2012b**)**. Data on "total area considered to be under protection from fire" were available at the state level and obtained for the year 1990 from 1984-1990 Wildfire Statistics prepared by the USDA Forest Service (USDA Forest Service 1992). Data for years 1998, 2002, 2004, 2006, and 2008 were obtained from the National Association of State Foresters (NASF 2011, 2008, 2007a, 2007b, 2007c). For states where data were available for all five years, the 1990 value was assumed for years 1990 to 1994, values for 1998 were assumed for years 1995 to 1998, values for 2002 were assumed for years 1999 to 2002, values for 2004 were assumed for years 2003 and 2004, values for 2006 were assumed for years 2005 and 2006, and values for 2008 were assumed for years 2008 to 2011. For states where data were available for all years except 2002, 2004 data were assumed for years 1999 to 2004. For states where data were available for all years except 2004, 2006 data were assumed for 2003 through 2008. For years where data were available for all years except 2006, 2004 data were assumed for years 2003 to 2008. Since both the 1998 and 2006 values are missing from the NASF data for Alaska, the 1990 value was assumed for years 1990 to 1997, the 2002 value was assumed for years 1998 to 2002, the 2004 value was assumed for years 2003 to 2006, and the 2008 value was assumed for 2007 to 2011. Similarly, since the NASF data for New Mexico lacks values for 2002 and 2004, the 1990 value was assumed for years 1990–1995, while the 1998 value was assumed for year 1996 through 2001, the 2006 data were assumed for 2002 to 2006, and the 2008 value was assumed for all remaining years. Illinois has not reported data on wildland since 2002, so the 1990 value was assumed for years 1990–1995, while the 1998 value was assumed for years 1995 through 2001, and the 2002 value was assumed for all remaining years. Total forestland area for the lower 48 states was divided by total area considered to be under protection from wildfire for the lower 48 states across the 1990 to 2011 time series to create ratios that were then applied to reported area burned to estimate the area of forestland burned for the lower 48 states. The ratio was applied to area burned from wildland fires and prescribed fires occurring in the lower 48 states. Reported area burned data for prescribed fires was available from 1998 to 2011 from the National Interagency Fire Center (NIFC 2012**)**. Data for the year 1998 was assumed for years 1990 to 1997.

Forest area burned data for Alaska are from the Alaska Department of Natural Resources (Alaska Department of Natural Resources 2008) or the Alaska Interagency Coordination Center (Alaska Interagency Coordination Center 2012). Data are acres of land which experienced fire activity on forest service land. Based on personal communication with the USDA Forest Service, forest areas under the protection of the USDA Forest Service serve as a proxy for coastal areas, which is where the majority of forest fires in Alaska occur (Heath 2008). According to expert judgment, the coastal area of Alaska included in this Inventory is mostly temperate rainforest and, therefore, there is little call for prescribed burns (Smith 2008a). It was, thus, assumed that reported area burned for prescribed fires covers only prescribed fires in the lower 48 states.

The average C density in the lower 48 states for aboveground biomass C, dead wood C, and litter layer varied between 69.4 and 78 Mg/ha, according to annual (1990–2011) data from FIA. In order to estimate these annual C densities in the lower 48 states, the C contained in the aboveground, deadwood, and litter C pools was first summed for each state and year. The methodology assumes that wildfires burn only those pools, and leaves the belowground carbon and soil carbon un-burnt. The methodology estimates the C density value by taking a weighted average of these summed C pools in each state and year. The states' C values are weighted according to area of forestland present in each state and year compared with the total A default value of 0.45 from IPCC (2006) was assumed for the amount of biomass burned by wildfire (combustion factor value). According to the estimates, wildfires in the lower 48 states emit between 6.5 and 75.5 Tg C/ha. For Alaska, the average C density reported by the USDA Forest Service varies between 139.5 and 144.7 Mg/ha, based on data from FIA. In the case of wildfires in Alaska, Alaska's C pool values are used instead of a weighted average for states. These values translate into 0 to 0.1 Tg C/ha emitted. Based on data from the USDA Forest Service, the average C density for prescribed fires varied between 24.9 and 25.9 Mg C/ha. For prescribed fires, the methodology assumes that only the litter and deadwood carbon pools burn. The weighted average C densities estimated for prescribed fires therefore only include the sum of these two pools, and excludes aboveground biomass. It is assumed that prescribed fires only occur in the lower 48 states (Smith 2008a). The default value of 0.45 from IPCC (2006) for wildfires was also assumed for the amount of biomass burned by prescribed fires (combustion factor value). As a result, prescribed fires are estimated to emit between 0.5 and 7.4 Tg C/ha.

Carbon density estimates for Mg C/ha were multiplied by estimates of forest area burned by year; the resulting estimates are displayed in Table A-232. C estimates were multiplied by 92.8 percent to account for the proportion of

carbon emitted as $CO_2$ and by 3.67 (i.e., 44/12) to yield $CO_2$ units. Total $CO_2$ emissions for wildfires and prescribed fires in the lower 48 states and wildfires in Alaska in 2011 were estimated to be 77.0 Tg/yr.

Table A-245: Areas (hectares) from wildfire statistics and corresponding estimates of carbon and $CO_2$ (Tg/yr) emissions for wildfires and prescribed fires in the lower 48 states and wildfires in Alaska[1]

| | Lower 48 States | | | | | | | | Alaska | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Wildfires | | | | Prescribed Fires | | | | Wildfires | | | |
| Year | Reported area burned[2] (ha) | Forest area burned[3] (ha) | Carbon emitted (Tg/yr) | $CO_2$ emitted (Tg/yr) | Reported area burned[2] (ha) | Forest area burned[3] (ha) | Carbon emitted (Tg/yr) | $CO_2$ emitted (Tg/yr) | Forest area burned[4] (acres) | Forest area burned (ha) | Carbon emitted (Tg/yr) | $CO_2$ emitted (Tg/yr) |
| 1990 | 579,589 | 304,896 | 10 | 32 | 355,432 | 186,977 | 2 | 7 | 8 | 3 | 0.000 | 0.001 |
| 1991 | 486,807 | 256,680 | 8 | 27 | 355,432 | 187,410 | 2 | 7 | 557 | 225 | 0.014 | 0.048 |
| 1992 | 785,892 | 415,350 | 13 | 44 | 355,432 | 187,848 | 2 | 7 | 47 | 19 | 0.001 | 0.004 |
| 1993 | 438,865 | 232,463 | 7 | 25 | 355,432 | 188,269 | 2 | 7 | 110 | 45 | 0.003 | 0.010 |
| 1994 | 1,540,987 | 817,947 | 26 | 88 | 355,432 | 188,661 | 2 | 7 | 23 | 9 | 0.001 | 0.002 |
| 1995 | 727,051 | 421,835 | 13 | 46 | 355,432 | 206,222 | 2 | 8 | 7 | 3 | 0.000 | 0.001 |
| 1996 | 2,212,309 | 1,322,557 | 42 | 144 | 355,432 | 212,483 | 2 | 8 | 103 | 42 | 0.003 | 0.009 |
| 1997 | 335,914 | 201,181 | 6 | 22 | 355,432 | 212,870 | 2 | 8 | 33 | 13 | 0.001 | 0.003 |
| 1998 | 489,246 | 293,485 | 9 | 32 | 355,432 | 213,213 | 2 | 8 | 2 | 1 | 0.000 | 0.000 |
| 1999 | 1,869,918 | 1,129,810 | 37 | 125 | 806,780 | 487,459 | 5 | 19 | 7 | 3 | 0.000 | 0.001 |
| 2000 | 2,685,981 | 1,624,782 | 53 | 180 | 77,789 | 47,055 | 1 | 2 | 1 | 1 | 0.000 | 0.000 |
| 2001 | 1,356,830 | 821,562 | 27 | 91 | 667,428 | 404,128 | 5 | 15 | 2,078 | 841 | 0.054 | 0.183 |
| 2002 | 2,023,976 | 1,222,755 | 40 | 137 | 1,086,503 | 656,395 | 7 | 25 | 28 | 11 | 0.001 | 0.002 |
| 2003 | 1,358,986 | 720,939 | 24 | 81 | 1,147,695 | 608,850 | 7 | 23 | 17 | 7 | 0.000 | 0.002 |
| 2004 | 637,258 | 344,217 | 11 | 39 | 996,453 | 538,237 | 6 | 21 | 23 | 9 | 0.001 | 0.002 |
| 2005 | 1,629,067 | 943,671 | 31 | 107 | 934,965 | 541,598 | 6 | 21 | 353 | 143 | 0.009 | 0.031 |
| 2006 | 3,888,011 | 2,257,840 | 76 | 257 | 1,100,966 | 639,352 | 7 | 24 | 8 | 3 | 0.000 | 0.001 |
| 2007 | 3,512,122 | 1,779,360 | 60 | 204 | 1,274,383 | 645,646 | 7 | 25 | 2 | 1 | 0.000 | 0.000 |
| 2008 | 2,099,984 | 1,066,094 | 36 | 122 | 783,068 | 397,565 | 4 | 15 | 1 | 0 | 0.000 | 0.000 |
| 2009 | 1,201,995 | 611,540 | 21 | 71 | 1,024,306 | 521,137 | 6 | 20 | 22 | 9 | 0.001 | 0.002 |
| 2010 | 929,687 | 473,991 | 16 | 55 | 980,903 | 500,103 | 6 | 19 | 12 | 5 | 0.000 | 0.001 |
| 2011 | 3,406,788 | 1,740,555 | 61 | 208 | 855,025 | 436,839 | 5 | 17 | 5 | 2 | 0.000 | 0.000 |

[1] Note that these emissions have already been accounted for in the estimates of net annual changes in carbon stocks, which accounts for the amount sequestered minus any emissions, including the assumption that combusted wood may continue to decay through time.
[2] National Interagency Fire Center (2012).
[3] Ratios calculated using forest land area estimates from FIA (USDA Forest Service 2012b) and wildland area under protection estimates from USDA Forest Service (1992) and the National Association of State Foresters (20011).
[4] 1990–2007 Alaskan forest fires data are from the Alaska Department of Natural Resources (2008). 2008–2011 data are from Alaska Interagency Coordination Center (2012).

***Non-$CO_2$***

Emissions of non-$CO_2$ gases from forest fires were estimated using the default IPCC (2003) methodology, IPCC (2006) emission ratios, and default IPCC (2006) combustion factor for wildfires. Emissions estimates for $CH_4$ and $N_2O$ are calculated by multiplying the total estimated $CO_2$ emitted from forest burned by gas-specific emissions ratios and conversion factors. The equations used are:

$$CH_4 \text{ Emissions} = (CO_2 \text{ released}) \times 92.8\% \times (44/12) \times (CH_4 \text{ to } CO_2 \text{ emission ratio})$$

$$N_2O \text{ Emissions} = (CO_2 \text{ released}) \times 92.8\% \times (44/12) \times (N_2O \text{ to } CO_2 \text{ emission ratio})$$

The resulting estimates are presented in Table A-246.

Table A-246: Estimated carbon released and estimates of non-$CO_2$ emissions (Tg/yr) for U.S. forests[1]

| Year | C emitted (Tg/yr) | $CH_4$ emitted (Tg/yr) | $N_2O$ (Tg/yr) |
|---|---|---|---|
| 1990 | 11.613 | 0.140 | 0.008 |
| 1991 | 10.155 | 0.125 | 0.007 |
| 1992 | 15.164 | 0.176 | 0.010 |
| 1993 | 9.446 | 0.118 | 0.007 |
| 1994 | 28.031 | 0.307 | 0.017 |
| 1995 | 15.731 | 0.184 | 0.010 |
| 1996 | 44.643 | 0.479 | 0.027 |
| 1997 | 8.843 | 0.114 | 0.006 |

| | | | |
|---|---|---|---|
| 1998 | 11.858 | 0.145 | 0.008 |
| 1999 | 42.077 | 0.485 | 0.027 |
| 2000 | 53.415 | 0.550 | 0.030 |
| 2001 | 31.440 | 0.367 | 0.020 |
| 2002 | 47.527 | 0.559 | 0.031 |
| 2003 | 30.629 | 0.382 | 0.021 |
| 2004 | 17.460 | 0.240 | 0.013 |
| 2005 | 37.532 | 0.445 | 0.025 |
| 2006 | 82.737 | 0.917 | 0.051 |
| 2007 | 67.088 | 0.758 | 0.042 |
| 2008 | 40.483 | 0.458 | 0.025 |
| 2009 | 26.634 | 0.332 | 0.018 |
| 2010 | 21.812 | 0.280 | 0.015 |
| 2011 | 66.209 | 0.727 | 0.040 |

[1] Calculated based on C emission estimates in Table A-232 and default factors in IPCC (2003, 2006)

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## 3.14. Methodology for Estimating $CH_4$ Emissions from Landfills

Landfill gas is a mixture of substances generated when bacteria decompose the organic materials contained in solid waste. By volume, landfill gas is about half $CH_4$ and half $CO_2$.[91] The amount and rate of $CH_4$ generation depends upon the quantity and composition of the landfilled material, as well as the surrounding landfill environment.

Not all $CH_4$ generated within a landfill is emitted to the atmosphere. The $CH_4$ can be extracted and either flared or utilized for energy, thus oxidizing the $CH_4$ to $CO_2$ during combustion. Of the remaining $CH_4$, a portion oxidizes to $CO_2$ as it travels through the top layer of the landfill cover. In general, landfill-related $CO_2$ emissions are of biogenic origin and primarily result from the decomposition, either aerobic or anaerobic, of organic matter such as food or yard wastes.[92] To estimate the amount of $CH_4$ produced in a landfill in a given year, information is needed on the type and quantity of waste in the landfill, as well as the landfill characteristics (e.g., size, aridity, waste density). This information is not available for the majority landfills in the United States. Consequently, to estimate $CH_4$ generation, a methodology was developed (i.e., the first order decay model) based on the quantity of waste placed in landfills nationwide each year and model parameters from the analysis of measured $CH_4$ generation rates for U.S. landfills with gas recovery systems.

From various studies and surveys of the generation and disposal of solid waste, estimates of the amount of waste placed in MSW and industrial waste landfills were developed. A database of measured $CH_4$ generation rates at landfills with gas recovery systems was compiled and analyzed. The results of this analysis and other studies were used to develop an estimate of the $CH_4$ generation potential for use in the first order decay model. In addition, the analysis and other studies provided estimates of the $CH_4$ generation rate constant as a function of precipitation. The first order decay model was applied to annual waste disposal estimates for each year and for three ranges of precipitation to estimate $CH_4$ generation rates nationwide for the years of interest. Based on the organic content of industrial wastes and the estimates of the fraction of these wastes sent to industrial waste landfills, $CH_4$ emissions from industrial waste landfills were also estimated using the first order decay model. Total $CH_4$ emissions were estimated by adding the $CH_4$ from MSW and industrial landfills and subtracting the amounts recovered for energy or flaring and the amount oxidized in the soil. The steps taken to estimate $CH_4$ emissions from U.S. landfills for the years 1990 through 2011 are discussed in greater detail below.

Figure A-22 presents the $CH_4$ emissions process—from waste generation to emissions—in graphical format.

#### Step 1: Estimate Annual Quantities of Solid Waste Placed in Landfills

For 1989 to 2011, estimates of the annual quantity of waste placed in MSW landfills were developed from a survey of State agencies as reported in BioCycle's State of Garbage (SOG) in America reports (BioCycle 2010), adjusted to include U.S. territories.[93] The SOG survey is the only continually updated nationwide survey of waste disposed in landfills in the United States. Table A-247 shows estimates of waste quantities contributing to $CH_4$ emissions. The table shows SOG estimates of total waste landfilled adjusted for U.S. territories for various years over the 1990 to 2011 timeframe.

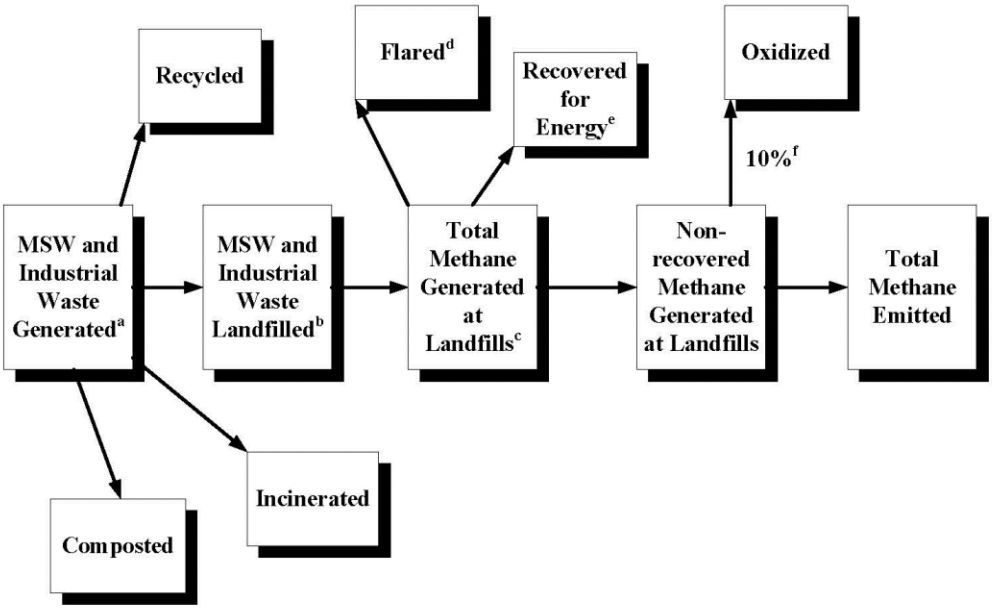
National landfill waste generation data for 1989 through 2008 were obtained from the SOG for every two years (BioCycle 2006, 2008, and 2010). A linear interpolation was used for the amount of waste generated in 2001, 2003, 2005, 2007, 2009, 2010, and 2011 because there were no BioCycle surveys for those years or a report was not yet available. The most recent SOG survey was published in December 2010 representing 2008 data. Upon publication of the next SOG survey, the waste landfilled for 2007, 2008, and 2009, 2010, and 2011 will be updated. Estimates of the quantity of waste landfilled from 1989 to the current inventory year are determined by applying a waste disposal factor to the total amount of waste generated (i.e., the SOG data). A waste disposal factor is determined for each year a SOG survey is published and is the ratio of the total amount of waste landfilled to the total amount of waste generated. The waste disposal factor is interpolated for the years in-between the SOG surveys.

[91] Typically, landfill gas also contains small amounts of nitrogen, oxygen, and hydrogen, less than 1 percent nonmethane volatile organic compounds (NMVOCs), and trace amounts of inorganic compounds.

[92] See Box 8-1 "Biogenic Emissions and Sinks of Carbon" in the Waste chapter for additional background on how biogenic emissions of landfill $CO_2$ are addressed in the U.S. Inventory.

[93] Since the SOG survey does not include U.S. territories, waste landfilled in U.S. territories was estimated using population data for the U.S territories (U.S. Census Bureau 2012) and the per capita rate for waste landfilled from BioCycle (2010).

Figure A-22: Methane Emissions Resulting from Landfilling Municipal and Industrial Waste




[a] BioCycle 2006 for MSW and activity factors for industrial waste.
[b] 1960 through 1988 based on EPA 1988 and EPA 1993; 1989 through 2006 based on BioCycle 2006.
[c] 2006 IPCC Guidelines – First Order Decay Model.
[d] EIA 2007 and flare vendor database.
[e] EIA 2007 and EPA (LMOP) 2007.
[f] 2006 IPCC Guidelines; Mancinelli and McKay 1985; Czepiel et al 1996

Table A-247: Solid Waste in MSW Landfills Contributing to $CH_4$ Emissions (Tg unless otherwise noted)

| Description | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Total Waste Generated[a] | 271 | 302 | 377 | 416 | 455 | 462 | 470 | 459 | 447 | 408 | 369 | 372 | 375 | 378 |
| Percent of Wastes Landfilled[a] | 77% | 63% | 61% | 63% | 66% | 65% | 64% | 64% | 65% | 67% | 69% | 69% | 69% | 69% |
| Total Wastes Landfilled[a] | 206 | 187 | 226 | 259 | 294 | 295 | 296 | 290 | 289 | 269 | 252 | 254 | 255 | 258 |
| Waste in Place (30 years)[b] | 4,671 | 5,054 | 5,362 | 5,562 | 5,562 | 5,709 | 5,854 | 5,998 | 6,133 | 6,259 | 6,366 | 6,453 | 6,538 | 6,622 |
| Waste Contributing to Emissions[c] | 6,808 | 7,772 | 8,787 | 9,340 | 9,340 | 9,635 | 9,931 | 10,221 | 10,505 | 10,773 | 11,025 | 11,279 | 11,534 | 11,792 |

[a] Source: *BioCycle* (2006, 2008, 2010), adjusted for missing U.S. territories using U.S. Census Bureau (2012) population data and per capita disposal rate from *BioCycle*. The data, originally reported in short tons, are converted to metric tons. Estimates shown for 2001, 2003, 2005, 2007, 2009, 2010, and 2011 are based on an interpolation between survey years and the increase in population because there were no surveys in these years.

[b] This estimate represents the waste that has been in place for 30 years or less, which contributes about 90 percent of the $CH_4$ generation. Values are based on EPA (1993).

[c] This estimate represents the cumulative amount of waste that has been placed in landfills from 1940 to the year indicated and is the sum of the annual disposal rates used in the first order decay model. Values are based on EPA (1993).

Estimates of the annual quantity of waste placed in landfills from 1960 through 1988 were developed from EPA's 1993 Report to Congress (EPA 1993) and a 1986 survey of MSW landfills (EPA 1988). Based on the national survey and estimates of the growth of commercial, residential and other wastes, the annual quantity of waste placed in landfills averaged 127 million metric tons in the 1960s, 154 million metric tons in the 1970s, 190 million metric tons in the 1990s, and 285 million metric tons in the 2000's. Estimates of waste placed in landfills in the 1940s and 1950s were developed based on U.S. population for each year and the per capital disposal rates from the 1960s.

**Step 2: Estimate $CH_4$ Generation at Municipal Solid Waste Landfills**

The $CH_4$ generation was estimated from the integrated form of the first order decay (FOD) model using the procedures and spreadsheets from IPCC (2006) for estimating $CH_4$ emissions from solid waste disposal. The form of the FOD model that was applied incorporates a time delay of 6 months after waste disposal before the generation of $CH_4$ begins.

The input parameters needed for the FOD model equations are the mass of waste disposed each year, which was discussed in the previous section, degradable organic carbon (DOC), and the decay rate constant (k). The DOC is determined from the $CH_4$ generation potential ($L_0$ in $m^3$ $CH_4$/Mg waste), which is discussed in more detail in subsequent paragraphs, and the following equation:

$$DOC = [L_0 \times 6.74 \times 10^{-4}] \div [F \times 16/12 \times DOC_f \times MCF]$$

Where,

| | | |
|---|---|---|
| DOC | = | degradable organic carbon (fraction, Gg C/Gg waste), |
| $L_0$ | = | $CH_4$ generation potential ($m^3$ $CH_4$/Mg waste), |
| $6.74 \times 10^{-4}$ | = | $CH_4$ density (Mg/$m^3$), |
| F | = | fraction of $CH_4$ by volume in generated landfill gas (equal to 0.5) |
| 16/12 | = | molecular weight ratio $CH_4$/C, |
| $DOC_f$ | = | fraction of DOC that can decompose in the anaerobic conditions in the landfill (fraction equal to 0.5 for MSW), and |
| MCF | = | methane correction factor for year of disposal (fraction equal to 1 for anaerobic managed sites). |

The DOC value used in the $CH_4$ generation estimates from MSW landfills is 0.203 based on the $CH_4$ generation potential of 100 $m^3$ $CH_4$/Mg waste as described below. Data from a set of 52 representative landfills across the U.S. in different precipitation ranges were chosen to evaluate $L_o$, and ultimately the country-specific DOC value. The 2004 Chartwell Municipal Solid Waste Facility Directory confirmed that each of the 52 landfills chosen accepted or accepts both MSW and construction and demolition (C&D) waste (Chartwell 2004; RTI 2009).

The methane generation potential ($L_o$) varies with the amount of organic content of the waste material. A higher $L_o$ occurrs with a higher content of organic waste. Waste composition data are not collected for all landfills nationwide; thus a default value must be used. Values for $L_o$ were evaluated from landfill gas recovery data for this set of 52 landfills, which resulted in a best fit value for $L_o$ of 99 $m^3$/Mg of waste (RTI 2004). This value compares favorably with a range of 50 to 162 (midrange of 106) $m^3$/Mg presented by Peer, Thorneloe, and Epperson (1993); a range of 87 to 91 $m^3$/Mg from a detailed analysis of 18 landfills sponsored by the Solid Waste Association of North America (SWANA 1998); and a value of 100 $m^3$/Mg recommended in EPA's compilation of emission factors (EPA 1998; EPA 2008) based on data from 21

landfills. Based on the results from these studies, a value of 100 $m^3$/Mg appears to be a reasonable best estimate to use in the FOD model for the national inventory.

The FOD model was applied to the gas recovery data for the 52 landfills to calculate the decay rate constant (k) directly for $L_0$ = 100 $m^3$/Mg. The rate constant was found to increase with annual average precipitation; consequently, average values of k were developed for three ranges of precipitation, shown in Table A- 248 and recommended in EPA's compilation of emission factors (EPA 2008).

Table A- 248. Average Values for Rate Constant (k) by Precipitation Range ($yr^{-1}$)

| Precipitation range (inches/year) | k ($yr^{-1}$) |
|---|---|
| <20 | 0.020 |
| 20-40 | 0.038 |
| >40 | 0.057 |

These values for k show reasonable agreement with the results of other studies. For example, EPA's compilation of emission factors (EPA 1998; EPA, 2008) recommends a value of 0.02 $yr^{-1}$ for arid areas (less than 20 inches/year of precipitation) and 0.04 $yr^{-1}$ for non-arid areas. The SWANA study of 18 landfills reported a range in values of k from 0.03 to 0.06 $yr^{-1}$ based on $CH_4$ recovery data collected generally in the time frame of 1986 to 1995.

Using data collected primarily for the year 2000, the distribution of waste in place versus precipitation was developed from over 400 landfills (RTI 2004). A distribution was also developed for population vs. precipitation for comparison. The two distributions were very similar and indicated that population in areas or regions with a given precipitation range was a reasonable proxy for waste landfilled in regions with the same range of precipitation. Using U.S. Census data and rainfall data, the distributions of population versus rainfall were developed for each Census decade from 1950 through 2000. The distributions showed that the U.S. population has shifted to more arid areas over the past several decades. Consequently, the population distribution was used to apportion the waste landfilled in each decade according to the precipitation ranges developed for k, as shown in Table A-249.

Table A-249. Percent of U.S. Population within Precipitation Ranges (%)

| Precipitation Range (inches/year) | 1950 | 1960 | 1970 | 1980 | 1990 | 2000 |
|---|---|---|---|---|---|---|
| <20 | 11 | 13 | 14 | 16 | 19 | 20 |
| 20-40 | 40 | 39 | 38 | 36 | 34 | 33 |
| >40 | 49 | 48 | 48 | 48 | 47 | 47 |

Source: RTI (2004) using population data from the U.S. Bureau of Census and precipitation data from the National Climatic Data Center's National Oceanic and Atmospheric Administration.

In developing the Inventory, the proportion of waste disposed of in managed landfills versus open dumps prior to 1980 was re-evaluated. Based on the historical data presented by Mintz et al. (2003), a timeline was developed for the transition from the use of open dumps for solid waste disposed to the use of managed landfills. Based on this timeline, it was estimated that 6 percent of the waste that was land disposed in 1940 was disposed of in managed landfills and 94 percent was managed in open dumps. Between 1940 and 1980, the fraction of waste land disposed transitioned towards managed landfills until 100 percent of the waste was disposed of in managed landfills in 1980. For wastes disposed of in dumps, a methane correction factor (MCF) of 0.6 was used based on the recommended IPCC default value for uncharacterized land disposal (IPCC 2006); this MCF is equivalent to assuming 50 percent of the open dumps are deep and 50 percent are shallow. The recommended IPCC default value for the MCF for managed landfills of 1 was used for the managed landfills (IPCC 2006).

**Step 3: Estimate $CH_4$ Generation at Industrial Landfills**

Industrial waste landfills receive waste from factories, processing plants, and other manufacturing activities. In national inventories prior to the 1990 through 2005 inventory, $CH_4$ generation at industrial landfills was estimated as seven percent of the total $CH_4$ generation from MSW landfills, based on a study conducted by EPA (1993). For the 1990 through 2007 and current inventories, the methodology was updated and improved by using activity factors (industrial production levels) to estimate the amount of industrial waste landfilled each year and by applying the FOD model to estimate $CH_4$ generation. A nationwide survey of industrial waste landfills found that over 99 percent of the organic waste placed in industrial landfills originated from two industries: food processing (meat, vegetables, fruits) and pulp and paper (EPA 1993). Data for annual nationwide production for the food processing and pulp and paper industries were taken from industry and government sources for recent years; estimates were developed for production for the earlier years for which data were not available. For the pulp and paper industry, production data published by the Lockwood-Post's Directory and U.S. Department of Agriculture were the primary sources for years 1965 through 2011. An extrapolation based on U.S. real gross domestic product was used for years 1940 through 1964. For the food processing industry,

production levels were obtained or developed from the U.S. Department of Agriculture for the years 1990 through 2011 (ERG 2012). An extrapolation based on U.S. population was used for the years 1940 through 1989.

In addition to production data for the pulp and paper and food processing industries, the following inputs were needed to use the FOD model for estimating $CH_4$ generation from industrial landfills: 1) quantity of waste that is disposed in industrial waste landfills (as a function of production), 2) $CH_4$ generation potential ($L_0$) or DOC, and 3) FOD decay constant (k). Research into waste generation and disposal in landfills for the pulp and paper industry indicated that the quantity of waste landfilled was about 0.050 Mg/Mg of product compared to 0.046 Mg/Mg product for the food processing industry (Weitz and Bahner 2006). These factors were applied to estimates of annual production to estimate annual waste disposal in landfills. Estimates for DOC were derived from available data (Kraft and Orender, 1993; NCASI 2008; Flores et al. 1999). The DOC value for industrial pulp and paper waste is estimated at 0.20 ($L_o$ of 99 $m^3$/Mg); the DOC value for industrial food waste is estimated as 0.26 ($L_o$ of 128 $m^3$/Mg) (Coburn 2008). Estimates for k were taken from the default values in the 2006 IPCC Guidelines; the value of k given for food waste with disposal in a wet temperate climate is 0.19 $yr^{-1}$, and the value given for paper waste is 0.06 $yr^{-1}$.

A literature review was conducted for the 1990 to 2010 inventory year with the intent of updating values for $L_o$ and k in the pulp and paper industry. Where pulp and paper mill wastewater treatment residuals or sludge are the primary constituents of pulp and paper waste landfilled, values for k range from 0.01/yr to 0.1/yr, while values for $L_o$ range from 50 $m^3$/Mg to 200 $m^3$/Mg[94]. Values for these factors are highly variable and are dependent on the soil moisture content, which is generally related to rainfall amounts. At this time, sufficient data were not obtained to warrant a change for the current inventory year. EPA is considering an update to the $L_o$ and k values for the pulp and paper sector and are currently gathering feedback from stakeholders.

As with MSW landfills, a similar trend in disposal practices from open dumps to managed landfills was expected for industrial waste landfills; therefore, the same time line that was developed for MSW landfills was applied to the industrial landfills to estimate the average MCF. That is, between 1940 and 1980, the fraction of waste land disposed transitioned from 6 percent managed landfills in 1940 and 94 percent open dumps to 100 percent managed landfills in 1980 and on. For wastes disposed of in dumps, an MCF of 0.6 was used and for wastes disposed of in managed landfills, an MCF of 1 was used, based on the recommended IPCC default values (IPCC 2006).

The parameters discussed above were used in the integrated form of the FOD model to estimate $CH_4$ generation from industrial waste landfills.

#### Step 4: Estimate $CH_4$ Emissions Avoided

The estimate of $CH_4$ emissions avoided (e.g., combusted) was based on landfill-specific data on landfill gas-to-energy (LFGTE) projects and flares. A destruction efficiency of 99 percent was applied to $CH_4$ recovered to estimate $CH_4$ emissions avoided. The value for efficiency was selected based on the range of efficiencies (86 to 99 percent) recommended for flares in EPA's "AP-42 Compilation of Air Pollutant Emission Factors, Draft Chapter 2.4" (EPA 2008), efficiencies used to establish new source performance standards (NSPS) for landfills, and in recommendations for closed flares used in the Landfill Methane Outreach Program (LMOP).

##### *Step 4a: Estimate $CH_4$ Emissions Avoided Through Landfill Gas-to-Energy (LFGTE) Projects*

The quantity of $CH_4$ avoided due to LFGTE systems was estimated based on information from two sources: (1) a database developed by the Energy Information Administration (EIA) for the voluntary reporting of greenhouse gases (EIA 2007) and (2) a database compiled by LMOP (EPA 2012). The EIA database included location information for landfills with LFGTE projects, estimates of $CH_4$ reductions, descriptions of the projects, and information on the methodology used to determine the $CH_4$ reductions. Generally the $CH_4$ reductions for each reporting year were based on the measured amount of landfill gas collected and the percent $CH_4$ in the gas. For the LMOP database, data on landfill gas flow and energy generation (i.e., MW capacity) were used to estimate the total direct $CH_4$ emissions avoided due to the LFGTE project. Detailed information on the landfill name, owner or operator, city, and state were available for both the EIA and LMOP databases; consequently, it was straightforward to identify landfills that were in both databases. The EIA database was given priority because reductions were reported for each year and were based on direct measurements. Landfills in the LMOP database that were also in the EIA database were dropped to avoid double counting.

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[94] Sources reviewed included Heath et al. 2010; Miner 2008; Skog 2008; Upton et al. 2008; Barlaz 2006; Sonne 2006; NCASI 2005; and Skog 2000.

#### *Step 4b: Estimate $CH_4$ Emissions Avoided Through Flaring*

The quantity of $CH_4$ flared was based on data from the EIA database and on information provided by flaring equipment vendors. To avoid double-counting, flares associated with landfills in the EIA and LMOP databases were excluded from the flare vendor database. As with the LFGTE projects, reductions from flaring landfill gas in the EIA database were based on measuring the volume of gas collected and the percent of $CH_4$ in the gas. The information provided by the flare vendors included information on the number of flares, flare design flow rates or flare dimensions, year of installation, and generally the city and state location of the landfill. When a range of design flare flow rates was provided by the flare vendor, the median landfill gas flow rate was used to estimate $CH_4$ recovered from each remaining flare (i.e., for each flare not associated with a landfill in the EIA or LMOP databases). Several vendors provided information on the size of the flare rather than the flare design gas flow rate. To estimate a median flare gas flow rate for flares associated with these vendors, the size of the flare was matched with the size and corresponding flow rates provided by other vendors. Some flare vendors reported the maximum capacity of the flare. An analysis of flare capacity versus measured $CH_4$ flow rates from the EIA database showed that the flares operated at 51 percent of capacity when averaged over the time series and at 72 percent of capacity for the highest flow rate for a given year. For those cases when the flare vendor supplied maximum capacity, the actual flow was estimated as 50 percent of capacity. Total $CH_4$ avoided through flaring from the flare vendor database was estimated by summing the estimates of $CH_4$ recovered by each flare for each year.

#### *Step 4c: Reduce $CH_4$ Emissions Avoided Through Flaring*

As mentioned in Step 4b, flares in the flare vendor database associated with landfills in the EIA and LMOP databases were excluded from the flare reduction estimates in the flare vendor database. If comprehensive data on flares were available, each LFGTE project in the EIA and LMOP databases would have an identified flare because it is assumed that most LFGTE projects have flares. However, given that the flare vendor data only covers approximately 50 to 75 percent of the flare population, an associated flare was not identified for all LFGTE projects. These LFGTE projects likely have flares, yet flares were unable to be identified for one of two reasons: 1) inadequate identifier information in the flare vendor data; or 2) a lack of the flare in the flare vendor database. For those projects for which a flare was not identified due to inadequate information, $CH_4$ avoided would be overestimated, as both the $CH_4$ avoided from flaring and the LFGTE project would be counted. To avoid overestimating emissions avoided from flaring, the $CH_4$ avoided from LFGTE projects with no identified flares was determined and the flaring estimate from the flare vendor database was reduced by this quantity (referred to as a flare correction factor) on a state-by-state basis. This step likely underestimates $CH_4$ avoided due to flaring but was applied to be conservative in the estimates of $CH_4$ emissions avoided.

Additional effort was undertaken to improve the methodology behind the flare correction factor for the 1990-2009 Inventory to reduce the total number of flares in the flare vendor database that were not matched (512) to landfills and/or LFGTE projects in the EIA and LMOP databases. Each flare in the flare vendor database not associated with a LFGTE project in the EIA or LMOP databases was investigated to determine if it could be matched to either a landfill in the EIA database or a LFGTE project in the LMOP database. For some unmatched flares, the location information was missing or incorrectly transferred to the flare vendor database. In other instances, the landfill names were slightly different between what the flare vendor provided and the actual landfill name as listed in the EIA and LMOP databases.

It was found that a large majority of the unmatched flares are associated with landfills in LMOP that are currently flaring, but are also considering LFGTE. These landfills projects considering a LFGTE project are labeled as candidate, potential, or construction in the LMOP database. The flare vendor database was improved to match flares with operational, shutdown as well as candidate, potential, and construction LFGTE projects, thereby reducing the total number of unidentified flares in the flare vendor database, all of which are used in the flare correction factor. The results of this effort significantly decreased the number of flares used in the flare correction factor, and consequently, increased recovered flare emissions, and decreased net emissions from landfills for the 1990-2009 Inventory. The revised state-by-state flare correction factors were applied to the entire Inventory time series.

#### Step 5: Estimate $CH_4$ Oxidation

A portion of the $CH_4$ escaping from a landfill oxidizes to $CO_2$ in the top layer of the soil. The amount of oxidation depends upon the characteristics of the soil and the environment. For purposes of this analysis, it was assumed that of the $CH_4$ generated, minus the amount of gas recovered for flaring or LFGTE projects, 10 percent was oxidized in the soil (Jensen and Pipatti 2002; Mancinelli and McKay 1985; Czepiel et al 1996). The factor of 10 percent is consistent with the value recommended in the 2006 IPCC revised guidelines for managed and covered landfills, and was therefore applied to the estimates of $CH_4$ generation minus recovery for both MSW and industrial landfills

A literature review was conducted in 2011 (RTI 2011) to provide recommendations for the most appropriate oxidation rate assumptions. It was found that oxidation values are highly variable and range from zero to over 100 percent (i.e., the landfill is considered to be an atmospheric sink by virtue of the landfill gas extraction system pulling atmospheric methane down through the cover). There is considerable uncertainty and variability surrounding estimates of the rate of oxidation because oxidation is difficult to measure and varies considerably with the presence of a gas collection system, thickness and type of the cover material, size and area of the landfill, climate, and the presence of cracks and/or fissures in the cover material through which methane can escape. IPCC (2006) notes that test results from field and laboratory studies may lead to over-estimations of oxidation in landfill cover soils because they largely determine oxidation using uniform and homogeneous soil layers. In addition, a number of studies note that gas escapes more readily through the side slopes of a landfill as compared to moving through the cover thus complicating the correlation between oxidation and cover type or gas recovery.

Sites with landfill gas collection systems are generally designed and managed better to improve gas recovery. More recent research (2006 to 2012) on landfill cover methane oxidation has relied on stable isotope techniques that may provide a more reliable measure of oxidation. Results from this recent research consistently point to higher cover soil methane oxidation rates than the IPCC (2006) default of 10 percent. A continued effort will be made to review the peer-reviewed literature to better understand how climate, cover type, and gas recovery influence the rate of oxidation at active and closed landfills. At this time, the IPCC recommended oxidation factor of 10 percent will continue to be used for all landfills.

#### Step 6: Estimate Total $CH_4$ Emissions

Total $CH_4$ emissions were calculated by adding emissions from MSW and industrial landfills, and subtracting $CH_4$ recovered and oxidized, as shown in Table A- 250.

Table A- 250: $CH_4$ Emissions from Landfills (Gg)

| Activity | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MSW $CH_4$ Generation | 8,219 | 9,132 | 9,854 | 10,068 | 10,367 | 10,754 | 11,126 | 11,486 | 11,812 | 12,106 | 12,342 | 12,519 | 12,694 | 12,866 |
| Industrial $CH_4$ Generation | 554 | 618 | 692 | 705 | 712 | 720 | 725 | 733 | 736 | 740 | 746 | 752 | 758 | 761 |
| **Potential Emissions** | **8,773** | **9,750** | **10,546** | **10,773** | **11,079** | **11,474** | **11,852** | **12,219** | **12,548** | **12,846** | **13,089** | **13,271** | **13,452** | **13,628** |
| Landfill Gas-to-Energy | (634) | (1,070) | (2,325) | (2,565) | (2,554) | (2,520) | (2,630) | (2,660) | (2,766) | (2,980) | (3,189) | (3,532) | (3,927) | (4,190) |
| Flare | (321) | (1,298) | (2,290) | (2,505) | (2,772) | (2,920) | (3,399) | (3,606) | (3,880) | (3,961) | (3,880) | (3,743) | (3,876) | (3,986) |
| **Emissions Avoided** | **(954)** | **(2,368)** | **(4,616)** | **(5,070)** | **(5,326)** | **(5,440)** | **(6,029)** | **(6,266)** | **(6,646)** | **(6,942)** | **(7,079)** | **(7,274)** | **(7,803)** | **(8,177)** |
| **Oxidation at MSW Landfills** | **(726)** | **(676)** | **(524)** | **(500)** | **(504)** | **(531)** | **(510)** | **(522)** | **(517)** | **(516)** | **(526)** | **(524)** | **(489)** | **(469)** |
| **Oxidation at Industrial Landfills** | **(55)** | **(62)** | **(69)** | **(71)** | **(71)** | **(72)** | **(73)** | **(73)** | **(74)** | **(74)** | **(75)** | **(75)** | **(76)** | **(76)** |
| **Net Emissions** | **7,037** | **6,644** | **5,337** | **5,133** | **5,177** | **5,430** | **5,240** | **5,357** | **5,311** | **5,314** | **5,409** | **5,397** | **5,084** | **4,906** |

Note: Totals may not sum exactly to the last significant figure due to rounding.
Note: MSW generation in Table A-248 represents emissions before oxidation. In other tables throughout the text, MSW generation estimates account for oxidation
Note: Parentheses denote negative values.

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# ANNEX 4 IPCC Reference Approach for Estimating $CO_2$ Emissions from Fossil Fuel Combustion

It is possible to estimate carbon dioxide ($CO_2$) emissions from fossil fuel consumption using alternative methodologies and different data sources than those described in the Estimating Emissions from Fossil Fuel Combustion Annex. For example, the UNFCCC reporting guidelines request that countries, in addition to their "bottom-up" sectoral methodology, complete a "top-down" Reference Approach for estimating $CO_2$ emissions from fossil fuel combustion. Section 1.3 of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reporting Instructions* states, "If a detailed, Sectoral Approach for energy has been used for the estimation of $CO_2$ from fuel combustion you are still asked to complete…the Reference Approach…for verification purposes" (IPCC/UNEP/OECD/IEA 1997). This reference method estimates fossil fuel consumption by adjusting national aggregate fuel production data for imports, exports, and stock changes rather than relying on end-user consumption surveys. The basic principle is that once C-based fuels are brought into a national economy, they are either saved in some way (e.g., stored in products, kept in fuel stocks, or left unoxidized in ash) or combusted, and therefore the C in them is oxidized and released into the atmosphere. Accounting for actual consumption of fuels at the sectoral or sub-national level is not required. The following discussion provides the detailed calculations for estimating $CO_2$ emissions from fossil fuel combustion from the United States using the IPCC-recommended Reference Approach.

### Step 1: Collect and Assemble Data in Proper Format

To ensure the comparability of national inventories, the IPCC has recommended that countries report energy data using the International Energy Agency (IEA) reporting convention. National energy statistics were collected in physical units from several EIA documents in order to obtain the necessary data on production, imports, exports, and stock changes.

It was necessary to make a number of modifications to these data to generate more accurate apparent consumption estimates of these fuels. The first modification adjusts for consumption of fossil fuel feedstocks accounted for in the Industrial Processes chapter, which include the following: unspecified coal for coal coke used in iron and steel production; natural gas, distillate fuel, and coal used in iron and steel production; natural gas used for ammonia production; petroleum coke used in the production of aluminum, ferroalloys, titanium dioxide, ammonia, and silicon carbide; and other oil and residual fuel oil used in the manufacture of C black. The second modification adjusts for the fact that EIA energy statistics include synthetic natural gas in coal and natural gas data. The third modification adjusts for the inclusion of ethanol in motor gasoline statistics. Ethanol is a biofuel, and net carbon fluxes from changes in biogenic carbon reservoirs in croplands are accounted for in the estimates for Land Use, Land-Use Change, and Forestry (see Chapter 7). The fourth modification adjusts for consumption of bunker fuels, which refer to quantities of fuels used for international transportation estimated separately from U.S. totals. The fifth modification consists of the addition of U.S. territories data that are typically excluded from the national aggregate energy statistics. The territories include Puerto Rico, U.S. Virgin Islands, Guam, American Samoa, Wake Island, and U.S. Pacific Islands. These data, as well as the production, import, export, and stock change statistics, are presented in Table A- 251.

The C content of fuel varies with the fuel's heat content. Therefore, for an accurate estimation of $CO_2$ emissions, fuel statistics were provided on an energy content basis (e.g., Btu or joules). Because detailed fuel production statistics are typically provided in physical units (as in Table A- 251 for 2011), they were converted to units of energy before $CO_2$ emissions were calculated. Fuel statistics were converted to their energy equivalents by using conversion factors provided by EIA. These factors and their data sources are displayed in Table A- 252. The resulting fuel type-specific energy data for 2011 are provided in Table A- 253.

### Step 2: Estimate Apparent Fuel Consumption

The next step of the IPCC Reference Approach is to estimate "apparent consumption" of fuels within the country. This requires a balance of primary fuels produced, plus imports, minus exports, and adjusting for stock changes. In this way, C enters an economy through energy production and imports (and decreases in fuel stocks) and is transferred out of the country through exports (and increases in fuel stocks). Thus, apparent consumption of primary fuels (including crude

oil, natural gas liquids, anthracite, bituminous, subbituminous and lignite coal, and natural gas) can be calculated as follows:

*Apparent Consumption = Production + Imports - Exports - Stock Change*

Flows of secondary fuels (e.g., gasoline, residual fuel, coke) should be added to primary apparent consumption. The production of secondary fuels, however, should be ignored in the calculations of apparent consumption since the C contained in these fuels is already accounted for in the supply of primary fuels from which they were derived (e.g., the estimate for apparent consumption of crude oil already contains the C from which gasoline would be refined). Flows of secondary fuels should therefore be calculated as follows:

*Secondary Consumption = Imports - Exports - Stock Change*

Note that this calculation can result in negative numbers for apparent consumption of secondary fuels. This result is perfectly acceptable since it merely indicates a net export or stock increase in the country of that fuel when domestic production is not considered.

Next, the apparent consumption and secondary consumption need to be adjusted for feedstock uses of fuels accounted for in the Industrial Processes chapter, international bunker fuels, and U.S. territory fuel consumption. Bunker fuels and feedstocks accounted for in the Industrial Processes chapter are subtracted from these estimates, while fuel consumption in U.S. territories is added.

The IPCC Reference Approach calls for estimating apparent fuel consumption before converting to a common energy unit. However, certain primary fuels in the United States (e.g., natural gas and steam coal) have separate conversion factors for production, imports, exports, and stock changes. In these cases, it is not appropriate to multiply apparent consumption by a single conversion factor since each of its components has different heat contents. Therefore, United States fuel statistics were converted to their heat equivalents before estimating apparent consumption. Results are provided in Table A- 252.

#### Step 3: Estimate Carbon Emissions

Once apparent consumption is estimated, the remaining calculations are similar to those for the "bottom-up" Sectoral Approach (see Estimating Emissions from Fossil Fuel Combustion Annex). Potential $CO_2$ emissions were estimated using fuel-specific C coefficients (see Table A- 253).[95] The C in products from non-energy uses of fossil fuels (e.g., plastics or asphalt) was then estimated and subtracted (see Table A-255). This step differs from the Sectoral Approach in that emissions from both fuel combustion and non-energy uses are accounted for in this approach. Finally, to obtain actual $CO_2$ emissions, net emissions were adjusted for any C that remained unoxidized as a result of incomplete combustion (e.g., C contained in ash or soot).[96] The fraction oxidized was assumed to be 100 percent for petroleum, coal, and natural gas based on guidance in IPCC (2006) (see Estimating Emissions from Fossil Fuel Combustion Annex).

#### Step 4: Convert to $CO_2$ Emissions

Because the IPCC reporting guidelines recommend that countries report greenhouse gas emissions on a full molecular weight basis, the final step in estimating $CO_2$ emissions from fossil fuel consumption was converting from units of C to units of $CO_2$. Actual C emissions were multiplied by the molecular-to-atomic weight ratio of $CO_2$ to C (44/12) to obtain total $CO_2$ emitted from fossil fuel combustion in teragrams (Tg). The results are contained in Table A- 254.

### Comparison Between Sectoral and Reference Approaches

These two alternative approaches can both produce reliable estimates that are comparable within a few percent. Note that the reference approach *includes* emissions from non-energy uses. Therefore, these totals should be compared to the aggregation of fuel use and emission totals from Emissions of $CO_2$ from Fossil Fuel Combustion and Carbon Emitted from Non-Energy Uses of Fossil Fuels Annexes. These two sections together are henceforth referred to as the Sectoral Approach. Other than this distinction, the major difference between methodologies employed by each approach lies in the energy data used to derive C emissions (i.e., the actual surveyed consumption for the Sectoral Approach versus apparent

[95] Carbon coefficients from EIA were used wherever possible. Because EIA did not provide coefficients for coal, the IPCC-recommended emission factors were used in the top-down calculations for these fuels. See notes in Table A- 254 for more specific source information.

consumption derived for the Reference Approach). In theory, both approaches should yield identical results. In practice, however, slight discrepancies occur. For the United States, these differences are discussed below.

### Differences in Total Amount of Energy Consumed

Table A-257 summarizes the differences between the Reference and Sectoral approaches in estimating total energy consumption in the United States. Although theoretically the two methods should arrive at the same estimate for U.S. energy consumption, the Reference Approach provides an energy consumption total that is 2.0 percent lower than the Sectoral Approach for 2011. The greatest differences lie in lower estimates for petroleum and coal consumption for the Reference Approach (4.3 percent and 1.3 percent, respectively) and higher estimates for natural gas consumption for the Reference Approach (0.7 percent).

There are several potential sources for the discrepancies in consumption estimates:

- *Product Definitions.* The fuel categories in the Reference Approach are different from those used in the Sectoral Approach, particularly for petroleum. For example, the Reference Approach estimates apparent consumption for crude oil. Crude oil is not typically consumed directly, but refined into other products. As a result, the United States does not focus on estimating the energy content of the various grades of crude oil, but rather estimating the energy content of the various products resulting from crude oil refining. The United States does not believe that estimating apparent consumption for crude oil, and the resulting energy content of the crude oil, is the most reliable method for the United States to estimate its energy consumption. Other differences in product definitions include using sector-specific coal statistics in the Sectoral Approach (i.e., residential, commercial, industrial coking, industrial other, and transportation coal), while the Reference Approach characterizes coal by rank (i.e. anthracite, bituminous, etc.). Also, the liquefied petroleum gas (LPG) statistics used in the bottom-up calculations are actually a composite category composed of natural gas liquids (NGL) and LPG.
- *Heat Equivalents.* It can be difficult to obtain heat equivalents for certain fuel types, particularly for categories such as "crude oil" where the key statistics are derived from thousands of producers in the United States and abroad.
- *Possible inconsistencies in U.S. Energy Data.* The United States has not focused its energy data collection efforts on obtaining the type of aggregated information used in the Reference Approach. Rather, the United States believes that its emphasis on collection of detailed energy consumption data is a more accurate methodology for the United States to obtain reliable energy data. Therefore, top-down statistics used in the Reference Approach may not be as accurately collected as bottom-up statistics applied to the Sectoral Approach.
- *Balancing Item.* The Reference Approach uses *apparent* consumption estimates while the Sectoral Approach uses *reported* consumption estimates. While these numbers should be equal, there always seems to be a slight difference that is often accounted for in energy statistics as a “balancing item.”

### Differences in Estimated $CO_2$ Emissions

Given these differences in energy consumption data, the next step for each methodology involved estimating emissions of $CO_2$. Table A-258 summarizes the differences between the two methods in estimated C emissions.

As mentioned above, for 2011, the Reference Approach resulted in a 2.0 percent lower estimate of energy consumption in the United States than the Sectoral Approach. The resulting emissions estimate for the Reference Approach was 1.6 percent lower. Estimates of natural gas emissions from the Reference Approach are higher (0.7 percent), and coal and petroleum emission estimates are lower (1.3 percent and 3.2 percent, respectively) than the Sectoral Approach. Potential reasons for these differences may include:

- *Product Definitions.* Coal data is aggregated differently in each methodology, as noted above. The format used for the Sectoral Approach likely results in more accurate estimates than in the Reference Approach. Also, the Reference Approach relies on a "crude oil" category for determining petroleum-related emissions. Given the many sources of crude oil in the United States, it is not an easy matter to track potential differences in C content between many different sources of crude; particularly since information on the C content of crude oil is not regularly collected.
- *Carbon Coefficients.* The Reference Approach relies on several default C coefficients by rank provided by IPCC (IPCC/UNEP/OECD/IEA 1997), while the Sectoral Approach uses annually updated category-specific coefficients by sector that are likely to be more accurate. Also, as noted above, the C coefficient for crude oil is more uncertain than that for specific secondary petroleum products, given the many sources and grades of crude oil consumed in the United States.

Although the two approaches produce similar results, the United States believes that the "bottom-up" Sectoral Approach provides a more accurate assessment of $CO_2$ emissions at the fuel level. This improvement in accuracy is largely a result of the data collection techniques used in the United States, where there has been more emphasis on obtaining the detailed products-based information used in the Sectoral Approach than obtaining the aggregated energy flow data used in the Reference Approach. The United States believes that it is valuable to understand both methods.

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Table A- 251: 2011 U.S. Energy Statistics (Physical Units)

| Fuel Category (Units) | Fuel Type | Production | Imports | Exports | Stock Change | Adjustment | Bunkers | U.S. Territories |
|---|---|---|---|---|---|---|---|---|
| **Solid Fuels (Thousand Short Tons)** | Anthracite Coal | 2,296 | [a] | [a] | [a] | | | |
| | Bituminous Coal | 500,546 | [a] | [a] | [a] | | | |
| | Sub-bituminous Coal | 510,540 | [a] | [a] | [a] | 367 | | |
| | Lignite | 80,953 | [a] | [a] | [a] | 4,695 | | |
| | Coke | | 1,418 | 970 | 38 | | | |
| | Unspecified Coal | | 13,088 | 107,259 | (7,328) | 2,488 | | 1,688 |
| **Gas Fuels (Million Cubic Feet)** | Natural Gas | 22,771,322 | 3,453,442 | 1,507,131 | 348,493 | 295,179 | | 27,193 |
| **Liquid Fuels (Thousand Barrels)** | Crude Oil | 2,065,172 | 3,261,422 | 17,158 | (33,345) | | | |
| | Nat Gas Liquids and LRGs | 808,865 | 91,447 | 90,968 | 8,592 | | | 3,107 |
| | Other Liquids | | 519,259 | 67,981 | 6,245 | | | |
| | Motor Gasoline | 22,432 | 38,237 | 174,776 | (2,626) | | | 46,419 |
| | Aviation Gasoline | | 61 | | 35 | | | |
| | Kerosene | | 944 | 2,195 | 30 | | | 1,273 |
| | Jet Fuel | | 25,028 | 35,324 | (1,735) | | 173,956 | 9,939 |
| | Distillate Fuel | | 65,234 | 311,747 | (15,094) | 509 | 17,486 | 22,821 |
| | Residual Fuel | | 119,888 | 154,921 | (7,158) | 10,000 | 82,451 | 26,048 |
| | Naphtha for petrochemical feedstocks | | 17,919 | | 408 | | | |
| | Petroleum Coke | | 4,912 | 182,222 | (1,483) | 6,724 | | |
| | Other Oil for petrochemical feedstocks | | 30,035 | | 251 | 5,636 | | |
| | Special Naphthas | | 4,180 | 13,586 | 45 | | | |
| | Lubricants | | 10,145 | 24,927 | 1,752 | | | 172 |
| | Waxes | | 1,779 | 2,011 | 83 | | | |
| | Asphalt/Road Oil | | 8,191 | 11,446 | (287) | | | |
| | Still Gas | | | | | | | |
| | Misc. Products | | 125 | 586 | (30) | | | 10,092 |

[a] Included in Unspecified Coal

Data Sources: Solid and Gas Fuels: EIA (2012a); Liquid Fuels: EIA (1995-2012).

Table A- 252: Conversion Factors to Energy Units (Heat Equivalents)

| Fuel Category (Units) | Fuel Type | Production | Imports | Exports | Stock Change | Adjustment | Bunkers | U.S. Territories |
|---|---|---|---|---|---|---|---|---|
| **Solid Fuels (Million Btu/Short Ton)** | Anthracite Coal | 22.57 | | | | | | |
| | Bituminous Coal | 23.89 | | | | | | |
| | Sub-bituminous Coal | 17.14 | | | | 28.16 | | |
| | Lignite | 12.87 | | | | 12.87 | | |
| | Coke | | 25.00 | 25.65 | 25.00 | | | |
| | Unspecified | | 25.00 | 25.97 | 20.86 | 227.08 | | 25.14 |
| **Natural Gas (BTU/Cubic Foot)** | | 1,022 | 1,025 | 1,009 | 1,022 | 1,021 | | 1,022 |
| **Liquid Fuels (Million Btu/Barrel)** | Crude Oil | 5.80 | 6.01 | 5.62 | 5.62 | | 5.62 | 5.62 |
| | Nat Gas Liquids and LRGs | 3.68 | 3.68 | 3.68 | 3.68 | | 3.68 | 3.68 |
| | Other Liquids | 5.83 | 5.83 | 5.83 | 5.83 | | 5.83 | 5.83 |
| | Motor Gasoline | 5.22 | 5.22 | 5.22 | 5.22 | 5.22 | 5.22 | 5.22 |
| | Aviation Gasoline | | 5.05 | 5.05 | 5.05 | | 5.05 | 5.05 |
| | Kerosene | | 5.67 | 5.67 | 5.67 | | 5.67 | 5.67 |
| | Jet Fuel | | 5.67 | 5.67 | 5.67 | | 5.55 | 5.67 |
| | Distillate Fuel | | 5.83 | 5.83 | 5.83 | 5.83 | 5.83 | 5.83 |
| | Residual Oil | | 6.29 | 6.29 | 6.29 | 6.29 | 6.29 | 6.29 |
| | Naphtha for petrochemical feedstocks | | 5.25 | 5.25 | 5.25 | | 5.25 | 5.25 |
| | Petroleum Coke | | 6.02 | 6.02 | 6.02 | 6.02 | 6.02 | 6.02 |
| | Other Oil for petrochemical feedstocks | | 5.83 | 5.83 | 5.83 | 5.83 | 5.83 | 5.83 |
| | Special Naphthas | | 5.25 | 5.25 | 5.25 | | 5.25 | 5.25 |
| | Lubricants | | 6.07 | 6.07 | 6.07 | | 6.07 | 6.07 |
| | Waxes | | 5.54 | 5.54 | 5.54 | | 5.54 | 5.54 |
| | Asphalt/Road Oil | | 6.64 | 6.64 | 6.64 | | 6.64 | 6.64 |
| | Still Gas | | 6.00 | 6.00 | 6.00 | | 6.00 | 6.00 |
| | Misc. Products | | 5.80 | 5.80 | 5.80 | | 5.80 | 5.80 |

Data Sources: Coal and lignite production: EIA (1992); Unspecified Solid Fuels: EIA (2012a); Coke, Natural Gas and Petroleum Products: EIA (2012b).

Table A- 253: 2011 Apparent Consumption of Fossil Fuels (TBtu)

| Fuel Category | Fuel Type | Production | Imports | Exports | Stock Change | Adjustment | Bunkers | U.S. Territories | Apparent Consumption |
|---|---|---|---|---|---|---|---|---|---|
| **Solid Fuels** | Anthracite Coal | 51.8 | | | | | | | **51.8** |
| | Bituminous Coal | 11,958.0 | | | | | | | **11,958.0** |
| | Sub-bituminous Coal | 8,750.7 | | | | 10.3 | | | **8,740.3** |
| | Lignite | 1,041.5 | | | | 60.4 | | | **981.1** |
| | Coke | | 35.5 | 24.9 | 1.0 | | | | **9.6** |
| | Unspecified | | 327.2 | 2,785.7 | (152.9) | 565.1 | | 42.4 | **(2,828.3)** |
| **Gas Fuels** | Natural Gas | 23,272.3 | 3,539.8 | 1,520.7 | 356.2 | 301.4 | | 27.8 | **24,661.6** |
| **Liquid Fuels** | Crude Oil | 11,978.0 | 19,591.4 | 96.4 | (187.4) | | | | **31,660.3** |
| | Nat Gas Liquids and LRGs | 2,972.6 | 336.1 | 334.3 | 31.6 | | | 11.4 | **2,954.2** |
| | Other Liquids | | 3,024.7 | 396.0 | 36.4 | | | | **2,592.3** |
| | Motor Gasoline | 117.1 | 199.5 | 912.0 | (13.7) | | | 242.2 | **(339.5)** |
| | Aviation Gasoline | | 0.3 | | 0.2 | | | | **0.1** |
| | Kerosene | | 5.4 | 12.4 | 0.2 | | | 7.2 | **(0.0)** |
| | Jet Fuel | | 141.9 | 200.3 | (9.8) | | 965.8 | 56.4 | **(958.0)** |
| | Distillate Fuel | | 380.0 | 1,815.9 | (87.9) | 3.0 | 101.9 | 132.9 | **(1,319.9)** |
| | Residual Oil | | 753.7 | 974.0 | (45.0) | 62.9 | 518.4 | 163.8 | **(592.7)** |
| | Naphtha for petrochemical feedstocks | | 94.0 | | 2.1 | | | | **91.9** |
| | Petroleum Coke | | 29.6 | 1,097.7 | (8.9) | 40.5 | | | **(1,099.7)** |
| | Other Oil for petrochemical feedstocks | | 175.0 | | 1.5 | 32.8 | | | **140.7** |
| | Special Naphthas | | 21.9 | 71.3 | 0.2 | | | | **(49.6)** |
| | Lubricants | | 61.5 | 151.2 | 10.6 | | | 1.0 | **(99.2)** |
| | Waxes | | 9.9 | 11.1 | 0.5 | | | | **(1.7)** |
| | Asphalt/Road Oil | | 54.4 | 76.0 | (1.9) | | | | **(19.7)** |
| | Still Gas | | | | | | | | |
| | Misc. Products | | 0.7 | 3.4 | (0.2) | | | 58.5 | **56.0** |
| **Total** | | **60,142.0** | **28,782.3** | **10,483.3** | **(67.4)** | **1,076.4** | **1,586.0** | **743.7** | **76,589.6** |

Note: Totals may not sum due to independent rounding.

Table A- 254: 2011 Potential $CO_2$ Emissions

| Fuel Category | Fuel Type | Apparent Consumption (QBtu) | Carbon Coefficients (Tg Carbon/QBtu) | Potential Emissions (Tg $CO_2$ Eq.) |
|---|---|---|---|---|
| **Solid Fuels** | Anthracite Coal | 0.05 | 28.28 | **5.4** |
| | Bituminous Coal | 11.96 | 25.44 | **1,115.5** |
| | Sub-bituminous Coal | 8.74 | 26.50 | **849.3** |
| | Lignite | 0.98 | 26.65 | **95.9** |
| | Coke | 0.01 | 31.00 | **1.1** |
| | Unspecified | (2.83) | 25.34 | **(262.7)** |
| **Gas Fuels** | Natural Gas | 24.66 | 14.46 | **1,307.1** |
| **Liquid Fuels** | Crude Oil | 31.66 | 20.31 | **2,357.2** |
| | Nat Gas Liquids and LRGs | 2.95 | 16.87 | **182.8** |
| | Other Liquids | 2.59 | 20.31 | **193.0** |
| | Motor Gasoline | (0.34) | 19.46 | **(24.2)** |
| | Aviation Gasoline | 0.00 | 18.86 | **0.0** |
| | Kerosene | (0.00) | 19.96 | **(0.0)** |
| | Jet Fuel | (0.96) | 19.70 | **(69.2)** |
| | Distillate Fuel | (1.32) | 20.17 | **(97.6)** |
| | Residual Oil | (0.59) | 20.48 | **(44.5)** |
| | Naphtha for petrochemical feedstocks | 0.09 | 18.55 | **6.3** |
| | Petroleum Coke | (1.10) | 27.85 | **(112.3)** |
| | Other Oil for petrochemical feedstocks | 0.14 | 20.17 | **10.4** |
| | Special Naphthas | (0.05) | 19.74 | **(3.6)** |
| | Lubricants | (0.10) | 20.20 | **(7.3)** |
| | Waxes | (0.00) | 19.80 | **(0.1)** |
| | Asphalt/Road Oil | (0.02) | 20.55 | **(1.5)** |
| | Still Gas | | 18.20 | |
| | Misc. Products | 0.06 | 20.31 | **4.2** |
| **Total** | | | | **5,505.5** |

Data Sources: C content coefficients by coal rank from USGS (1998) and SAIC (2004); Unspecified Solid Fuels, EIA (2012), Natural Gas and Liquid Fuels: EPA (2010).
Note: Totals may not sum due to independent rounding.

Table A-255: 2011 Non-Energy Carbon Stored in Products

| Fuel Type | Consumption for Non-Energy Use (TBtu) | Carbon Coefficients (Tg Carbon/QBtu) | Carbon Content (Tg Carbon) | Fraction Sequestered | Carbon Stored (Tg $CO_2$ Eq.) |
|---|---|---|---|---|---|
| Coal | 60.8 | 31.00 | 1.89 | 0.10 | 0.7 |
| Natural Gas | 222.2 | 14.46 | 3.21 | 0.59 | 7.0 |
| Asphalt & Road Oil | 859.5 | 20.55 | 17.67 | 1.00 | 64.5 |
| LPG | 1,969.6 | 17.06 | 33.60 | 0.59 | 73.3 |
| Lubricants | 276.8 | 20.20 | 5.59 | 0.09 | 1.9 |
| Pentanes Plus | 26.3 | 19.10 | 0.50 | 0.59 | 1.1 |
| Petrochemical Feedstocks | [a] | [a] | [a] | [a] | 41.2 |
| Petroleum Coke | 0.0 | 27.85 | 0.00 | 0.30 | 0.0 |
| Special Naphtha | 20.6 | 19.74 | 0.41 | 0.60 | 0.9 |
| Waxes/Misc. | [a] | [a] | [a] | [a] | 1.3 |
| Misc. U.S. Territories Petroleum | [a] | [a] | [a] | [a] | 0.9 |
| **Total** | | | | | **192.8** |

[a] Values for Misc. U.S. Territories Petroleum, Petrochemical Feedstocks and Waxes/Misc. are not shown because these categories are aggregates of numerous smaller components.

Note: Totals may not sum due to independent rounding.

Table A-256: 2011 Reference Approach $CO_2$ Emissions from Fossil Fuel Consumption (Tg $CO_2$ Eq. unless otherwise noted)

| Fuel Category | Potential Emissions | Carbon Sequestered | Net Emissions | Fraction Oxidized | Total Emissions |
|---|---|---|---|---|---|
| Coal | 1,804.4 | 0.7 | 1,803.7 | 100.0% | **1,803.7** |
| Petroleum | 2,393.5 | 185.1 | 2,208.4 | 100.0% | **2,208.4** |
| Natural Gas | 1,307.1 | 7.0 | 1,300.1 | 100.0% | **1,300.1** |
| **Total** | **5,505.0** | **192.8** | **5,312.2** | | **5,312.2** |

Note: Totals may not sum due to independent rounding.

Table A-257: Fuel Consumption in the United States by Estimating Approach (TBtu)*

| Approach | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sectoral** | **69,379** | **74,602** | **77,036** | **78,092** | **78,519** | **79,825** | **82,252** | **80,710** | **81,494** | **82,020** | **83,687** | **83,723** | **82,731** | **84,136** | **81,473** | **76,845** | **79,239** | **78,143** |
| Coal | 18,072 | 19,187 | 20,068 | 20,529 | 20,823 | 20,830 | 21,748 | 21,121 | 21,192 | 21,625 | 21,893 | 22,187 | 21,834 | 22,067 | 21,751 | 19,232 | 20,329 | 19,153 |
| Natural Gas | 19,184 | 22,170 | 22,589 | 22,723 | 22,323 | 22,366 | 23,392 | 22,466 | 23,163 | 22,561 | 22,623 | 22,282 | 21,960 | 23,371 | 23,589 | 23,187 | 23,989 | 24,492 |
| Petroleum | 32,123 | 33,246 | 34,379 | 34,840 | 35,373 | 36,629 | 37,111 | 37,123 | 37,139 | 37,834 | 39,170 | 39,253 | 38,937 | 38,698 | 36,133 | 34,426 | 34,921 | 34,497 |
| **Reference (Apparent)** | **68,646** | **73,644** | **75,958** | **77,498** | **77,524** | **78,734** | **81,187** | **80,227** | **80,964** | **81,419** | **83,149** | **83,162** | **81,924** | **83,764** | **80,129** | **76,407** | **77,475** | **76,590** |
| Coal | 17,573 | 18,567 | 19,425 | 20,105 | 19,981 | 20,030 | 20,957 | 20,710 | 20,797 | 21,081 | 21,735 | 21,986 | 21,534 | 21,577 | 21,391 | 19,243 | 19,582 | 18,913 |
| Natural Gas | 19,672 | 22,274 | 22,696 | 22,828 | 22,403 | 22,458 | 23,484 | 22,535 | 23,238 | 22,630 | 22,690 | 22,349 | 22,029 | 23,441 | 23,661 | 23,271 | 24,086 | 24,662 |
| Petroleum | 31,402 | 32,802 | 33,836 | 34,565 | 35,140 | 36,246 | 36,745 | 36,982 | 36,928 | 37,707 | 38,723 | 38,828 | 38,361 | 38,746 | 35,077 | 33,893 | 33,807 | 33,015 |
| **Difference** | **-1.1%** | **-1.3%** | **-1.4%** | **-0.8%** | **-1.3%** | **-1.4%** | **-1.3%** | **-0.6%** | **-0.7%** | **-0.7%** | **-0.6%** | **-0.7%** | **-1.0%** | **-0.4%** | **-1.6%** | **-0.6%** | **-2.2%** | **-2.0%** |
| Coal | -2.8% | -3.2% | -3.2% | -2.1% | -4.0% | -3.8% | -3.6% | -1.9% | -1.9% | -2.5% | -0.7% | -0.9% | -1.4% | -2.2% | -1.7% | 0.1% | -3.7% | -1.3% |
| Natural Gas | 2.5% | 0.5% | 0.5% | 0.5% | 0.4% | 0.4% | 0.4% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.3% | 0.4% | 0.4% | 0.7% |
| Petroleum | -2.2% | -1.3% | -1.6% | -0.8% | -0.7% | -1.0% | -1.0% | -0.4% | -0.6% | -0.3% | -1.1% | -1.1% | -1.5% | 0.1% | -2.9% | -1.5% | -3.2% | -4.3% |

* Includes U.S. territories. Does not include international bunker fuels.

Note: Totals may not sum due to independent rounding.

Table A-258: $CO_2$ Emissions from Fossil Fuel Combustion by Estimating Approach (Tg $CO_2$ Eq.)

| Approach | 1990 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sectoral** | **4,837** | **5,148** | **5,330** | **5,405** | **5,453** | **5,535** | **5,715** | **5,624** | **5,663** | **5,725** | **5,836** | **5,871** | **5,801** | **5,897** | **5,721** | **5,343** | **5,515** | **5,399** |
| Coal | 1,719 | 1,823 | 1,907 | 1,950 | 1,980 | 1,983 | 2,071 | 2,011 | 2,022 | 2,066 | 2,093 | 2,121 | 2,083 | 2,106 | 2,076 | 1,835 | 1,941 | 1,828 |
| Natural Gas | 1,007 | 1,164 | 1,185 | 1,192 | 1,169 | 1,173 | 1,228 | 1,178 | 1,215 | 1,183 | 1,189 | 1,172 | 1,157 | 1,231 | 1,243 | 1,221 | 1,264 | 1,291 |
| Petroleum | 2,111 | 2,161 | 2,238 | 2,263 | 2,304 | 2,379 | 2,415 | 2,435 | 2,426 | 2,476 | 2,554 | 2,578 | 2,561 | 2,560 | 2,402 | 2,286 | 2,311 | 2,281 |
| **Reference (Apparent)** | **4,782** | **5,109** | **5,280** | **5,399** | **5,406** | **5,477** | **5,662** | **5,619** | **5,660** | **5,714** | **5,849** | **5,866** | **5,774** | **5,885** | **5,644** | **5,344** | **5,403** | **5,312** |
| Coal | 1,654 | 1,756 | 1,837 | 1,902 | 1,894 | 1,903 | 1,989 | 1,968 | 1,976 | 2,002 | 2,065 | 2,088 | 2,050 | 2,053 | 2,037 | 1,833 | 1,865 | 1,804 |
| Natural Gas | 1,034 | 1,171 | 1,192 | 1,199 | 1,174 | 1,179 | 1,234 | 1,182 | 1,220 | 1,188 | 1,194 | 1,176 | 1,161 | 1,235 | 1,247 | 1,227 | 1,270 | 1,300 |
| Petroleum | 2,094 | 2,182 | 2,251 | 2,298 | 2,337 | 2,396 | 2,439 | 2,469 | 2,464 | 2,523 | 2,590 | 2,602 | 2,563 | 2,596 | 2,360 | 2,284 | 2,268 | 2,208 |
| **Difference** | **-1.1%** | **-0.8%** | **-0.9%** | **-0.1%** | **-0.9%** | **-1.0%** | **-0.9%** | **-0.1%** | **0.0%** | **-0.2%** | **0.2%** | **-0.1%** | **-0.5%** | **-0.2%** | **-1.3%** | **0.0%** | **-2.0%** | **-1.6%** |
| Coal | -3.8% | -3.7% | -3.7% | -2.5% | -4.3% | -4.0% | -4.0% | -2.2% | -2.2% | -3.1% | -1.3% | -1.5% | -1.6% | -2.5% | -1.9% | -0.1% | -3.9% | -1.3% |
| Natural Gas | 2.7% | 0.6% | 0.6% | 0.6% | 0.4% | 0.5% | 0.5% | 0.3% | 0.4% | 0.4% | 0.4% | 0.3% | 0.3% | 0.3% | 0.3% | 0.4% | 0.4% | 0.7% |
| Petroleum | -0.8% | 0.9% | 0.6% | 1.5% | 1.5% | 0.7% | 1.0% | 1.4% | 1.6% | 1.9% | 1.4% | 0.9% | 0.1% | 1.4% | -1.7% | -0.1% | -1.9% | -3.2% |

* Includes U.S. territories. Does not include international bunker fuels.

Note: Totals may not sum due to independent rounding.

# ANNEX 5 Assessment of the Sources and Sinks of Greenhouse Gas Emissions Not Included

Although this report is intended to be a comprehensive assessment of anthropogenic[97] sources and sinks of greenhouse gas emissions for the United States, certain sources have been identified but not included in the estimates presented for various reasons. Before discussing these sources, however, it is important to note that processes or activities that are not *anthropogenic in origin* or do not result in a *net source or sink* of greenhouse gas emissions are intentionally excluded from a national inventory of anthropogenic greenhouse gas emissions, in line with guidance from the IPCC in their guidelines for national inventories.

Given a source category that is both anthropogenic and results in net greenhouse gas emissions, reasons for not including a source related to an anthropogenic activity include one or more of the following:

- Though an estimating method has been developed, data were not adequately available to calculate emissions.
- Emissions were implicitly accounted for within another source category (e.g., $CO_2$ from Fossil Fuel Combustion).

It is also important to note that the United States believes that the sources discussed below are very low in comparison with the overall estimate of total U.S. greenhouse gas emissions, and not including them introduces a very minor bias. In general, the emission sources described in this annex are for source categories with methodologies introduced in the 2006 IPCC Guidelines for which data collection has not been sufficient to pursue an initial estimation of greenhouse gases.

### $N_2O$ from Caprolactam Production

Caprolactam is a widely used chemical intermediate, primarily to produce nylon-6. All processes for producing caprolactam involve the catalytic oxidation of ammonia, with $N_2O$ being produced as a by-product.. More research is required to determine this source's significance because there is currently insufficient information available on caprolactam production to estimate emissions in the United States.

### $CO_2$ and $CH_4$ from Calcium Carbide Production

$CO_2$ is formed by the oxidation of petroleum coke in the production of calcium carbide. These $CO_2$ emissions are implicitly accounted for in the storage factor calculation for the non-energy use of petroleum coke in the Energy chapter. There is currently not sufficient data on coke consumption for calcium carbide production to estimate emissions from this source.

### $CO_2$ from Graphite Consumption in Ferroalloy and Steel Production

Emissions from "graphite," "wood," or "biomass" in calculating $CO_2$ emissions from ferroalloy production, iron and steel production or other "Industrial Processes" included in Chapter 4 of the inventory are not explicitly calculated. It is assumed that 100 percent of the C used in ferroalloy production is derived from petroleum coke and that all of the C used in iron and steel production is derived from coal coke or petroleum coke. It is also assumed that all of the C used in lead and zinc production is derived from coal coke. It is possible that some non-coke C is used in the production of ferroalloys, lead, zinc, and iron and steel, but no data are available to conduct inventory calculations for sources of C other than petroleum coke and coal coke used in these processes.

[97] The term "anthropogenic," in this context, refers to greenhouse gas emissions and removals that are a direct result of human activities or are the result of natural processes that have been affected by human activities ("2006 IPCC Guidelines for National Greenhouse Gas Inventories").

Non-fuel uses of coal coke and petroleum coke are accounted for in the Industrial Process chapter, either directly for iron and steel, aluminum, ferroalloy, lead, zinc, and titanium dioxide production, or indirectly by applying a storage factor to "uncharacterized" non-fuel uses of petroleum coke and coal coke. Non-fuel uses of wood and biomass are not accounted for in the Energy or Industrial Process chapters, as all uses of wood and biomass are accounted for in the Land Use, Land-Use Change, and Forestry chapter. It is assumed for the purposes of the $CO_2$ emission calculation that no wood or other biogenic C is used in any of these industrial processes. Some biogenic C may be used in these industrial processes but sufficient data to estimate emissions are not available.

Consumption of either natural or synthetic graphite is not explicitly accounted for in the Industrial Process chapter. It is assumed that all of the C used in manufacturing C anodes for production of aluminum, ferroalloys, and electric arc furnace (EAF) steel are derived directly from petroleum coke and coal tar pitch (a coal coke byproduct), not from natural graphite or synthetic graphite sources. Some amount of C used in these industrial processes may be derived from natural or synthetic graphite sources, but sufficient data to estimate emissions are not currently available.

#### Miscellaneous $SF_6$ Uses

Sulfur hexafluoride ($SF_6$) is used in several applications for which estimates have not been provided in this inventory. Sulfur hexafluoride may be emitted from the production, leakage, and dismantling of radar, tracer, and night vision equipment. Emissions from this source are believed to be minor, and no data were available for estimating the emissions. Sulfur hexafluoride may be used in foam insulation, for dry etching, in laser systems, for indoor air quality testing, for laboratory hood testing, for chromatography, in tandem accelerators, in loudspeakers, in shock absorbers, and for certain biomedical applications. Emissions from this source are believed to be minor, and no data were available for estimating the emissions. Sulfur hexafluoride may be emitted from the production, breakage, or leakage of soundproof double-glazed windows. Emissions from this source are believed to be minor, and no data were available for estimating the emissions. Sulfur hexafluoride may be emitted from applications involving the production of sport shoes, tires, and tennis balls. Emissions from this source are believed to be minor, and no data were available for estimating the emissions. Sulfur hexafluoride may be emitted from applications involving tracer gasses to detect leakage from pressure vessels and as a tracer gas in the open air. Emissions from this source are believed to be minor, and no data were available for estimating the emissions.

#### $CO_2$ from Non-Hazardous Industrial Waste Incineration and Medical Waste Incineration

Waste incineration is incorporated in two sections of the energy chapter of the inventory: in the section on $CO_2$ emissions from waste incineration, and in the calculation of emissions and storage from non-energy uses of fossil fuels. The former section addresses fossil-derived materials (such as plastics) that are discarded as part of the municipal wastestream and combusted (generally for energy recovery). The latter addresses two types of combustion: hazardous waste incineration of organic materials (assumed to be fossil-derived), in which regulated wastes are burned without energy recovery, and burning of fossil-derived materials for energy recovery. There additional categories of waste incineration that is not included in our calculus: industrial non-hazardous waste and medical waste incineration. Data are not readily available for these sources. Further research is needed to estimate the magnitude of $CO_2$ emissions, though they are believed to be very low in comparison with the overall emissions of waste incineration sources that are covered.

# ANNEX 6 Additional Information

## 6.1. Global Warming Potential Values

Global Warming Potentials (GWPs) are intended as a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas. It is defined as the cumulative radiative forcing—both direct and indirect effects—integrated over a period of time from the emission of a unit mass of gas relative to some reference gas (IPCC 1996). Carbon dioxide ($CO_2$) was chosen as this reference gas. Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The relationship between gigagrams (Gg) of a gas and teragrams of $CO_2$ equivalents (Tg $CO_2$ Eq.) can be expressed as follows:

$$\text{Tg}\,CO_2\ \text{Eq} = (\text{Gg of gas}) \times (\text{GWP}) \times \left(\frac{\text{Tg}}{1{,}000\,\text{Gg}}\right)$$

Where,

| | |
|---|---|
| Tg $CO_2$ Eq. | = Teragrams of Carbon Dioxide Equivalents |
| Gg | = Gigagrams (equivalent to a thousand metric tons) |
| GWP | = Global Warming Potential |
| Tg | = Teragrams |

GWP values allow policy makers to compare the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of ±35 percent, though some GWPs have larger uncertainty than others, especially those in which lifetimes have not yet been ascertained. In the following decision, the parties to the UNFCCC have agreed to use consistent GWPs from the IPCC Second Assessment Report (SAR), based upon a 100 year time horizon, although other time horizon values are available (see Table A-259).

> *In addition to communicating emissions in units of mass, Parties may choose also to use global warming potentials (GWPs) to reflect their inventories and projections in carbon dioxide-equivalent terms, using information provided by the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report. Any use of GWPs should be based on the effects of the greenhouse gases over a 100-year time horizon. In addition, Parties may also use other time horizons.*[98]

Greenhouse gases with relatively long atmospheric lifetimes (e.g., $CO_2$, $CH_4$, $N_2O$, HFCs, PFCs, and $SF_6$) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. However, the short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, other indirect greenhouse gases (e.g., $NO_x$ and NMVOCs), and tropospheric aerosols (e.g., $SO_2$ products and black carbon) vary spatially, and consequently it is difficult to quantify their global radiative forcing impacts. GWP values are generally not attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere.

Table A-259: Global Warming Potentials (GWP) and Atmospheric Lifetimes (Years) of Gases Used in this Report

| Gas | Atmospheric Lifetime | 100-year GWP[a] | 20-year GWP | 500-year GWP |
|---|---|---|---|---|
| Carbon dioxide ($CO_2$) | 50-200 | 1 | 1 | 1 |
| Methane ($CH_4$)[b] | 12±3 | 21 | 56 | 6.5 |
| Nitrous oxide ($N_2O$) | 120 | 310 | 280 | 170 |
| HFC-23 | 264 | 11,700 | 9,100 | 9,800 |
| HFC-32 | 5.6 | 650 | 2,100 | 200 |
| HFC-125 | 32.6 | 2,800 | 4,600 | 920 |

[98] Framework Convention on Climate Change; FCCC/CP/1996/15/Add.1; 29 October 1996; Report of the Conference of the Parties at its second session; held at Geneva from 8 to 19 July 1996; Addendum; Part Two: Action taken by the Conference of the Parties at its second session; Decision 9/CP.2; Communications from Parties included in Annex I to the Convention: guidelines, schedule and process for consideration; Annex: Revised Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention; p. 18. FCCC (1996)

| | | | | |
|---|---|---|---|---|
| HFC-134a | 14.6 | 1,300 | 3,400 | 420 |
| HFC-143a | 48.3 | 3,800 | 5,000 | 1,400 |
| HFC-152a | 1.5 | 140 | 460 | 42 |
| HFC-227ea | 36.5 | 2,900 | 4,300 | 950 |
| HFC-236fa | 209 | 6,300 | 5,100 | 4,700 |
| HFC-43-10mee | 17.1 | 1,300 | 3,000 | 400 |
| $CF_4$ | 50,000 | 6,500 | 4,400 | 10,000 |
| $C_2F_6$ | 10,000 | 9,200 | 6,200 | 14,000 |
| $C_3F_8$ | 2,600 | 7,000 | 4,800 | 10,100 |
| $C_4F_{10}$ | 2,600 | 7,000 | 4,800 | 10,100 |
| c-$C_4F_8$ | 3,200 | 8,700 | 6,000 | 12,700 |
| $C_5F_{12}$ | 4,100 | 7,500 | 5,100 | 11,000 |
| $C_6F_{14}$ | 3,200 | 7,400 | 5,000 | 10,700 |
| $SF_6$ | 3,200 | 23,900 | 16,300 | 34,900 |

Source: IPCC (1996)
[a] GWPs used in this report are calculated over 100 year time horizon.
[b] The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of $CO_2$ is not included.

Table A-260 presents direct and net (i.e., direct and indirect) GWPs for ozone-depleting substances (ODSs). Ozone-depleting substances directly absorb infrared radiation and contribute to positive radiative forcing; however, their effect as ozone-depleters also leads to a negative radiative forcing because ozone itself is a potent greenhouse gas. There is considerable uncertainty regarding this indirect effect; therefore, a range of net GWPs is provided for ozone depleting substances. The IPCC Guidelines and the UNFCCC do not include reporting instructions for estimating emissions of ODSs because their use is being phased-out under the Montreal Protocol (see note below Table A-260). The effects of these compounds on radiative forcing are not addressed in this report

Table A-260: Net 100-year Global Warming Potentials for Select Ozone Depleting Substances

| Gas | Direct | $Net_{min}$ | $Net_{max}$ |
|---|---|---|---|
| CFC-11 | 4,600 | (600) | 3,600 |
| CFC-12 | 10,600 | 7,300 | 9,900 |
| CFC-113 | 6,000 | 2,200 | 5,200 |
| HCFC-22 | 1,700 | 1,400 | 1,700 |
| HCFC-123 | 120 | 20 | 100 |
| HCFC-124 | 620 | 480 | 590 |
| HCFC-141b | 700 | (5) | 570 |
| HCFC-142b | 2,400 | 1,900 | 2,300 |
| $CHCl_3$ | 140 | (560) | 0 |
| $CCl_4$ | 1,800 | (3,900) | 660 |
| $CH_3Br$ | 5 | (2,600) | (500) |
| Halon-1211 | 1,300 | (24,000) | (3,600) |
| Halon-1301 | 6,900 | (76,000) | (9,300) |

Source: IPCC (2001)
Parentheses indicate negative values.
Note: Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as ozone depleting substances (ODSs). However, they are also potent greenhouse gases. Recognizing the harmful effects of these compounds on the ozone layer, in 1987 many governments signed the Montreal Protocol on Substances that Deplete the Ozone Layer to limit the production and importation of a number of CFCs and other halogenated compounds. The United States furthered its commitment to phase-out ODSs by signing and ratifying the Copenhagen Amendments to the Montreal Protocol in 1992. Under these amendments, the United States committed to ending the production and importation of halons by 1994, and CFCs by 1996.

The IPCC has published its Fourth Assessment Report (AR4), providing the most current and comprehensive scientific assessment of climate change (IPCC 2007). Within this report, the GWPs of several gases were revised relative to the SAR and the IPCC's Third Assessment Report (TAR) (IPCC 2001). Thus the GWPs used in this report have been updated twice by the IPCC; although the SAR GWPs are used throughout this report, it is informative to review the changes to the GWPs and the impact such improved understanding has on the total GWP-weighted emissions of the United States. All GWPs use $CO_2$ as a reference gas; a change in the radiative efficiency of $CO_2$ thus impacts the GWP of all other greenhouse gases. Since the SAR and TAR, the IPCC has applied an improved calculation of $CO_2$ radiative forcing and an improved $CO_2$ response function. The GWPs are drawn from IPCC/TEAP (2005) and the TAR, with updates for those cases where new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases have been recalculated. Because the revised radiative forcing of $CO_2$ is about 8 percent lower than that in the TAR, the GWPs of the other gases relative to $CO_2$ tend to be larger, taking into account

revisions in lifetimes. However, there were some instances in which other variables, such as the radiative efficiency or the chemical lifetime, were altered that resulted in further increases or decreases in particular GWP values. In addition, the values for radiative forcing and lifetimes have been calculated for a variety of halocarbons, which were not presented in the SAR. Updates in some well-mixed HFC compounds (including HFC-23, HFC-32, HFC-134a, and HFC-227ea) for AR4 result from investigation into radiative efficiencies in these compounds, with some GWPs changing by up to 40 percent; with this change, the uncertainties associated with these well-mixed HFCs are thought to be approximately 12 percent.

Table A- 261 compares the lifetimes and GWPs for the SAR, TAR, and AR4.

Table A- 261: Comparison of GWPs and lifetimes used in the SAR, TAR, and AR4

| | Lifetime (years) | | | GWP (100 year) | | | Difference (relative to SAR) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Gas** | **SAR** | **TAR** | **AR4** | **SAR** | **TAR** | **AR4** | **TAR** | **TAR (%)** | **AR4** | **AR4 (%)** |
| **Carbon dioxide ($CO_2$)** | 50-200 | 5-200[a] | 5-200[a] | 1 | 1 | 1 | NC | NC | NC | NC |
| **Methane ($CH_4$)[b]** | 12±3 | 8.4/12[c] | 8.7/12[c] | 21 | 23 | 25 | 2 | 10% | 4 | 19% |
| **Nitrous oxide ($N_2O$)** | 120 | 120/114 [c] | 120/114 [c] | 310 | 296 | 298 | (14) | (5%) | (12) | (4%) |
| **Hydrofluorocarbons** | | | | | | | | | | |
| HFC-23 | 264 | 260 | 270 | 11,700 | 12,000 | 14,800 | 300 | 3% | 3,100 | 26% |
| HFC-32 | 5.6 | 5.0 | 4.9 | 650 | 550 | 675 | (100) | (15%) | 25 | 4% |
| HFC-125 | 32.6 | 29 | 29 | 2,800 | 3,400 | 3,500 | 600 | 21% | 700 | 25% |
| HFC-134a | 14.6 | 13.8 | 14 | 1,300 | 1,300 | 1,430 | NC | NC | 130 | 10% |
| HFC-143a | 48.3 | 52 | 52 | 3,800 | 4,300 | 4,470 | 500 | 13% | 670 | 18% |
| HFC-152a | 1.5 | 1.4 | 1.4 | 140 | 120 | 124 | (20) | (14%) | (16) | (11%) |
| HFC-227ea | 36.5 | 33.0 | 34.2 | 2,900 | 3,500 | 3,220 | 600 | 21% | 320 | 11% |
| HFC-236fa | 209 | 220 | 240 | 6,300 | 9,400 | 9,810 | 3,100 | 49% | 3,510 | 56% |
| HFC-245fa | NA | 7.2 | 7.6 | NA | 950 | 1,030 | NA | NA | NA | NA |
| HFC-365mfc | NA | 9.9 | 6.6 | NA | 890 | 794 | NA | NA | NA | NA |
| HFC-43-10mee | 17.1 | 15 | 15.9 | 1,300 | 1,500 | 1,640 | 200 | 15% | 340 | 26% |
| **Fully Fluorinated Species** | | | | | | | | | | |
| $SF_6$ | 3,200 | 3,200 | 3200 | 23,900 | 22,200 | 22,800 | (1,700) | (7%) | (1,100) | (5%) |
| $CF_4$ | 50,000 | 50,000 | 50,000 | 6,500 | 5,700 | 7,390 | (800) | (12%) | 890 | 14% |
| $C_2F_6$ | 10,000 | 10,000 | 10,000 | 9,200 | 11,900 | 12,200 | 2,700 | 29% | 3,000 | 33% |
| $C_3F_8$ | 2,600 | 2,600 | 2,600 | 7,000 | 8,600 | 8,830 | 1,600 | 23% | 1,830 | 26% |
| $C_4F_{10}$ | 2,600 | 2,600 | 2,600 | 7,000 | 8,600 | 8,860 | 1,600 | 23% | 1,860 | 27% |
| c-$C_4F_8$ | 3,200 | 3,200 | 3,200 | 8,700 | 10,000 | 10,300 | 1,300 | 15% | 1,600 | 18% |
| $C_5F_{12}$ | 4,100 | 4,100 | 4,100 | 7,500 | 8,900 | 9,160 | 1,400 | 19% | 1,660 | 22% |
| $C_6F_{14}$ | 3,200 | 3,200 | 3,200 | 7,400 | 9,000 | 9,300 | 1,600 | 22% | 1,900 | 26% |
| **Others[d]** | | | | | | | | | | |
| $NF_3$ | NA | 740 | 740 | NA | 10,800 | 17,200 | NA | NA | NA | NA |

NC (No Change)
NA (Not Applicable)
[a] No single lifetime can be determined for $CO_2$. (See IPCC 2001)
[b] The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of $CO_2$ is not included.
[c] Methane and nitrous oxide have chemical feedback systems that can alter the length of the atmospheric response, in these cases, global mean atmospheric lifetime (LT) is given first, followed by perturbation time (PT).
[d] Gases whose lifetime has been determined only via indirect means or for whom there is uncertainty over the loss process.
Note: Parentheses indicate negative values.
Source: IPCC (2001)

The choice of GWPs between the SAR, TAR, and AR4 has an impact on both the overall emissions estimated by the inventory, as well as the trend in emissions over time. To summarize, Table A-262 shows the overall trend in U.S. greenhouse gas emissions, by gas, from 1990 through 2011 using the three GWP sets. The table also presents the impact of TAR and AR4 GWPs on the total emissions for 1990 and for 2011.

Table A-262: Effects on U.S. Greenhouse Gas Emissions Using TAR, SAR, and AR4 GWPs (Tg $CO_2$ Eq.)

| Gas | Trend from 1990 to 2011 | | | Revisions to Annual Estimates (relative to SAR) | | | |
|---|---|---|---|---|---|---|---|
| | | | | TAR | AR4 | TAR | AR4 |
| | SAR | TAR | AR4 | 1990 | | 2011 | |
| $CO_2$ | 525.0 | 525.0 | 525.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $CH_4$ | (57.9) | (63.4) | (68.9) | 61.0 | 121.9 | 55.4 | 110.9 |
| $N_2O$ | 14.5 | 13.9 | 14.0 | (16.3) | (14.0) | (17.0) | (14.6) |
| HFCs, PFCs, and $SF_6$* | 55.1 | 60.6 | 59.1 | (2.2) | 11.8 | 3.3 | 15.7 |
| **Total** | **536.8** | **536.1** | **529.1** | **42.4** | **119.7** | **41.7** | **112.1** |
| **Percent Change** | **9%** | **9%** | **8%** | **0.7%** | **1.9%** | **0.6%** | **1.7%** |

NC (No Change)
*Includes $NF_3$
Note: Totals may not sum due to independent rounding. Excludes sinks. Parentheses indicate negative values.

When the GWPs from the AR4 are applied to the emission estimates presented in this report, total emissions for the year 2011 are 6,820.3Tg $CO_2$ Eq., as compared to 6708.3 Tg $CO_2$ Eq. when the GWPs from the SAR are used (a 1.6 percent difference). Table A-263 provides a detailed summary of U.S. greenhouse gas emissions and sinks for 1990 through 2011, using the GWPs from the AR4. The percent change in emissions is equal to the percent change in the GWP; however, in cases where multiple gases are emitted in varying amounts the percent change is variable over the years, such as with substitutes for ozone depleting substances. Table A-264 summarizes the resulting change in emissions from SAR to AR4 GWPs for 1990 through 2011 including the percent change for 2011.

Table A-263: Recent Trends in U.S. Greenhouse Gas Emissions and Sinks using the AR4 GWPs (Tg $CO_2$ Eq.)

| Gas/Source | 1990 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|
| **CO2** | **5,079.9** | **6,089.7** | **6,024.0** | **6,123.4** | **5,935.7** | **5,515.0** | **5,711.1** | **5,604.9** |
| Fossil Fuel Combustion | 4,719.6 | 5,729.0 | 5,656.9 | 5,762.6 | 5,581.5 | 5,219.4 | 5,382.9 | 5,269.3 |
| Electricity Generation | 1,820.8 | 2,402.1 | 2,346.4 | 2,412.8 | 2,360.9 | 2,146.4 | 2,259.2 | 2,158.5 |
| Transportation | 1,465.0 | 1,872.0 | 1,882.0 | 1,899.6 | 1,798.6 | 1,739.5 | 1,748.6 | 1,742.1 |
| Industrial | 848.6 | 823.4 | 848.1 | 844.4 | 806.5 | 726.1 | 767.0 | 766.5 |
| Residential | 338.3 | 357.9 | 321.5 | 341.6 | 349.3 | 339.0 | 336.7 | 329.8 |
| Commercial | 219.0 | 223.5 | 208.6 | 218.9 | 225.1 | 224.6 | 221.8 | 222.7 |
| U.S. Territories | 27.9 | 50.0 | 50.3 | 45.2 | 41.0 | 43.8 | 49.6 | 49.7 |
| Non-Energy Use of Fuels | 117.4 | 142.7 | 144.9 | 134.9 | 139.5 | 124.0 | 132.8 | 130.6 |
| Iron and Steel Production & Metallurgical Coke Production | 99.8 | 66.7 | 69.4 | 71.3 | 66.8 | 43.0 | 55.7 | 64.3 |
| Natural Gas Systems | 37.7 | 29.9 | 30.0 | 30.9 | 32.6 | 32.2 | 32.3 | 32.3 |
| Cement Production | 33.3 | 45.2 | 45.8 | 44.5 | 40.5 | 29.0 | 30.9 | 31.6 |
| Lime Production | 11.5 | 14.3 | 15.0 | 14.6 | 14.3 | 11.2 | 13.1 | 13.8 |
| Incineration of Waste | 8.0 | 12.5 | 12.5 | 12.7 | 11.9 | 11.7 | 12.0 | 12.0 |
| Limestone and Dolomite Use | 4.9 | 6.3 | 7.3 | 7.4 | 5.9 | 7.6 | 9.6 | 9.2 |
| Ammonia Production | 13.0 | 9.2 | 8.8 | 9.1 | 7.9 | 7.9 | 8.7 | 8.8 |
| Cropland Remaining Cropland | 7.1 | 7.9 | 7.9 | 8.2 | 8.6 | 7.2 | 8.4 | 8.1 |
| Urea Consumption for Non-Agricultural Purposes | 3.8 | 3.7 | 3.5 | 4.9 | 4.1 | 3.4 | 4.4 | 4.3 |
| Petrochemical Production | 3.4 | 4.3 | 4.0 | 4.1 | 3.6 | 2.8 | 3.5 | 3.5 |
| Aluminum Production | 6.8 | 4.1 | 3.8 | 4.3 | 4.5 | 3.0 | 2.7 | 3.3 |
| Soda Ash Production and Consumption | 2.8 | 3.0 | 2.9 | 2.9 | 3.0 | 2.6 | 2.7 | 2.7 |
| Titanium Dioxide Production | 1.2 | 1.8 | 1.8 | 1.9 | 1.8 | 1.6 | 1.8 | 1.9 |
| Carbon Dioxide Consumption | 1.4 | 1.3 | 1.7 | 1.9 | 1.8 | 1.8 | 2.2 | 1.8 |
| Ferroalloy Production | 2.2 | 1.4 | 1.5 | 1.6 | 1.6 | 1.5 | 1.7 | 1.7 |
| Glass Production | 1.5 | 1.9 | 2.1 | 1.5 | 1.5 | 1.0 | 1.5 | 1.3 |
| Zinc Production | 0.6 | 1.0 | 1.0 | 1.0 | 1.2 | 0.9 | 1.2 | 1.3 |
| Phosphoric Acid Production | 1.5 | 1.4 | 1.2 | 1.2 | 1.2 | 1.0 | 1.0 | 1.1 |
| Wetlands Remaining Wetlands | 1.0 | 1.1 | 0.9 | 1.0 | 1.0 | 1.1 | 1.0 | 0.9 |
| Lead Production | 0.5 | 0.6 | 0.6 | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 |
| Petroleum Systems | 0.4 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Silicon Carbide Production and Consumption | 0.4 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.2 | 0.2 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *Land Use, Land-Use Change, and Forestry (Sink)[a]* | *(872.7)* | *(1027.9)* | *(994.7)* | *(982.6)* | *(955.8)* | *(935.6)* | *(941.9)* | *(958.3)* |
| *Wood Biomass and Ethanol Consumption[b]* | *218.6* | *228.7* | *232.7* | *238.3* | *251.7* | *245.1* | *264.5* | *264.5* |
| *International Bunker Fuels[c]* | *132.8* | *134.3* | *124.5* | *122.0* | *124.9* | *110.7* | *126.9* | *116.2* |
| **CH4** | **761.9** | **707.3** | **732.5** | **737.1** | **737.2** | **719.4** | **706.2** | **693.0** |
| Natural Gas Systems | 192.0 | 189.8 | 201.2 | 200.9 | 195.0 | 179.9 | 171.4 | 166.1 |
| Enteric Fermentation | 158.0 | 163.0 | 165.8 | 168.8 | 168.3 | 167.3 | 165.8 | 163.5 |
| Landfills | 175.9 | 133.9 | 132.8 | 132.9 | 135.2 | 134.9 | 127.1 | 122.7 |
| Coal Mining | 100.1 | 67.7 | 69.3 | 68.9 | 79.9 | 83.7 | 86.2 | 75.3 |
| Manure Management | 37.5 | 56.6 | 57.2 | 62.3 | 61.3 | 60.1 | 61.7 | 62.0 |
| Petroleum Systems | 41.9 | 34.8 | 34.7 | 35.5 | 35.8 | 36.4 | 36.7 | 37.5 |
| Wastewater Treatment | 19.0 | 19.6 | 19.8 | 19.8 | 19.8 | 19.6 | 19.5 | 19.2 |
| Forest Land Remaining Forest Land | 3.0 | 9.6 | 21.1 | 17.1 | 10.3 | 6.8 | 5.6 | 16.9 |
| Rice Cultivation | 8.5 | 8.2 | 7.0 | 7.4 | 8.6 | 8.7 | 10.2 | 7.9 |
| Stationary Combustion | 8.9 | 7.9 | 7.3 | 7.6 | 7.8 | 7.5 | 7.5 | 7.5 |
| Abandoned Underground Coal Mines | 7.2 | 6.6 | 6.5 | 6.3 | 6.3 | 6.1 | 5.9 | 5.8 |
| Petrochemical Production | 2.7 | 3.7 | 3.8 | 3.9 | 3.4 | 3.4 | 3.7 | 3.7 |
| Mobile Combustion | 5.6 | 2.9 | 2.8 | 2.6 | 2.4 | 2.3 | 2.2 | 2.1 |
| Composting | 0.4 | 1.9 | 1.9 | 2.0 | 2.0 | 1.9 | 1.8 | 1.8 |
| Iron and Steel Production & Metallurgical Coke Production | 1.1 | 0.9 | 0.9 | 0.8 | 0.8 | 0.4 | 0.6 | 0.7 |
| Field Burning of Agricultural Residues | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 |
| Ferroalloy Production | + | + | + | + | + | + | + | + |
| Silicon Carbide Production and Consumption | + | + | + | + | + | + | + | + |
| Incineration of Waste | + | + | + | + | + | + | + | + |
| *International Bunker Fuels[c]* | *0.2* | *0.2* | *0.2* | *0.2* | *0.2* | *0.2* | *0.2* | *0.2* |
| **N2O** | **347.4** | **357.4** | **372.7** | **385.3** | **360.4** | **348.2** | **353.7** | **361.4** |
| Agricultural Soil Management | 235.8 | 243.5 | 252.0 | 266.3 | 260.4 | 256.1 | 258.3 | 256.2 |
| Stationary Combustion | 11.8 | 19.8 | 19.9 | 20.3 | 20.3 | 19.9 | 21.7 | 21.1 |
| Mobile Combustion | 42.0 | 35.3 | 32.4 | 27.9 | 24.3 | 21.7 | 19.7 | 17.6 |
| Manure Management | 13.8 | 16.4 | 17.2 | 17.3 | 17.1 | 17.0 | 17.1 | 17.3 |
| Nitric Acid Production | 17.5 | 16.3 | 15.9 | 19.0 | 16.2 | 13.5 | 16.1 | 14.9 |
| Forest Land Remaining Forest Land | 2.0 | 6.7 | 14.2 | 11.6 | 7.1 | 4.8 | 4.0 | 11.5 |
| Adipic Acid Production | 15.2 | 7.1 | 8.6 | 10.3 | 2.5 | 2.7 | 4.2 | 10.2 |
| Wastewater Treatment | 3.3 | 4.5 | 4.6 | 4.6 | 4.7 | 4.8 | 4.9 | 5.0 |
| N2O from Product Uses | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 |
| Composting | 0.3 | 1.7 | 1.7 | 1.8 | 1.8 | 1.7 | 1.6 | 1.6 |
| Settlements Remaining Settlements | 0.9 | 1.4 | 1.4 | 1.5 | 1.4 | 1.3 | 1.4 | 1.3 |
| Incineration of Waste | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Field Burning of Agricultural Residues | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Wetlands Remaining Wetlands | + | + | + | + | + | + | + | + |
| *International Bunker Fuels[c]* | *1.2* | *1.2* | *1.1* | *1.1* | *1.1* | *1.0* | *1.1* | *1.0* |
| **HFCs, PFCs, and SF6** | **102.0** | **150.0** | **149.6** | **155.0** | **149.7** | **138.4** | **151.4** | **161.1** |
| **HFCs** | **46.6** | **127.7** | **128.5** | **133.5** | **130.2** | **123.0** | **134.0** | **143.0** |
| Substitution of Ozone Depleting Substances[d] | 0.3 | 107.4 | 110.6 | 111.6 | 112.6 | 115.9 | 125.5 | 133.7 |
| HCFC-22 Production | 46.1 | 20.0 | 17.5 | 21.5 | 17.2 | 6.8 | 8.0 | 8.8 |
| Semiconductor Manufacture | 0.2 | 0.3 | 0.3 | 0.4 | 0.4 | 0.3 | 0.5 | 0.4 |
| **PFCs** | **24.3** | **7.9** | **8.0** | **9.8** | **8.6** | **6.0** | **7.8** | **9.2** |
| Semiconductor Manufacture | 2.9 | 4.5 | 5.1 | 5.3 | 5.5 | 4.2 | 5.9 | 5.7 |
| Aluminum Production | 21.5 | 3.4 | 2.9 | 4.5 | 3.2 | 1.9 | 1.9 | 3.5 |
| **SF6** | **31.1** | **14.3** | **13.1** | **11.7** | **10.9** | **9.4** | **9.6** | **8.9** |
| Electrical Transmission and Distribution | 25.4 | 10.6 | 9.4 | 8.4 | 8.2 | 7.7 | 7.4 | 6.7 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Magnesium Production and Processing | 5.2 | 2.8 | 2.7 | 2.5 | 1.8 | 1.0 | 1.2 | 1.3 |
| Semiconductor Manufacture | 0.5 | 0.9 | 0.9 | 0.8 | 0.8 | 0.7 | 1.0 | 0.9 |
| **Total** | **6,291.2** | **7,304.3** | **7,278.7** | **7,400.7** | **7,183.0** | **6,720.9** | **6,922.3** | **6,820.3** |

+ Does not exceed 0.05 Tg CO2 Eq.
[a] The net CO2 flux total includes both emissions and sequestration, and constitutes a sink in the United States. Parentheses indicate negative values or sequestration.
[b] Emissions from Wood Biomass and Ethanol Consumption are not included specifically in summing energy sector totals.
[c] Emissions from International Bunker Fuels are not included in totals.
[d] Small amounts of PFC emissions also result from this source.
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table A-264: Change in U.S. Greenhouse Gas Emissions and Sinks Using SAR vs. AR4 GWPs (Tg $CO_2$ Eq.)

| Gas/Source | 1990 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | Percent Change in 2011 |
|---|---|---|---|---|---|---|---|---|---|
| **$CO_2$** | **NC** | **NC** | **NC** | **NC** | **NC** | **NC** | **NC** | **NC** | **NC** |
| **$CH_4$** | **121.9** | **113.2** | **117.2** | **117.9** | **118.0** | **115.1** | **113.0** | **110.9** | **19%** |
| Natural Gas Systems | 30.7 | 30.4 | 32.2 | 32.1 | 31.2 | 28.8 | 27.4 | 26.6 | 19% |
| Enteric Fermentation | 25.3 | 26.1 | 26.5 | 27.0 | 26.9 | 26.8 | 26.5 | 26.2 | 19% |
| Landfills | 28.1 | 21.4 | 21.2 | 21.3 | 21.6 | 21.6 | 20.3 | 19.6 | 19% |
| Coal Mining | 16.0 | 10.8 | 11.1 | 11.0 | 12.8 | 13.4 | 13.8 | 12.0 | 19% |
| Manure Management | 6.0 | 9.1 | 9.2 | 10.0 | 9.8 | 9.6 | 9.9 | 9.9 | 19% |
| Petroleum Systems | 6.7 | 5.6 | 5.6 | 5.7 | 5.7 | 5.8 | 5.9 | 6.0 | 19% |
| Wastewater Treatment | 3.0 | 3.1 | 3.2 | 3.2 | 3.2 | 3.1 | 3.1 | 3.1 | 19% |
| Forest Land Remaining Forest Land | 0.5 | 1.5 | 3.4 | 2.7 | 1.7 | 1.1 | 0.9 | 2.7 | 19% |
| Rice Cultivation | 1.4 | 1.3 | 1.1 | 1.2 | 1.4 | 1.4 | 1.6 | 1.3 | 19% |
| Stationary Combustion | 1.4 | 1.3 | 1.2 | 1.2 | 1.3 | 1.2 | 1.2 | 1.2 | 19% |
| Abandoned Underground Coal Mines | 1.2 | 1.1 | 1.0 | 1.0 | 1.0 | 1.0 | 0.9 | 0.9 | 19% |
| Petrochemical Production | 0.4 | 0.6 | 0.6 | 0.6 | 0.5 | 0.6 | 0.6 | 0.6 | 19% |
| Mobile Combustion | 0.9 | 0.5 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.3 | 19% |
| Composting | 0.1 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 19% |
| Iron and Steel Production & Metallurgical Coke Production | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 19% |
| Field Burning of Agricultural Residues | + | + | + | + | + | + | + | + | 19% |
| Ferroalloy Production | + | + | + | + | + | + | + | + | 19% |
| Silicon Carbide Production and Consumption | + | + | + | + | + | + | + | + | 19% |
| Incineration of Waste | + | + | + | + | + | + | + | + | 19% |
| *International Bunker Fuels*[a] | + | + | + | + | + | + | + | + | *19%* |
| **$N_2O$** | **(14.0)** | **(14.4)** | **(15.0)** | **(15.5)** | **(14.5)** | **(14.0)** | **(14.2)** | **(14.6)** | **(4%)** |
| Agricultural Soil Management | (9.5) | (9.8) | (10.1) | (10.7) | (10.5) | (10.3) | (10.4) | (10.3) | (4%) |
| Stationary Combustion | (0.5) | (0.8) | (0.8) | (0.8) | (0.8) | (0.8) | (0.9) | (0.9) | (4%) |
| Mobile Combustion | (1.7) | (1.4) | (1.3) | (1.1) | (1.0) | (0.9) | (0.8) | (0.7) | (4%) |
| Manure Management | (0.6) | (0.7) | (0.7) | (0.7) | (0.7) | (0.7) | (0.7) | (0.7) | (4%) |
| Nitric Acid Production | (0.7) | (0.7) | (0.6) | (0.8) | (0.7) | (0.5) | (0.6) | (0.6) | (4%) |
| Forest Land Remaining Forest Land | (0.1) | (0.3) | (0.6) | (0.5) | (0.3) | (0.2) | (0.2) | (0.5) | (4%) |
| Adipic Acid Production | (0.6) | (0.3) | (0.3) | (0.4) | (0.1) | (0.1) | (0.2) | (0.4) | (4%) |
| Wastewater Treatment | (0.1) | (0.2) | (0.2) | (0.2) | (0.2) | (0.2) | (0.2) | (0.2) | (4%) |
| $N_2O$ from Product Uses | (0.2) | (0.2) | (0.2) | (0.2) | (0.2) | (0.2) | (0.2) | (0.2) | (4%) |
| Composting | (0.0) | (0.1) | (0.1) | (0.1) | (0.1) | (0.1) | (0.1) | (0.1) | (4%) |
| Settlements Remaining Settlements | (0.0) | (0.1) | (0.1) | (0.1) | (0.1) | (0.1) | (0.1) | (0.1) | (4%) |
| Incineration of Waste | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (4%) |
| Field Burning of Agricultural Residues | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (4%) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Wetlands Remaining Wetlands | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (4%) |
| *International Bunker Fuels*[a] | *(0.0)* | *(0.0)* | *(0.0)* | *(0.0)* | *(0.0)* | *(0.0)* | *(0.0)* | *(0.0)* | *(4%)* |
| **HFCs, PFCs, and $SF_6$** | **11.8** | **13.8** | **13.9** | **15.1** | **14.2** | **12.2** | **14.1** | **15.7** | **11%** |
| **HFCs** | **9.7** | **12.7** | **12.5** | **13.5** | **12.7** | **11.0** | **12.7** | **14.0** | **11%** |
| Substitution of Ozone Depleting Substances | (0.0) | 8.5 | 8.8 | 8.9 | 9.1 | 9.6 | 10.9 | 12.1 | 10% |
| HCFC-22 Production | 9.7 | 4.2 | 3.7 | 4.5 | 3.6 | 1.4 | 1.7 | 1.8 | 26% |
| Semiconductor Manufacture | 0.045 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 26% |
| **PFCs** | **3.7** | **1.8** | **2.0** | **2.2** | **2.0** | **1.6** | **1.9** | **2.2** | **31%** |
| Semiconductor Manufacture | 0.6 | 1.3 | 1.6 | 1.5 | 1.6 | 1.3 | 1.6 | 1.7 | 41% |
| Aluminum Production | 3.0 | 0.5 | 0.4 | 0.6 | 0.5 | 0.3 | 0.3 | 0.5 | 18% |
| **$SF_6$** | **(1.5)** | **(0.7)** | **(0.6)** | **(0.6)** | **(0.5)** | **(0.5)** | **(0.5)** | **(0.4)** | **(5%)** |
| Electrical Transmission and Distribution | (1.2) | (0.5) | (0.5) | (0.4) | (0.4) | (0.4) | (0.4) | (0.3) | (5%) |
| Magnesium Production and Processing | (0.3) | (0.1) | (0.1) | (0.1) | (0.1) | (0.0) | (0.1) | (0.1) | (5%) |
| Semiconductor Manufacture | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (5%) |
| **Total** | **119.7** | **112.6** | **116.1** | **117.5** | **117.7** | **113.2** | **112.8** | **112.1** | **1.7%** |

NC (No change)
+ Does not exceed 0.05 Tg $CO_2$ Eq.
[a] Emissions from International Bunker Fuels are not included in totals.
Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Table A-265 below shows a comparison of total emissions estimates by sector using both the IPCC SAR and AR4 GWP values. For most sectors, the change in emissions was minimal. The effect on emissions from waste was by far the greatest (17.8 percent in 2011), due the predominance of $CH_4$ emissions in this sector. Emissions from all other sectors were comprised of mainly $CO_2$ or a mix of gases, which moderated the effect of the changes.

Table A-265: Comparison of Emissions by Sector using IPCC SAR and AR4 GWP Values (Tg $CO_2$ Eq.)

| Sector | 1990 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|
| **Energy** | | | | | | | | |
| SAR GWP (Used in Inventory) | 5,238.2 | 6,232.2 | 6,169.9 | 6,262.3 | 6,087.4 | 5,696.6 | 5,864.2 | 5,732.5 |
| AR4 GWP, Updated | 5,292.9 | 6,279.5 | 6,219.3 | 6,311.8 | 6,137.9 | 5,745.4 | 5,912.1 | 5,778.0 |
| Difference (%) | 1.0% | 0.8% | 0.8% | 0.8% | 0.8% | 0.9% | 0.8% | 0.8% |
| **Industrial Processes** | | | | | | | | |
| SAR GWP (Used in Inventory) | 316.1 | 330.8 | 335.7 | 347.2 | 318.8 | 265.4 | 303.4 | 326.4 |
| AR4 GWP, Updated | 327.3 | 344.4 | 349.3 | 361.8 | 332.9 | 277.5 | 317.3 | 341.9 |
| Difference (%) | 3.5% | 4.1% | 4.1% | 4.2% | 4.4% | 4.6% | 4.6% | 4.7% |
| **Solvent and Other Product Use** | | | | | | | | |
| SAR GWP (Used in Inventory) | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 |
| AR4 GWP, Updated | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 |
| Difference (%) | -3.9% | -3.9% | -3.9% | -3.9% | -3.9% | -3.9% | -3.9% | -3.9% |
| **Agriculture** | | | | | | | | |
| SAR GWP (Used in Inventory) | 431.2 | 462.0 | 473.6 | 495.6 | 489.0 | 482.8 | 486.4 | 480.8 |
| AR4 GWP, Updated | 453.9 | 488.0 | 499.6 | 522.4 | 516.0 | 509.6 | 513.4 | 507.2 |
| Difference (%) | 5.2% | 5.6% | 5.5% | 5.4% | 5.5% | 5.6% | 5.5% | 5.5% |
| **Land Use, Land-Use Change, and Forestry** | | | | | | | | |
| SAR GWP (Used in Inventory) | (859.0) | (1,002.5) | (952.0) | (945.4) | (928.6) | (915.1) | (922.2) | (921.8) |
| AR4 GWP, Updated | (858.6) | (1,001.3) | (949.2) | (943.2) | (927.3) | (914.3) | (921.5) | (919.7) |
| Difference (%) | 0.0% | -0.1% | -0.3% | -0.2% | -0.1% | -0.1% | -0.1% | -0.2% |
| **Waste** | | | | | | | | |
| SAR GWP (Used in Inventory) | 167.8 | 136.9 | 136.3 | 136.5 | 138.7 | 138.1 | 131.4 | 127.6 |
| AR4 GWP, Updated | 198.9 | 161.6 | 160.8 | 161.0 | 163.5 | 162.9 | 154.9 | 150.4 |
| Difference (%) | 18.5% | 18.0% | 18.0% | 17.9% | 17.9% | 17.9% | 17.9% | 17.8% |
| **Net Emissions (Sources and Sinks)** | | | | | | | | |
| **SAR GWP (Used in Inventory)** | **5,298.8** | **6,163.9** | **6,167.9** | **6,300.6** | **6,109.6** | **5,672.1** | **5,867.6** | **5,750.0** |
| **AR4 GWP** | **5,418.6** | **6,276.4** | **6,283.9** | **6,418.1** | **6,227.2** | **5,785.3** | **5,980.4** | **5,862.0** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Difference (%)** | **2.3%** | **1.8%** | **1.9%** | **1.9%** | **1.9%** | **2.0%** | **1.9%** | **1.9%** |

Note: Totals may not sum due to independent rounding. Parentheses indicate negative values.

Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends, as shown in Table A-266 and Table A-267.

Table A-266: Change in U.S. Greenhouse Gas Emissions and Sinks Using TAR vs. AR4 GWPs (Tg $CO_2$ Eq.)

| Gas | 1990 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|
| $CO_2$ | NC | NC | NC | NC | NC | NC | NC | NC |
| $CH_4$ | 61.0 | 56.6 | 58.6 | 59.0 | 59.0 | 57.6 | 56.5 | 55.4 |
| $N_2O$ | 2.3 | 2.4 | 2.5 | 2.6 | 2.4 | 2.3 | 2.4 | 2.4 |
| HFCs | 8.8 | 12.2 | 11.9 | 12.6 | 11.7 | 9.7 | 10.4 | 10.9 |
| PFCs* | 4.4 | 1.2 | 1.2 | 1.5 | 1.2 | 0.9 | 1.0 | 1.4 |
| $SF_6$ | 0.8 | 0.4 | 0.3 | 0.3 | 0.3 | 0.2 | 0.3 | 0.2 |
| **Total** | **77.3** | **72.8** | **74.6** | **75.9** | **74.6** | **70.7** | **70.5** | **70.3** |

NC (No change)
*Includes $NF_3$
Note: Totals may not sum due to independent rounding.

Table A-267: Change in U.S. Greenhouse Gas Emissions Using TAR vs. AR4 GWPs (Percent)

| Gas/Source | 1990 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|
| **$CO_2$** | NC | NC | NC | NC | NC | NC | NC | NC |
| **$CH_4$** | 8.7% | 8.7% | 8.7% | 8.7% | 8.7% | 8.7% | 8.7% | 8.7% |
| **$N_2O$** | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% | 0.7% |
| **HFCs** | 2.7% | 2.7% | 2.7% | 2.7% | 2.7% | 2.7% | 2.7% | 2.7% |
| Substitution of Ozone Depleting Substances | 23.2% | 10.6% | 10.2% | 10.4% | 9.8% | 8.5% | 8.4% | 8.2% |
| HCFC-22 Production[b] | 3.3% | 8.5% | 8.4% | 8.2% | 8.0% | 7.8% | 7.5% | 7.3% |
| Semiconductor Manufacture[c] | 23.3% | 23.3% | 23.3% | 23.3% | 23.3% | 23.3% | 23.3% | 23.3% |
| **PFCs** | 23.3% | 23.3% | 23.3% | 23.3% | 23.3% | 23.3% | 23.3% | 23.3% |
| Semiconductor Manufacture[c] | 22.4% | 17.7% | 17.6% | 17.7% | 16.9% | 17.5% | 15.3% | 17.6% |
| Aluminum Production[a] | 10.0% | 13.1% | 14.2% | 13.2% | 13.6% | 15.3% | 13.5% | 15.0% |
| **$SF_6$** | 24.2% | 24.4% | 24.2% | 23.4% | 22.9% | 22.8% | 21.5% | 22.1% |
| **Total** | **1.2%** | **1.6%** | **1.6%** | **1.6%** | **1.7%** | **1.7%** | **1.7%** | **1.7%** |

NC (No change)
[a] PFC emissions from $CF_4$ and $C_2F_6$
[b] HFC-23 emitted
[c] Emissions from HFC-23, $CF_4$, $C_2F_6$, $C_3F_8$, $SF_6$, and the addition of $NF_3$
Note: Excludes Sinks.

## References


IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon , D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom 996 pp.

IPCC (2001) Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change, J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell (eds.). Cambridge University Press. Cambridge, United Kingdom.

## 6.2. Ozone Depleting Substance Emissions

Ozone is present in both the stratosphere,[99] where it shields the earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere,[100] where it is the main component of anthropogenic photochemical "smog." Chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs), along with certain other chlorine and bromine containing compounds, have been found to deplete the ozone levels in the stratosphere. These compounds are commonly referred to as ozone depleting substances (ODSs). If left unchecked, stratospheric ozone depletion could result in a dangerous increase of ultraviolet radiation reaching the earth's surface. In 1987, nations around the world signed the *Montreal Protocol on Substances that Deplete the Ozone Layer*. This landmark agreement created an international framework for limiting, and ultimately eliminating, the production of most ozone depleting substances. ODSs have historically been used in a variety of industrial applications, including refrigeration and air conditioning, foam blowing, fire extinguishing, sterilization, solvent cleaning, and as an aerosol propellant.

In the United States, the Clean Air Act Amendments of 1990 provide the legal instrument for implementation of the *Montreal Protocol* controls. The Clean Air Act classifies ozone depleting substances as either Class I or Class II, depending upon the ozone depletion potential (ODP) of the compound.[101] The production of CFCs, halons, carbon tetrachloride, and methyl chloroform─all Class I substances─has already ended in the United States. However, large amounts of these chemicals remain in existing equipment,[102] and stockpiles of the ODSs, as well as material recovered from equipment being decommissioned, are used for maintaining the existing equipment. As a result, emissions of Class I compounds will continue, albeit in ever decreasing amounts, for many more years. Class II designated substances, all of which are HCFCs, have been, or are being, phased out at later dates than Class I compounds because they have lower ozone depletion potentials. These compounds served, and in some cases continue to serve, as interim replacements for Class I compounds in many industrial applications. The use and emissions of HCFCs in the United States is anticipated to continue for several decades as equipment that use Class I substances and Class II substances are retired from use. Under current controls, however, the production for domestic use of all HCFCs in the United States will end by the year 2030.

In addition to contributing to ozone depletion, CFCs, halons, carbon tetrachloride, methyl chloroform, and HCFCs are also potent greenhouse gases. However, the depletion of the ozone layer has a cooling effect on the climate that counteracts the direct warming from tropospheric emissions of ODSs. Stratospheric ozone influences the earth's radiative balance by absorption and emission of longwave radiation from the troposphere as well as absorption of shortwave radiation from the sun; overall, stratospheric ozone has a warming effect.

The IPCC has prepared both direct GWPs and net (combined direct warming and indirect cooling) GWP ranges for some of the most common ozone depleting substances (IPCC 1996). See Annex 6.1, Global Warming Potential Values, for a listing of the net GWP values for ODS.

Although the IPCC emission inventory guidelines do not require the reporting of emissions of ozone depleting substances, the United States believes that no inventory is complete without the inclusion of these compounds. Emission estimates for several ozone depleting substances are provided in Table A- 268.

Table A- 268: Emissions of Ozone Depleting Substances (Gg)

| Compound | 1990 | 1995 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Class I** | | | | | | | | | | | | | | |
| CFC-11 | 29.0 | 12.1 | 12.7 | 12.7 | 12.6 | 12.7 | 12.4 | 12.2 | 12.2 | 11.1 | 9.9 | 8.6 | 8.3 | 7.8 |
| CFC-12 | 108.7 | 65.9 | 32.9 | 26.8 | 21.7 | 17.2 | 12.9 | 9.0 | 6.4 | 5.9 | 4.9 | 4.0 | 3.6 | 3.1 |

[99] The stratosphere is the layer from the top of the troposphere up to about 50 kilometers. Approximately 90 percent of atmospheric ozone is within the stratosphere. The greatest concentration of ozone occurs in the middle of the stratosphere, in a region commonly called the ozone layer.

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

[101] Substances with an ozone depletion potential of 0.2 or greater are designated as Class I. All other designated substances that deplete stratospheric ozone but which have an ODP of less than 0.2 are Class II.

[102] Older refrigeration and air-conditioning equipment, fire extinguishing systems, meter-dose inhalers, and foam products blown with CFCs/HCFCs may still contain ODS.

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CFC-113 | 59.4 | | 11.5 | | + | + | + | + | + | + | + | + | + | + | + |
| CFC-114 | 5.4 | | 1.1 | | 0.5 | 0.4 | 0.4 | 0.3 | 0.3 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 |
| CFC-115 | 8.9 | | 6.8 | | 4.2 | 3.8 | 3.4 | 3.0 | 2.6 | 2.1 | 1.6 | 1.1 | 0.7 | 0.3 | 0.1 | 0.1 |
| Carbon Tetrachloride | 4.3 | | 0.9 | | + | + | + | + | + | + | + | + | + | + | + | + |
| Methyl Chloroform | 222.5 | | 72.1 | | + | + | + | + | + | + | + | + | + | + | + | + |
| Halon-1211 | 1.6 | | 1.6 | | 1.1 | 0.9 | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 |
| Halon-1301 | 1.6 | | 1.6 | | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.4 | 1.3 | 1.1 | 0.9 | 0.8 | 0.7 | 0.6 |
| **Class II** | | | | | | | | | | | | | | | | |
| HCFC-22 | 49.3 | | 57.2 | | 72.0 | 74.6 | 77.6 | 79.2 | 81.4 | 82.2 | 84.6 | 85.6 | 87.3 | 87.7 | 84.2 | 83.0 |
| HCFC-123 | + | | 0.3 | | 0.6 | 0.6 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| HCFC-124 | + | | 1.3 | | 1.5 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.5 | 1.6 | 1.6 | 1.6 | 0.7 | 0.7 |
| HCFC-141b | 1.0 | | 4.0 | | 7.0 | 6.7 | 5.6 | 4.0 | 4.1 | 4.2 | 4.3 | 5.5 | 6.9 | 8.4 | 8.7 | 9.0 |
| HCFC-142b | 2.1 | | 3.6 | | 2.7 | 2.8 | 2.9 | 3.0 | 3.2 | 3.3 | 3.4 | 3.5 | 3.7 | 2.5 | 1.1 | 1.2 |
| HCFC-225ca/cb | + | | 0.1 | | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |

+ Does not exceed 0.05 Gg.

## Methodology and Data Sources

Emissions of ozone depleting substances were estimated using the EPA's Vintaging Model. The model, named for its method of tracking the emissions of annual "vintages" of new equipment that enter into service, is a "bottom-up" model. It models the consumption of chemicals based on estimates of the quantity of equipment or products sold, serviced, and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment. The Vintaging Model makes use of this market information to build an inventory of the in-use stocks of the equipment in each of the end-uses. Emissions are estimated by applying annual leak rates, service emission rates, and disposal emission rates to each population of equipment. By aggregating the emission and consumption output from the different end-uses, the model produces estimates of total annual use and emissions of each chemical. Please see Annex 3.8, Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances, of this Inventory for a more detailed discussion of the Vintaging Model.

## Uncertainties

Uncertainties exist with regard to the levels of chemical production, equipment sales, equipment characteristics, and end-use emissions profiles that are used by these models. Please see the ODS Substitutes section of this report for a more detailed description of the uncertainties that exist in the Vintaging Model.

## References

IPCC (1996) Climate Change 1995: The Science of Climate Change. Intergovernmental Panel on Climate Change, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell. (eds.). Cambridge University Press. Cambridge, United Kingdom.

## 6.3. Sulfur Dioxide Emissions – TO BE UPDATED

Sulfur dioxide ($SO_2$), emitted into the atmosphere through natural and anthropogenic processes, affects the Earth's radiative budget through photochemical transformation into sulfate aerosols that can (1) scatter sunlight back to space, thereby reducing the radiation reaching the Earth's surface; (2) affect cloud formation; and (3) affect atmospheric chemical composition (e.g., stratospheric ozone, by providing surfaces for heterogeneous chemical reactions). The overall effect of $SO_2$-derived aerosols on radiative forcing is believed to be negative (IPCC 2007). However, because $SO_2$ is short-lived and unevenly distributed through the atmosphere, its radiative forcing impacts are highly uncertain. Sulfur dioxide emissions have been provided below in Table A-269.

The major source of $SO_2$ emissions in the United States is the burning of sulfur containing fuels, mainly coal. Metal smelting and other industrial processes also release significant quantities of $SO_2$. The largest contributor to U.S. emissions of $SO_2$ is electricity generation, accounting for 60 percent of total $SO_2$ emissions in 2011 (see Table A-270); coal combustion accounted for approximately 92 percent of that total. The second largest source was industrial fuel combustion, which produced 18 percent of 2011 $SO_2$ emissions. Overall, $SO_2$ emissions in the United States decreased by 59 percent from 1990 to 2011. The majority of this decline came from reductions from electricity generation, primarily due to increased consumption of low sulfur coal from surface mines in western states.

Sulfur dioxide is important for reasons other than its effect on radiative forcing. It is a major contributor to the formation of urban smog and acid rain. As a contributor to urban smog, high concentrations of $SO_2$ can cause significant increases in acute and chronic respiratory diseases. In addition, once $SO_2$ is emitted, it is chemically transformed in the atmosphere and returns to earth as the primary contributor to acid deposition, or acid rain. Acid rain has been found to accelerate the decay of building materials and paints, and to cause the acidification of lakes and streams and damage trees. As a result of these harmful effects, the United States has regulated the emissions of $SO_2$ under the Clean Air Act. The EPA has also developed a strategy to control these emissions via four programs: (1) the National Ambient Air Quality Standards program,[103] (2) New Source Performance Standards,[104] (3) the New Source Review/Prevention of Significant Deterioration Program,[105] and (4) the sulfur dioxide allowance program.[106]

Table A-269: $SO_2$ Emissions (Gg)

| Sector/Source | 1990 | 2000 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|
| **Energy** | **19,628** | **13,797** | **12,634** | **11,568** | **10,991** | **9,573** | **7,800** | **7,800** | **7,800** |
| Stationary Combustion | 18,407 | 12,849 | 11,541 | 10,612 | 10,172 | 8,891 | 7,167 | 7,167 | 7,167 |
| Mobile Combustion | 793 | 632 | 889 | 750 | 611 | 472 | 455 | 455 | 455 |
| Oil and Gas Activities | 390 | 287 | 181 | 182 | 184 | 187 | 154 | 154 | 154 |
| Waste Combustion | 38 | 29 | 24 | 24 | 24 | 23 | 24 | 24 | 24 |
| **Industrial Processes** | **1,307** | **1,031** | **831** | **818** | **807** | **795** | **798** | **798** | **798** |
| Chemical Manufacturing | 269 | 307 | 228 | 230 | 230 | 231 | 222 | 222 | 222 |
| Metals Processing | 659 | 284 | 159 | 167 | 176 | 184 | 158 | 158 | 158 |
| Storage and Transport | 6 | 5 | 3 | 3 | 4 | 4 | 2 | 2 | 2 |
| Other Industrial Processes | 362 | 372 | 327 | 318 | 308 | 298 | 324 | 324 | 324 |
| Miscellaneous* | 11 | 64 | 114 | 102 | 89 | 77 | 91 | 91 | 91 |
| **Solvent Use** | **+** | **1** | **+** | **+** | **+** | **+** | **+** | **+** | **+** |
| Degreasing | + | + | + | + | + | + | + | + | + |
| Graphic Arts | + | + | + | + | + | + | + | + | + |
| Dry Cleaning | NA | + | + | + | + | + | + | + | + |
| Surface Coating | + | + | + | + | + | + | + | + | + |
| Other Industrial | + | 1 | + | + | + | + | + | + | + |
| Non-industrial | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| **Agriculture** | **NA** | **NA** | **NA** | **NA** | **NA** | **NA** | **NA** | **NA** | **NA** |
| Agricultural Burning | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| **Waste** | **+** | **1** | **1** | **1** | **1** | **1** | **1** | **1** | **1** |
| Landfills | + | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Wastewater Treatment | + | + | + | + | + | + | + | + | + |

[103] [42 U.S.C § 7409, CAA § 109]
[104] [42 U.S.C § 7411, CAA § 111]
[105] [42 U.S.C § 7473, CAA § 163]
[106] [42 U.S.C § 7651, CAA § 401]

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Miscellaneous Waste | + | | + | | + | + | + | + | + | + | + |
| **Total** | **20,935** | | **14,830** | | **13,466** | **12,388** | **11,799** | **10,368** | **8,599** | **8,599** | **8,599** |

Source: Data taken from EPA (2005) and disaggregated based on EPA (2003).
* Miscellaneous includes other combustion and fugitive dust categories.
+ Does not exceed 0.5 Gg
NA (Not Available)
Note: Totals may not sum due to independent rounding.

Table A-270: $SO_2$ Emissions from Electricity Generation (Gg)

| Fuel Type | 1990 | | 2000 | | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | 13,808 | | 9,620 | | 8,680 | 7,846 | 7,459 | 6,300 | 4,718 | 4,718 | 4,718 |
| Petroleum | 580 | | 428 | | 458 | 414 | 393 | 332 | 249 | 249 | 249 |
| Natural Gas | 1 | | 157 | | 174 | 157 | 149 | 126 | 94 | 94 | 94 |
| Misc. Internal Combustion | 45 | | 54 | | 57 | 52 | 49 | 41 | 31 | 31 | 31 |
| Other | NA | | 78 | | 71 | 64 | 61 | 51 | 38 | 38 | 38 |
| **Total** | **14,433** | | **10,338** | | **9,439** | **8,532** | **8,111** | **6,851** | **5,131** | **5,131** | **5,131** |

Source: Data taken from EPA (2009 and 2010) and disaggregated based on EPA (2003).
Note: Totals may not sum due to independent rounding.

## References


EPA (2010). "2009 Average annual emissions, all criteria pollutants in MS Excel." *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*. Office of Air Quality Planning and Standards.

EPA (2009). "1970 - 2008 Average annual emissions, all criteria pollutants in MS Excel." National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data. Office of Air Quality Planning and Standards. Available online at <http://www.epa.gov/ttn/chief/trends/index.html>.

EPA (2003) E-mail correspondence. Air pollutant data. Office of Air Pollution to the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency (EPA). December 22, 2003.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon , D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press. Cambridge, United Kingdom.

## 6.4. Complete List of Source Categories

| Chapter/Source | Gas(es) |
|---|---|
| **Energy** | |
| Fossil Fuel Combustion | $CO_2$ |
| Non-Energy Use of Fossil Fuels | $CO_2$ |
| Stationary Combustion (excluding $CO_2$) | $CH_4$, $N_2O$, CO, $NO_x$, NMVOC |
| Mobile Combustion (excluding $CO_2$) | $CH_4$, $N_2O$, CO, $NO_x$, NMVOC |
| Coal Mining | $CH_4$ |
| Abandoned Underground Coal Mines | $CH_4$ |
| Natural Gas Systems | $CH_4$ |
| Petroleum Systems | $CH_4$ |
| Incineration of Waste | $CO_2$, $CH_4$, $N_2O$ |
| **Industrial Processes** | |
| Titanium Dioxide Production | $CO_2$ |
| Aluminum Production | $CO_2$, $CF_4$, $C_2F_6$ |
| Iron and Steel Production | $CO_2$, $CH_4$ |
| Ferroalloy Production | $CO_2$, $CH_4$ |
| Ammonia Production | $CO_2$ |
| Urea Consumption for Non-Agricultural Purposes | $CO_2$ |
| Cement Production | $CO_2$ |
| Lime Production | $CO_2$ |
| Limestone and Dolomite Use | $CO_2$ |
| Soda Ash Production and Consumption | $CO_2$ |
| Glass Production | $CO_2$ |
| Carbon Dioxide Consumption | $CO_2$ |
| Phosphoric Acid Production | $CO_2$ |
| Petrochemical Production | $CH_4$, $CO_2$ |
| Silicon Carbide Production and Consumption | $CH_4$, $CO_2$ |
| Lead Production | $CO_2$ |
| Zinc Production | $CO_2$ |
| Adipic Acid Production | $N_2O$ |
| Nitric Acid Production | $N_2O$ |
| Substitution of Ozone Depleting Substances | HFCs, PFCs[a] |
| HCFC-22 Production | HFC-23 |
| Semiconductor Manufacture | HFCs, PFCs, $SF_6$[b] |
| Electrical Transmission and Distributing | $SF_6$ |
| Magnesium Production and Processing | $SF_6$ |
| **Solvent and Other Product Use** | CO, $NO_x$, NMVOC |
| $N_2O$ Product Usage | $N_2O$ |
| **Agriculture** | |
| Enteric Fermentation | $CH_4$ |
| Manure Management | $CH_4$, $N_2O$ |
| Rice Cultivation | $CH_4$ |
| Field Burning of Agricultural Residues | $CH_4$, $N_2O$ |
| Agricultural Soil Management | $N_2O$, CO, $NO_x$ |
| **Land Use, Land-Use Change, and Forestry** | |
| $CO_2$ Flux | $CO_2$ (sink) |
| Cropland Remaining Cropland | $CO_2$ |
| Settlements Remaining Settlements | $N_2O$ |
| Forestland Remaining Forestland | $CH_4$, $N_2O$ |
| Wetlands Remaining Wetlands | $CO_2$, $N_2O$ |
| **Waste** | |
| Landfills | $CH_4$ |
| Wastewater Treatment | $CH_4$, $N_2O$ |
| Composting | $CH_4$, $N_2O$ |

[a] Includes HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-236fa, $CF_4$, HFC-152a, HFC-227ea, HFC-245fa, HFC-4310mee, and PFC/PFPEs.
[b] Includes such gases as HFC-23, $CF_4$, $C_2F_6$, $SF_6$.

# 6.5. Constants, Units, and Conversions

## Metric Prefixes

Although most activity data for the United States is gathered in customary U.S. units, these units are converted into metric units per international reporting guidelines. Table A- 271 provides a guide for determining the magnitude of metric units.

Table A- 271: Guide to Metric Unit Prefixes

| Prefix/Symbol | Factor |
|---|---|
| atto (a) | $10^{-18}$ |
| femto (f) | $10^{-15}$ |
| pico (p) | $10^{-12}$ |
| nano (n) | $10^{-9}$ |
| micro (μ ) | $10^{-6}$ |
| milli (m) | $10^{-3}$ |
| centi (c) | $10^{-2}$ |
| deci (d) | $10^{-1}$ |
| deca (da) | 10 |
| hecto (h) | $10^{2}$ |
| kilo (k) | $10^{3}$ |
| mega (M) | $10^{6}$ |
| giga (G) | $10^{9}$ |
| tera (T) | $10^{12}$ |
| peta (P) | $10^{15}$ |
| exa (E) | $10^{18}$ |

## Unit Conversions

1 kilogram = 2.205 pounds
1 pound = 0.454 kilograms
1 short ton = 2,000 pounds = 0.9072 metric tons
1 metric ton = 1,000 kilograms = 1.1023 short tons

1 cubic meter = 35.315 cubic feet
1 cubic foot = 0.02832 cubic meters
1 U.S. gallon = 3.785412 liters
1 barrel (bbl) = 0.159 cubic meters
1 barrel (bbl) = 42 U.S. gallons
1 liter = 0.001 cubic meters

1 foot = 0.3048 meters
1 meter = 3.28 feet
1 mile = 1.609 kilometers
1 kilometer = 0.622 miles

1 acre = 43,560 square feet = 0.4047 hectares = 4,047 square meters
1 square mile = 2.589988 square kilometers

To convert degrees Fahrenheit to degrees Celsius, subtract 32 and multiply by 5/9

To convert degrees Celsius to Kelvin, add 273.15 to the number of Celsius degrees

## Density Conversions[107]

| | | | |
|---|---|---|---|
| Methane | 1 cubic meter | = | 0.67606 kilograms |
| Carbon dioxide | 1 cubic meter | = | 1.85387 kilograms |

| | | | | | |
|---|---|---|---|---|---|
| Natural gas liquids | 1 metric ton | = | 11.6 barrels | = | 1,844.2 liters |
| Unfinished oils | 1 metric ton | = | 7.46 barrels | = | 1,186.04 liters |
| Alcohol | 1 metric ton | = | 7.94 barrels | = | 1,262.36 liters |
| Liquefied petroleum gas | 1 metric ton | = | 11.6 barrels | = | 1,844.2 liters |
| Aviation gasoline | 1 metric ton | = | 8.9 barrels | = | 1,415.0 liters |
| Naphtha jet fuel | 1 metric ton | = | 8.27 barrels | = | 1,314.82 liters |
| Kerosene jet fuel | 1 metric ton | = | 7.93 barrels | = | 1,260.72 liters |
| Motor gasoline | 1 metric ton | = | 8.53 barrels | = | 1,356.16 liters |
| Kerosene | 1 metric ton | = | 7.73 barrels | = | 1,228.97 liters |
| Naphtha | 1 metric ton | = | 8.22 barrels | = | 1,306.87 liters |
| Distillate | 1 metric ton | = | 7.46 barrels | = | 1,186.04 liters |
| Residual oil | 1 metric ton | = | 6.66 barrels | = | 1,058.85 liters |
| Lubricants | 1 metric ton | = | 7.06 barrels | = | 1,122.45 liters |
| Bitumen | 1 metric ton | = | 6.06 barrels | = | 963.46 liters |
| Waxes | 1 metric ton | = | 7.87 barrels | = | 1,251.23 liters |
| Petroleum coke | 1 metric ton | = | 5.51 barrels | = | 876.02 liters |
| Petrochemical feedstocks | 1 metric ton | = | 7.46 barrels | = | 1,186.04 liters |
| Special naphtha | 1 metric ton | = | 8.53 barrels | = | 1,356.16 liters |
| Miscellaneous products | 1 metric ton | = | 8.00 barrels | = | 1,271.90 liters |

## Energy Conversions

### Converting Various Energy Units to Joules

The common energy unit used in international reports of greenhouse gas emissions is the joule. A joule is the energy required to push with a force of one Newton for one meter. A terajoule (TJ) is one trillion ($10^{12}$) joules. A British thermal unit (Btu, the customary U.S. energy unit) is the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit at or near 39.2 Fahrenheit.

1 TJ =
- $2.388 \times 10^{11}$ calories
- 23.88 metric tons of crude oil equivalent
- 947.8 million Btus
- 277,800 kilowatt-hours

### Converting Various Physical Units to Energy Units

Data on the production and consumption of fuels are first gathered in physical units. These units must be converted to their energy equivalents. The conversion factors in Table A-272 can be used as default factors, if local data are not available. See Appendix A of EIA's *Annual Energy Review 2009* (EIA 2010) for more detailed information on the energy content of various fuels.

[107] Reference: EIA (2007)

Table A-272: Conversion Factors to Energy Units (Heat Equivalents)

| Fuel Type (Units) | Factor |
|---|---|
| **Solid Fuels (Million Btu/Short ton)** | |
| Anthracite coal | 22.573 |
| Bituminous coal | 23.89 |
| Sub-bituminous coal | 17.14 |
| Lignite | 12.866 |
| Coke | 24.8 |
| **Natural Gas (Btu/Cubic foot)** | **1,026** |
| **Liquid Fuels (Million Btu/Barrel)** | |
| Motor gasoline | 5,218 |
| Aviation gasoline | 5.048 |
| Kerosene | 5.670 |
| Jet fuel, kerosene-type | 5.670 |
| Distillate fuel | 5.825 |
| Residual oil | 6.287 |
| Naphtha for petrochemicals | 5.248 |
| Petroleum coke | 6.024 |
| Other oil for petrochemicals | 5.825 |
| Special naphthas | 5.248 |
| Lubricants | 6.065 |
| Waxes | 5.537 |
| Asphalt | 6.636 |
| Still gas | 6.000 |
| Misc. products | 5.796 |

Note: For petroleum and natural gas, *Annual Energy Review 2009* (EIA 2010). For coal ranks, *State Energy Data Report 1992* (EIA 1993). All values are given in higher heating values (gross calorific values).

## References


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## 6.6. Abbreviations

| | |
|---|---|
| AAPFCO | American Association of Plant Food Control Officials |
| ABS | Acrylonitrile butadiene styrene |
| ACC | American Chemistry Council |
| AEDT | U.S. FAA Aviation Environmental Design Tool |
| AFEAS | Alternative Fluorocarbon Environmental Acceptability Study |
| AFV | Alternative fuel vehicle |
| AGA | American Gas Association |
| AHEF | Atmospheric and Health Effect Framework |
| AISI | American Iron and Steel Institute |
| ANL | Argonne National Laboratory |
| APC | American Plastics Council |
| API | American Petroleum Institute |
| APTA | American Public Tranpsortation Association |
| AR4 | IPCC Fourth Assessment Report |
| ARI | Advanced Resources International |
| ASAE | American Society of Agricultural Engineers |
| ASTM | American Society for Testing and Materials |
| BCEF | Biomass conversion and expansion factors |
| BEA | Bureau of Economic Analysis, U.S. Department of Commerce |
| BLM | Bureau of Land Management |
| BoC | Bureau of Census |
| BOD | Biological oxygen demand |
| BOD5 | Biochemical oxygen demand over a 5-day period |
| BOEMRE | Bureau of Ocean Energy Management, Regulation and Enforcement |
| BOF | Basic oxygen furnace |
| BRS | Biennial Reporting System |
| BTS | Bureau of Transportation Statistics, U.S. Department of Transportation |
| Btu | British thermal unit |
| C | Carbon |
| C&EN | Chemical and Engineering News |
| CAAA | Clean Air Act Amendments of 1990 |
| CAPP | Canadian Association of Petroleum Producers |
| CARB | California Air Resources Board |
| CBI | Confidential business information |
| CEFM | Cattle Enteric Fermentation Model |
| CFC | Chlorofluorocarbon |
| CFR | Code of Federal Regulations |
| CGA | Compressed Gas Association |
| $CH_4$ | Methane |
| CHP | Combined heat and power |
| CIGRE | International Council on Large Electric Systems |
| CKD | Cement kiln dust |
| CMA | Chemical Manufacturer's Association |
| CMOP | Coalbed Methane Outreach Program |
| CMR | Chemical Market Reporter |
| CNG | Compressed natural gas |
| $CO_2$ | Carbon dioxide |
| COD | Chemical oxygen demand |
| COGCC | Colorado Oil and Gas Conservation Commission |
| CRF | Common Reporting Format |
| CRM | Component ratio method |
| CRP | Conservation Reserve Program |
| CTIC | Conservation Technology Information Center |
| CVD | Chemical vapor deposition |
| CWNS | Clean Watershed Needs Survey |
| d.b.h | Diameter breast height |
| DE | Digestible energy |
| DESC | Defense Energy Support Center-DoD's defense logistics agency |

| | |
|---|---|
| DFAMS | Defense Fuels Automated Management System |
| DHS | Department of Homeland Security |
| DM | Dry matter |
| DOC | Degradable organic carbon |
| DOC | U.S. Department of Commerce |
| DoD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| DOI | U.S. Department of the Interior |
| DOT | U.S. Department of Transportation |
| EAF | Electric arc furnace |
| EF | Emission factor |
| EFMA | European Fertilizer Manufacturers Association |
| EJ | Exajoule |
| EGR | Exhaust gas recirculation |
| EIA | Energy Information Administration, U.S. Department of Energy |
| EIIP | Emissions Inventory Improvement Program |
| EOR | Enhanced oil recovery |
| EPA | U.S. Environmental Protection Agency |
| ERS | Economic Research Service |
| EVI | Enhanced Vegetation Index |
| FAA | Federal Aviation Administration |
| FAO | Food and Agricultural Organization |
| FCCC | Framework Convention on Climate Change |
| FEB | Fiber Economics Bureau |
| FERC | Federal Energy Regulatory Commission |
| FGD | Flue gas desulfurization |
| FHWA | Federal Highway Administration |
| FIA | Forest Inventory and Analysis |
| FIADB | Forest Inventory and Analysis Database |
| FIPR | Florida Institute of Phosphate Research |
| FQSV | First-quarter of silicon volume |
| FTP | Federal Test Procedure |
| g | gram |
| GCV | Gross calorific value |
| GDP | Gross domestic product |
| Gg | Gigagram |
| GHG | Greenhouse gas |
| GHGRP | Greenhouse Gas Reporting Program |
| GRI | Gas Research Institute |
| Gg | Gigajoule |
| GSAM | Gas Systems Analysis Model |
| GWP | Global warming potential |
| ha | Hectare |
| HBFC | Hydrobromofluorocarbon |
| HC | Hydrocarbon |
| HCFC | Hydrochlorofluorocarbon |
| HDDV | Heavy duty diesel vehicle |
| HDGV | Heavy duty gas vehicle |
| HDPE | High density polyethylene |
| HFC | Hydrofluorocarbon |
| HFE | Hydrofluoroethers |
| HHV | Higher Heating Value |
| HMA | Hot Mix Asphalt |
| HTF | Heat Transfer Fluid |
| HTS | Harmonized Tariff Schedule |
| HWP | Harvested wood product |
| IBF | International bunker fuels |
| IC | Integrated Circuit |
| ICAO | International Civil Aviation Organization |
| IDB | Integrated Database |
| IEA | International Energy Association |

| | |
|---|---|
| IFO | Intermediate Fuel Oil |
| IISRP | International Institute of Synthetic Rubber Products |
| ILENR | Illinois Department of Energy and Natural Resources |
| IMO | International Maritime Organization |
| IPAA | Independent Petroleum Association of America |
| IPCC | Intergovernmental Panel on Climate Change |
| ITC | U.S. International Trade Commission |
| ITRS | International Technology Roadmap for Semiconductors |
| JWR | Jim Walters Resources |
| KCA | Key category analysis |
| kg | Kilogram |
| kWh | Kilowatt hour |
| LDDT | Light duty diesel truck |
| LDDV | Light duty diesel vehicle |
| LDGT | Light duty gas truck |
| LDGV | Light duty gas vehicle |
| LDPE | Low density polyethylene |
| LEV | Low emission vehicles |
| LFG | Landfill gas |
| LFGTE | Landfill gas-to-energy |
| LHV | Lower Heating Value |
| LKD | Lime kiln dust |
| LLDPE | Linear low density polyethylene |
| LMOP | EPA's Landfill Methane Outreach Program |
| LNG | Liquefied natural gas |
| LPG | Liquefied petroleum gas(es) |
| LTO | Landing and take-off |
| LULUCF | Land use, land-use change, and forestry |
| MC | Motorcycle |
| MCF | Methane conversion factor |
| MCFD | Thousand cubic feet per day |
| MDI | Metered dose inhalers |
| MECS | EIA Manufacturer's Energy Consumption Survey |
| MGO | Marine gas oil |
| MJ | Megajoule |
| MLRA | Major Land Resource Area |
| mm | Milimeter |
| MMBtu | Million British thermal units |
| MMCF | Million cubic feet |
| MMCFD | Million cubic feet per day |
| MMS | Minerals Management Service |
| MMTCE | Million metric tons carbon equivalent |
| MODIS | Moderate Resolution Imaging Spectroadiometer |
| MoU | Memorandum of Understanding |
| MOVES | U.S. EPA's Motor Vehicle Emission Simulator model |
| MPG | Miles per gallon |
| MRV | Monitoring, reporting, and verification |
| MSHA | Mine Safety and Health Administration |
| MSW | Municipal solid waste |
| MT | Metric ton |
| MTBE | Methyl Tertiary Butyl Ether |
| $N_2O$ | Nitrous oxide |
| NA | Not available |
| NACWA | National Association of Clean Water Agencies |
| NAHMS | National Animal Health Monitoring System |
| NAICS | North American Industry Classification System |
| NAPAP | National Acid Precipitation and Assessment Program |
| NARR | North American Regional Reanalysis Product |
| NASF | National Association of State Foresters |
| NASS | USDA's National Agriculture Statistics Service |
| NC | No change |

| | |
|---|---|
| NCV | Net calorific value |
| NE | Not estimated |
| NEI | National Emissions Inventory |
| NEMA | National Electrical Manufacturers Association |
| NEU | Non-Energy Use |
| NEV | Neighborhood Electric Vehicle |
| NGL | Natural gas liquids |
| NIR | National Inventory Report |
| NLCD | National Land Cover Dataset |
| NMVOC | Non-methane volatile organic compound |
| NOx | Nitrogen oxides |
| NPRA | National Petroleum and Refiners Association |
| NRC | National Research Council |
| NRCS | Natural Resources Conservation Service |
| NRI | National Resources Inventory |
| NSCEP | National Service Center for Environmental Publications |
| NSCR | Non-selective catalytic reduction |
| NSPS | New source performance standards |
| NWS | National Weather Service |
| OAP | EPA Office of Atmospheric Programs |
| OAQPS | EPA Office of Air Quality Planning and Standards |
| ODP | Ozone depleting potential |
| ODS | Ozone depleting substances |
| OECD | Organization of Economic Co-operation and Development |
| OEM | Original equipment manufacturers |
| OMS | EPA Office of Mobile Sources |
| ORNL | Oak Ridge National Laboratory |
| OSHA | Occupational Safety and Health Administration |
| OTA | Office of Technology Assessment |
| OTAQ | EPA Office of Transportation and Air Quality |
| PAH | Polycyclic aromatic hydrocarbons |
| PCC | Precipitate calcium carbonate |
| PDF | Probability Density Function |
| PECVD | Plasma enhanced chemical vapor deposition |
| PET | Polyethylene terephthalate |
| PET | Potential evapotranspiration |
| PEVM | PFC Emissions Vintage Model |
| PFC | Perfluorocarbon |
| PFPE | Perfluoropolyether |
| POTW | Publicly Owned Treatment Works |
| Ppbv | Parts per billion ($10^9$) by volume |
| Ppm | Parts per million |
| Ppmv | Parts per million($10^6$) by volume |
| Pptv | Parts per trillion ($10^{12}$) by volume |
| PRP | Pasture/Range/Paddock |
| PS | Polystyrene |
| PSU | Primary Sample Unit |
| PU | Polyurethane |
| PVC | Polyvinyl chloride |
| PV | Photovoltaic |
| QA/QC | Quality Assurance and Quality Control |
| QBtu | Quadrillion Btu |
| R&D | Research and Development |
| RCRA | Resource Conservation and Recovery Act |
| RMA | Rubber Manufacturers' Association |
| RPA | Resources Planning Act |
| SAE | Society of Automotive Engineers |
| SAGE | System for assessing Aviation's Global Emissions |
| SAN | Styrene Acrylonitrile |
| SAR | IPCC Second Assessment Report |
| SCR | Selective catalytic reduction |

| | |
|---|---|
| SEC | Securities and Exchange Commission |
| SEMI | Semiconductor Equipment and Materials Industry |
| $SF_6$ | Sulfur hexafluoride |
| SICAS | Semiconductor International Capacity Statistics |
| SNAP | Significant New Alternative Policy Program |
| SNG | Synthetic natural gas |
| SOC | Soil Organic Carbon |
| SSURGO | Soil Survey Geographic Database |
| STMC | Scrap Tire Management Council |
| SULEV | Super Ultra Low Emissions Vehicle |
| SWANA | Solid Waste Association of North America |
| SWDS | Solid waste disposal sites |
| TA | Treated anaerobically (wastewater) |
| TAM | Typical animal mass |
| TAME | Tertiary amyl methyl ether |
| TAR | IPCC Third Assessment Report |
| TBtu | Trillion Btu |
| TDN | Total digestible nutrients |
| TFI | The Fertilizer Institute |
| Tg | Teragrams |
| Tg $CO_2$ Eq. | Teragrams carbon dioxide equivalent |
| TIGER | Topologically Integrated Geographic Encoding and Referencing survey |
| TJ | Terajoule |
| TLEV | Traditional low emissions vehicle |
| TMLA | Total Manufactured Layer Area |
| TRI | Toxic Release Inventory |
| TSDF | Hazardous waste treatment, storage, and disposal facility |
| TVA | Tennessee Valley Authority |
| UDI | Utility Data Institute |
| UFORE | U.S. Forest Service's Urban Forest Effects model |
| UG | Underground (coal mining) |
| U.S. | United States |
| U.S. ITC | United States International Trade Commission |
| UEP | United Egg Producers |
| ULEV | Ultra low emission vehicle |
| UNEP | United Nations Environmental Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| USAA | U.S. Aluminum Association |
| USAF | United States Air Force |
| USDA | United States Department of Agriculture |
| USFS | United States Forest Service |
| USGS | United States Geological Survey |
| VAIP | EPA's Voluntary Aluminum Industrial Partnership |
| VKT | Vehicle kilometers traveled |
| VMT | Vehicle miles traveled |
| VOCs | Volatile organic compounds |
| VS | Volatile solids |
| WFF | World Fab Forecast (previously WFW, World Fab Watch) |
| WGC | World Gas Conference |
| WIP | Waste in place |
| WMO | World Meteorological Organization |
| WMS | Waste management systems |
| WW | Wastewater |
| WWTP | Wastewater treatment plant |
| ZEVs | Zero emissions vehicles |

## 6.7. Chemical Formulas

Table A-273: Guide to Chemical Formulas

| Symbol | Name |
|---|---|
| Al | Aluminum |
| $Al_2O_3$ | Aluminum Oxide |
| Br | Bromine |
| C | Carbon |
| $CH_4$ | Methane |
| $C_2H_6$ | Ethane |
| $C_3H_8$ | Propane |
| $CF_4$ | Perfluoromethane |
| $C_2F_6$ | Perfluoroethane, hexafluoroethane |
| c-$C_3F_6$ | Perfluorocyclopropane |
| $C_3F_8$ | Perfluoropropane |
| c-$C_4F_8$ | Perfluorocyclobutane |
| $C_4F_{10}$ | Perfluorobutane |
| $C_5F_{12}$ | Perfluoropentane |
| $C_6F_{14}$ | Perfluorohexane |
| $CF_3I$ | Trifluoroiodomethane |
| $CFCl_3$ | Trichlorofluoromethane (CFC-11) |
| $CF_2Cl_2$ | Dichlorodifluoromethane (CFC-12) |
| $CF_3Cl$ | Chlorotrifluoromethane (CFC-13) |
| $C_2F_3Cl_3$ | Trichlorotrifluoroethane (CFC-113)* |
| $CCl_3CF_3$ | CFC-113a* |
| $C_2F_4Cl_2$ | Dichlorotetrafluoroethane (CFC-114) |
| $C_2F_5Cl$ | Chloropentafluoroethane (CFC-115) |
| $CHCl_2F$ | HCFC-21 |
| $CHF_2Cl$ | Chlorodifluoromethane (HCFC-22) |
| $C_2F_3HCl_2$ | HCFC-123 |
| $C_2F_4HCl$ | HCFC-124 |
| $C_2FH_3Cl_2$ | HCFC-141b |
| $C_2H_3F_2Cl$ | HCFC-142b |
| $CF_3CF_2CHCl_2$ | HCFC-225ca |
| $CClF_2CF_2CHClF$ | HCFC-225cb |
| $CCl_4$ | Carbon tetrachloride |
| $CHClCCl_2$ | Trichloroethylene |
| $CCl_2CCl_2$ | Perchloroethylene, tetrachloroethene |
| $CH_3Cl$ | Methylchloride |
| $CH_3CCl_3$ | Methylchloroform |
| $CH_2Cl_2$ | Methylenechloride |
| $CHCl_3$ | Chloroform, trichloromethane |
| $CHF_3$ | HFC-23 |
| $CH_2F_2$ | HFC-32 |
| $CH_3F$ | HFC-41 |
| $C_2HF_5$ | HFC-125 |
| $C_2H_2F_4$ | HFC-134 |
| $CH_2FCF_3$ | HFC-134a |
| $C_2H_3F_3$ | HFC-143* |
| $C_2H_3F_3$ | HFC-143a* |
| $CH_2FCH_2F$ | HFC-152* |
| $C_2H_4F_2$ | HFC-152a* |
| $CH_3CH_2F$ | HFC-161 |
| $C_3HF_7$ | HFC-227ea |
| $CF_3CF_2CH_2F$ | HFC-236cb |
| $CF_3CHFCHF_2$ | HFC-236ea |
| $C_3H_2F_6$ | HFC-236fa |
| $C_3H_3F_5$ | HFC-245ca |
| $CHF_2CH_2CF_3$ | HFC-245fa |
| $CF_3CH_2CF_2CH_3$ | HFC-365mfc |

| | |
|---|---|
| $C_5H_2F_{10}$ | HFC-43-10mee |
| $CF_3OCHF_2$ | HFE-125 |
| $CF_2HOCF_2H$ | HFE-134 |
| $CH_3OCF_3$ | HFE-143a |
| $CF_3CHFOCF_3$ | HFE-227ea |
| $CF_3CHClOCHF_2$ | HCFE-235da2 |
| $CF_3CHFOCHF_2$ | HFE-236ea2 |
| $CF_3CH_2OCF_3$ | HFE-236fa |
| $CF_3CF_2OCH_3$ | HFE-245cb2 |
| $CHF_2CH_2OCF_3$ | HFE-245fa1 |
| $CF_3CH_2OCHF_2$ | HFE-245fa2 |
| $CHF_2CF_2OCH_3$ | HFE-254cb2 |
| $CF_3CH_2OCH_3$ | HFE-263fb2 |
| $CF_3CF_2OCF_2CHF_2$ | HFE-329mcc2 |
| $CF_3CF_2OCH_2CF_3$ | HFE-338mcf2 |
| $CF_3CF_2CF_2OCH_3$ | HFE-347mcc3 |
| $CF_3CF_2OCH_2CHF_2$ | HFE-347mcf2 |
| $CF_3CHFCF_2OCH_3$ | HFE-356mec3 |
| $CHF_2CF_2CF_2OCH_3$ | HFE-356pcc3 |
| $CHF_2CF_2OCH_2CHF_2$ | HFE-356pcf2 |
| $CHF_2CF_2CH_2OCHF_2$ | HFE-356pcf3 |
| $CF_3CF_2CH_2OCH_3$ | HFE-365mcf3 |
| $CHF_2CF_2OCH_2CH_3$ | HFE-374pcf2 |
| $C_4F_9OCH_3$ | HFE-7100 |
| $C_4F_9OC_2H_5$ | HFE-7200 |
| $CHF_2OCF_2OC_2F_4OCHF_2$ | H-Galden 1040x |
| $CHF_2OCF_2OCHF_2$ | HG-10 |
| $CHF_2OCF_2CF_2OCHF_2$ | HG-01 |
| $CH_3OCH_3$ | Dimethyl ether |
| $CH_2Br_2$ | Dibromomethane |
| $CH_2BrCl$ | Dibromochloromethane |
| $CHBr_3$ | Tribromomethane |
| $CHBrF_2$ | Bromodifluoromethane |
| $CH_3Br$ | Methylbromide |
| $CF_2BrCl$ | Bromodichloromethane (Halon 1211) |
| $CF_3Br(CBrF_3)$ | Bromotrifluoromethane (Halon 1301) |
| $CF_3I$ | FIC-13I1 |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| $CaCO_3$ | Calcium carbonate, Limestone |
| $CaMg(CO_3)_2$ | Dolomite |
| CaO | Calcium oxide, Lime |
| Cl | atomic Chlorine |
| F | Fluorine |
| Fe | Iron |
| $Fe_2O_3$ | Ferric oxide |
| FeSi | Ferrosilicon |
| H, $H_2$ | atomic Hydrogen, molecular Hydrogen |
| $H_2O$ | Water |
| $H_2O_2$ | Hydrogen peroxide |
| OH | Hydroxyl |
| N, $N_2$ | atomic Nitrogen, molecular Nitrogen |
| $NH_3$ | Ammonia |
| $NH_4^+$ | Ammonium ion |
| $HNO_3$ | Nitric acid |
| $NF_3$ | Nitrogen trifluoride |
| $N_2O$ | Nitrous oxide |
| NO | Nitric oxide |
| $NO_2$ | Nitrogen dioxide |
| $NO_3$ | Nitrate radical |
| Na | Sodium |

| | |
|---|---|
| $Na_2CO_3$ | Sodium carbonate, soda ash |
| $Na_3AlF_6$ | Synthetic cryolite |
| O, $O_2$ | atomic Oxygen, molecular Oxygen |
| $O_3$ | Ozone |
| S | atomic Sulfur |
| $H_2SO_4$ | Sulfuric acid |
| $SF_6$ | Sulfur hexafluoride |
| $SF_5CF_3$ | Trifluoromethylsulphur pentafluoride |
| $SO_2$ | Sulfur dioxide |
| Si | Silicon |
| SiC | Silicon carbide |
| $SiO_2$ | Quartz |

* Distinct isomers.

# ANNEX 7 Uncertainty – TO BE UDPATED

The annual U.S. Inventory presents the best effort to produce estimates for greenhouse gas source and sink categories in the United States. These estimates were generated according to the UNFCCC reporting guidelines, following the recommendations set forth in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997), the *IPCC Good Practice Guidance* (IPCC 2000), the Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003), and the *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). This Annex provides an overview of the uncertainty analysis conducted to support the U.S. Inventory, describes the sources of uncertainty characterized throughout the Inventory associated with various source categories (including emissions and sinks), and describes the methods through which uncertainty information was collected, quantified, and presented.

## 7.1. Overview

The current inventory emission estimates for some source categories, such as for $CO_2$ Emissions from Fossil Fuel Combustion, have relatively low level of uncertainty associated with them. However, for some other source categories, the inventory emission estimates are considered less certain. The two major types of uncertainty associated with these emission estimates are (1) model uncertainty, which arises when the emission and/or removal estimation models used in developing the inventory estimates do not fully and accurately characterize the respective emission and/or removal processes (due to a lack of technical details or other resources), resulting in the use of incorrect or incomplete estimation methodologies and (2) parameter uncertainty, which arises due to a lack of precise input data such as emission factors and activity data.

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

Parameter uncertainty is, therefore, the principal type and source of uncertainty associated with the national inventory emission estimates and is the main focus of the quantitative uncertainty analyses in this report. Parameter uncertainty has been quantified for all of the emission sources and sinks in the U.S. Inventory, with the exception of one very small emission source category, $CH_4$ emissions from Incineration of Waste, which was included in the 1990-2008 National GHG Inventory for the first time, and two other source categories (International Bunker Fuels and biomass energy consumption) whose emissions are not included in the Inventory totals.

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

## 7.2. Methodology and Results

The United States has developed a quality assurance and quality control (QA/QC) and uncertainty management plan (EPA 2002) in accordance with the IPCC *Good Practice Guidance* (IPCC 2000). Like the QA/QC plan, the uncertainty management plan is part of a continually evolving process. The uncertainty management plan provides for a quantitative assessment of the inventory analysis itself, thereby contributing to continuing efforts to understand both what causes uncertainty and how to improve inventory quality. Although the plan provides both general and specific guidelines for implementing quantitative uncertainty analysis, its components are intended to evolve over time, consistent with the

inventory estimation process. The U.S. plan includes procedures and guidelines, and forms and templates, for developing quantitative assessments of uncertainty in the national Inventory estimates (EPA 2002).

The IPCC *Good Practice Guidance* recommends two approaches—Tier 1 and Tier 2—for developing quantitative estimates of uncertainty in the inventory estimate of individual source categories and the overall inventory. Of these, the Tier 2 approach is both more flexible and reliable than Tier 1; both methods are described in the next section. The United States is in the process of implementing a multi-year strategy to develop quantitative estimates of uncertainty for all source categories using the Tier 2 approach. For the current Inventory, a Tier 2 approach was implemented for all source categories with the exception of Composting and parts of Agricultural Soil Management source categories.

The current Inventory reflects significant improvements over the previous publication in the extent to which the Tier 2 approach to uncertainty analysis was adopted. Each of the new Tier 2 analyses reflects additional detail and characterization of input parameters using statistical data collection, expert elicitation methods and more informed judgment. In following the UNFCCC requirement under Article 4.1, emissions from International Bunker Fuels and Indirect Greenhouse Gas Emissions are not included in the total emissions estimated for the U.S. Inventory; therefore, no quantitative uncertainty estimates have been developed for these source categories.[108] Emissions from biomass combustion are accounted for implicitly in the LULUCF chapter through the calculation of changes in carbon stocks. The Energy sector does provide an estimate of $CO_2$ emissions from bioenergy consumption provided as a memo item for informational purposes in line with the UNFCCC reporting requirements.

#### Tier 1 and Tier 2 Approach

The Tier 1 method for estimating uncertainty is based on the error propagation equation. This equation combines the uncertainty associated with the activity data and the uncertainty associated with the emission (or the other) factors. The Tier 1 approach is applicable where emissions (or removals) are usually estimated as the product of an activity value and an emission factor or as the sum of individual sub-source category values. Inherent in employing the Tier 1 method are the assumptions that, for each source category, (i) both the activity data and the emission factor values are approximately normally distributed, (ii) the coefficient of variation (i.e., the ratio of the standard deviation to the mean) associated with each input variable is less than 30 percent, and (iii) the input variables within and across (sub-) source categories are not correlated (i.e., value of each variable is independent of the values of other variables).

The Tier 2 method is preferred (i) if the uncertainty associated with the input variables is significantly large, (ii) if the distributions underlying the input variables are not normal, (iii) if the estimates of uncertainty associated with the input variables are correlated, and/or (iv) if a sophisticated estimation methodology and/or several input variables are used to characterize the emission (or removal) process correctly. In practice, the Tier 2 is the preferred method of uncertainty analysis for all source categories where sufficient and reliable data are available to characterize the uncertainty of the input variables.

The Tier 2 method employs the Monte Carlo Stochastic Simulation technique (also referred to as the Monte Carlo method). Under this method, estimates of emissions (or removals) for a particular source category are generated many times (equal to the number of simulations specified) using an uncertainty model, which is an emission (or removal) estimation equation that imitates or is the same as the inventory estimation model for a particular source category. These estimates are generated using the respective, randomly-selected values for the constituent input variables using commercially available simulation software such as *@RISK* or *Crystal Ball*.

#### Characterization of Uncertainty in Input Variables

Both Tier 1 and Tier 2 uncertainty analyses require that all the input variables are well-characterized in terms of their Probability Density Functions (PDFs). In the absence of particularly convincing data measurements, sufficient data samples, or expert judgments that determined otherwise, the PDFs incorporated in the current source category uncertainty analyses were limited to normal, lognormal, uniform, triangular, and beta distributions. The choice among these five PDFs depended largely on the observed or measured data and expert judgment.

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

**Source Category Inventory Uncertainty Estimates**

Discussion surrounding the input parameters and sources of uncertainty for each source category appears in the body of this report. Table A-274 summarizes results based on assessments of source category-level uncertainty. The table presents base year (1990 or 1995) and current year (2010) emissions for each source category. The combined uncertainty (at the 95 percent confidence interval) for each source category is expressed as the percentage deviation above and below the total 2010 emissions estimated for that source category. Source category trend uncertainty is described subsequently in this Appendix.

Table A-274: Summary Results of Source Category Uncertainty Analyses

| Source Category | Base Year Emissions[*,a] | 2010 Emissions [a] | 2010 Uncertainty[b] | |
|---|---|---|---|---|
| | Tg $CO_2$ Eq. | Tg $CO_2$ Eq. | Low | High |
| **$CO_2$** | **5,100.1** | **5,706.0** | **-2%** | **4%** |
| Fossil Fuel Combustion[c] | 4,737.9 | 5,387.4 | -2% | 5% |
| Non-Energy Use of Fuels | 119.6 | 125.1 | -17% | 23% |
| Iron and Steel Production & Metallurgical Coke Production | 99.6 | 54.3 | -16% | 17% |
| Natural Gas Systems | 37.6 | 32.3 | -19% | 30% |
| Cement Production | 33.3 | 30.5 | -13% | 14% |
| Lime Production | 11.5 | 13.2 | -8% | 9% |
| Incineration of Waste | 8.0 | 12.1 | -21% | 24% |
| Limestone and Dolomite Use | 5.1 | 10.0 | -13% | 18% |
| Ammonia Production | 13.0 | 8.7 | -10% | 25% |
| Cropland Remaining Cropland | 7.1 | 8.0 | -56% | 48% |
| Urea Consumption for Non-Agricultural Purposes | 3.8 | 4.4 | -47% | 14% |
| Soda Ash Production and Consumption | 4.1 | 3.7 | -7% | 7% |
| Petrochemical Production | 3.3 | 3.3 | -26% | 29% |
| Aluminum Production | 6.8 | 3.0 | -49% | 2% |
| Carbon Dioxide Consumption | 1.4 | 2.2 | -25% | 30% |
| Titanium Dioxide Production | 1.2 | 1.9 | -13% | 13% |
| Ferroalloy Production | 2.2 | 1.7 | -12% | 12% |
| Zinc Production | 0.6 | 1.2 | -17% | 19% |
| Phosphoric Acid Production | 1.5 | 1.0 | -18% | 18% |
| Wetlands Remaining Wetlands | 1.0 | 1.0 | -33% | 38% |
| Lead Production | 0.5 | 0.5 | -15% | 15% |
| Petroleum Systems | 0.4 | 0.3 | -24% | 149% |
| Silicon Carbide Production and Consumption | 0.4 | 0.2 | -9% | 10% |
| *Land Use, Land-Use Change, and Forestry (Sink)[d]* | *(881.8)* | *(1,074.7)* | *11%* | *-11%* |
| *Biomass - Wood[f]* | *215.2* | *191.6* | *NE* | *NE* |
| *International Bunker Fuels[e]* | *111.8* | *127.8* | *NE* | *NE* |
| *Biomass – Ethanol[f]* | *4.2* | *74.5* | *NE* | *NE* |
| **$CH_4$** | **668.3** | **666.5** | **-13%** | **13%** |
| Natural Gas Systems | 189.6 | 215.4 | -19% | 30% |
| Enteric Fermentation | 133.8 | 141.3 | -11% | 18% |
| Landfills | 147.7 | 107.8 | -52% | 44% |
| Coal Mining | 84.1 | 72.6 | -13% | 16% |
| Manure Management | 31.7 | 52.0 | -18% | 20% |
| Petroleum Systems | 35.2 | 31.0 | -24% | 149% |
| Wastewater Treatment | 15.9 | 16.3 | -25% | 31% |
| Rice Cultivation | 7.1 | 8.6 | -65% | 153% |
| Stationary Combustion | 7.5 | 6.3 | -40% | 128% |
| Abandoned Underground Coal Mines | 6.0 | 5.0 | -22% | 21% |
| Forest Land Remaining Forest Land | 2.5 | 4.8 | -79% | 148% |
| Mobile Combustion | 4.7 | 1.9 | -10% | 9% |
| Composting | 0.3 | 1.6 | -50% | 50% |
| Petrochemical Production | 0.9 | 0.9 | -29% | 30% |
| Iron and Steel Production & Metallurgical Coke Production | 1.0 | 0.5 | -21% | 22% |
| Field Burning of Agricultural Residues | 0.2 | 0.2 | -40% | 42% |

| | | | | |
|---|---|---|---|---|
| Ferroalloy Production | + | + | -12% | 12% |
| Silicon Carbide Production and Consumption | + | + | -9% | 9% |
| Incineration of Waste | + | + | NE | NE |
| *International Bunker Fuels*[e] | *0.2* | *0.2* | *NE* | *NE* |
| **$N_2O$** | **316.2** | **306.2** | **-14%** | **41%** |
| Agricultural Soil Management | 200.0 | 207.8 | -21% | 57% |
| Stationary Combustion | 12.3 | 22.6 | -56% | 72% |
| Mobile Combustion | 43.9 | 20.6 | -6% | 26% |
| Manure Management | 14.8 | 18.3 | -16% | 24% |
| Nitric Acid Production | 17.6 | 16.7 | -39% | 40% |
| Wastewater Treatment | 3.5 | 5.0 | -77% | 99% |
| $N_2O$ from Product Uses | 4.4 | 4.4 | -8% | 8% |
| Forest Land Remaining Forest Land | 2.1 | 4.3 | -72% | 137% |
| Adipic Acid Production | 15.8 | 2.8 | -9% | 9% |
| Composting | 0.4 | 1.7 | -50% | 50% |
| Settlements Remaining Settlements | 1.0 | 1.4 | -49% | 163% |
| Incineration of Waste | 0.5 | 0.4 | -50% | 320% |
| Field Burning of Agricultural Residues | 0.1 | 0.1 | -29% | 31% |
| Wetlands Remaining Wetlands | + | + | -74% | 42% |
| *International Bunker Fuels*[e] | *0.2* | *0.2* | *NE* | *NE* |
| **HFCs, PFCs, and $SF_6$** | **120.6** | **140.3** | **-1%** | **11%** |
| Substitution of Ozone Depleting Substances[g] | 30.8 | 112.2 | -1% | 13% |
| Electrical Transmission and Distribution | 26.7 | 11.8 | -22% | 25% |
| HCFC-22 Production | 36.4 | 8.1 | -7% | 10% |
| Semiconductor Manufacture | 2.9 | 5.4 | -10% | 10% |
| Aluminum Production | 18.4 | 1.6 | -51% | 6% |
| Magnesium Production and Processing | 5.4 | 1.3 | -4% | 4% |
| **Total**[h] | **6,205.3** | **6,819.1** | **-2%** | **5%** |
| **Net Emissions (Sources and Sinks)**[h] | **5,323.4** | **5,744.4** | **-3%** | **6%** |

Notes:
Totals may not sum due to independent rounding.
*Base Year is 1990 for all sources except Substitution of Ozone Depleting Substances, for which the United States has chosen 1995.
+ Does not exceed 0.05 Tg $CO_2$ Eq.
NE: Not Estimated
[a] Emission estimates reported in this table correspond to emissions from only those source categories for which quantitative uncertainty was performed for the current Inventory. Thus the totals reported for 2010 in this table exclude approximately 2.8 Tg $CO_2$ Eq. of emissions for which quantitative uncertainty was not assessed. Hence, these emission estimates do not match the final total U.S. greenhouse gas emission estimates presented in this Inventory. All uncertainty estimates correspond only to the totals reported in this table.
[b] The uncertainty estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5$^{th}$ percentile and the upper bound corresponding to 97.5$^{th}$ percentile.
[c] This source category's inventory estimates exclude $CO_2$ emissions from geothermal sources, as quantitative uncertainty analysis was not performed for that sub-source category. Hence, for this source category, the emissions reported in this table do not match the emission estimates presented in the Energy chapter of the Inventory.
[d] Sinks are only included in Net Emissions.
[e] Emissions from International Bunker Fuels are not included in the totals.
[f] Emissions from Wood Biomass and Ethanol Consumption are not included specifically in summing energy sector totals.
[g] This source category's estimate for 2010 excludes 2.4 Tg of $CO_2$ Eq. from several very small emission sources, as uncertainty associated with those sources was not assessed. Hence, for this source category, the emissions reported in this table do not match the emission estimates presented in the Industrial Processes chapter of the Inventory.
[h] Totals exclude emissions for which uncertainty was not quantified. The Base Year emissions correspond to 1990 estimates for all source categories, with the exception of Substitution of ODS, for which the estimates correspond to 1995. Similarly, the total for HFCs, PFCs, and $SF_6$ for the Base Year includes 1995 emission estimates for Substitution of ODS and 1990 emission estimates for all other source categories.

### Overall (Aggregate) Inventory Level Uncertainty Estimates

The overall level uncertainty estimate for the U.S. greenhouse gas emissions inventory was developed using the IPCC Tier 2 uncertainty estimation methodology. The uncertainty models of all the emission source categories could not be directly integrated to develop the overall uncertainty estimates due to software constraints in integrating multiple, large uncertainty models. Therefore, an alternative approach was adopted to develop the overall uncertainty estimates. The Monte Carlo simulation output data for each emission source category uncertainty analysis were combined by type of gas and the probability distributions were fitted to the combined simulation output data, where such simulated output data

were available. If such detailed output data were not available for particular emissions sources, individual probability distributions were assigned to those source category emission estimates based on the most detailed data available from the quantitative uncertainty analysis performed.

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

The overall uncertainty model results indicate that the 2010 U.S. greenhouse gas emissions are estimated to be within the range of approximately 6,682 to 7,137 Tg $CO_2$ Eq., reflecting a relative 95 percent confidence interval uncertainty range of -2 percent to 5 percent with respect to the total U.S. greenhouse gas emission estimate of approximately 6,819 Tg $CO_2$ Eq. The uncertainty interval associated with total $CO_2$ emissions, which constitute about 84 percent of the total U.S. greenhouse gas emissions in 2010, ranges from -2 percent to 4 percent of total $CO_2$ emissions estimated. The results indicate that the uncertainty associated with the inventory estimate of the total $CH_4$ emissions ranges from -13 percent to 13 percent, uncertainty associated with the total inventory $N_2O$ emission estimate ranges from -14 percent to 41 percent, and uncertainty associated with high GWP gas emissions ranges from -1 percent to 11 percent.

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

Table A-275. Quantitative Uncertainty Assessment of Overall National Inventory Emissions (Tg $CO_2$ Eq. and Percent)

| Gas | 2010 Emission Estimate[a] (Tg $CO_2$ Eq.) | Uncertainty Range Relative to Emission Estimate[b] (Tg $CO_2$ Eq.) | | (%) | | Mean[c] (Tg $CO_2$ Eq.) | Standard Deviation[c] (Tg $CO_2$ Eq.) |
|---|---|---|---|---|---|---|---|
| | | Lower Bound[d] | Upper Bound[d] | Lower Bound | Upper Bound | | |
| $CO_2$ | 5,706.0 | 5,570 | 5,958 | -2% | 4% | 5,763 | 101 |
| $CH_4$[e] | 666.5 | 578 | 751 | -13% | 13% | 658 | 43 |
| $N_2O$[e] | 306.2 | 265 | 431 | -14% | 41% | 339 | 43 |
| PFC, HFC & $SF_6$[e] | 140.3 | 138 | 156 | -1% | 11% | 147 | 4 |
| **Total** | **6,819.1** | **6,682** | **7,137** | **-2%** | **5%** | **6,906** | **117** |
| **Net Emissions (Sources and Sinks)** | **5,744.4** | **5,575** | **6,094** | **-3%** | **6%** | **5,830** | **133** |

Notes:
[a] Emission estimates reported in this table correspond to emissions from only those source categories for which quantitative uncertainty was performed this year. Thus the totals reported in this table exclude approximately 2.8 Tg $CO_2$ Eq. of emissions for which quantitative uncertainty was not assessed. Hence, these emission estimates do not match the final total U.S. greenhouse gas emission estimates presented in this Inventory.
[b] The lower and upper bounds for emission estimates correspond to a 95 percent confidence interval, with the lower bound corresponding to 2.5th percentile and the upper bound corresponding to 97.5th percentile.
[c] Mean value indicates the arithmetic average of the simulated emission estimates; standard deviation indicates the extent of deviation of the simulated values from the mean.
[d] The lower and upper bound emission estimates for the sub-source categories do not sum to total emissions because the low and high estimates for total emissions were calculated separately through simulations.
[e] The overall uncertainty estimates did not take into account the uncertainty in the GWP values for $CH_4$, $N_2O$ and high GWP gases used in the inventory emission calculations for 2010.

### Trend Uncertainty

In addition to the estimates of uncertainty associated with the current year's emission estimates, this Annex also presents the estimates of trend uncertainty. The *IPCC Good Practice Guidance* defines trend as the difference in emissions between the base year (i.e., 1990) and the current year (i.e., 2010) inventory estimates. However, for purposes of understanding the concept of trend uncertainty, the emission trend is defined in this Inventory as the percentage change in the emissions (or removal) estimated for the current year, relative to the emission (or removal) estimated for the base year. The uncertainty associated with this emission trend is referred to as trend uncertainty.

Under the Tier 1 approach, the trend uncertainty for a source category is estimated using the sensitivity of the calculated difference between the base year and the current year (i.e., 2010) emissions to an incremental (i.e., 1 percent) increase in one or both of these values for that source category. The two sensitivities are expressed as percentages: Type A sensitivity highlights the effect on the difference between the base and the current year emissions caused by a 1 percent change in both, while Type B sensitivity highlights the effect caused by a change to only the current year's emissions.

Both sensitivities are simplifications introduced in order to analyze the correlation between the base and the current year estimates. Once calculated, the two sensitivities are combined using the error propagation equation to estimate the overall trend uncertainty.

Under the Tier 2 approach, the trend uncertainty is estimated using Monte Carlo Stochastic Simulation technique. The trend uncertainty analysis takes into account the fact that the base and the current year estimates often share input variables. For purposes of the current Inventory, a simple approach has been adopted, under which the base year source category emissions (or removals) are assumed to exhibit the same uncertainty characteristics as the current year emissions (or removals). Source category-specific PDFs for base year estimates were developed using current year (i.e.,2010) uncertainty output data. These were adjusted to account for differences in magnitude between the two years' inventory estimates. Then, for each source category, a trend uncertainty estimate was developed using the Monte Carlo method. The overall inventory trend uncertainty estimate was developed by combining all source category-specific trend uncertainty estimates. These trend uncertainty estimates present the range of likely change from base year to 2010, and are shown in Table A- 276.

Table A- 276. Quantitative Assessment of Trend Uncertainty (Tg $CO_2$ Eq. and Percent)

| Gas/Source | Base Year Emissions[*,a] | 2010 Emissions [a] | Emissions Trend [a] | Trend Range[a,b] | |
|---|---|---|---|---|---|
| | (Tg CO2 Eq.) | | (%) | (%) | |
| | | | | Lower Bound | Upper Bound |
| **$CO_2$** | **5,100.1** | **5,706.0** | **12%** | **7%** | **17%** |
| Fossil Fuel Combustion[c] | 4,737.9 | 5,387.4 | 14% | 8% | 19% |
| Non-Energy Use of Fuels | 119.6 | 125.1 | 5% | -19% | 36% |
| Iron and Steel Production & Metallurgical Coke Production | 99.6 | 54.3 | -46% | -57% | -32% |
| Natural Gas Systems | 37.6 | 32.3 | -14% | -40% | 22% |
| Cement Production | 33.3 | 30.5 | -8% | -24% | 11% |
| Incineration of Waste | 8.0 | 12.1 | 51% | 10% | 107% |
| Lime Production | 11.5 | 13.2 | 14% | 1% | 29% |
| Limestone and Dolomite Use | 5.1 | 10 | 95% | 57% | 142% |
| Ammonia Production | 13 | 8.7 | -33% | -47% | -16% |
| Cropland Remaining Cropland | 7.1 | 8.0 | 14% | -53% | 177% |
| Urea Consumption for Non-Agricultural Purposes | 3.8 | 4.4 | 15% | -34% | 99% |
| Soda Ash Production and Consumption | 4.1 | 3.7 | -10% | -18% | 0% |
| Petrochemical Production | 3.3 | 3.3 | 1% | -33% | 51% |
| Aluminum Production | 6.8 | 3 | -56% | -74% | -27% |
| Carbon Dioxide Consumption | 1.4 | 2.2 | 56% | 4% | 133% |
| Ferroalloy Production | 2.2 | 1.7 | -23% | -35% | -8% |
| Titanium Dioxide Production | 1.2 | 1.9 | 57% | 31% | 88% |
| Wetlands Remaining Wetlands | 1 | 1 | -5% | -43% | 58% |
| Phosphoric Acid Production | 1.5 | 1 | -33% | -49% | -14% |
| Zinc Production | 0.6 | 1.2 | 85% | 44% | 139% |
| Petroleum Systems | 0.4 | 0.3 | -14% | -63% | 101% |
| Lead Production | 0.5 | 0.5 | 5% | -15% | 30% |
| Silicon Carbide Production and Consumption | 0.4 | 0.2 | -52% | -58% | -45% |
| *Land Use, Land-Use Change, and Forestry (Sink)[d]* | *(881.8)* | *(1,074.7)* | *22%* | *4%* | *42%* |
| *Biomass – Wood[e]* | *215.2* | *191.6* | *-11%* | *NE* | *NE* |
| *International Bunker Fuels[f]* | *111.8* | *127.8* | *14%* | *NE* | *NE* |
| *Biomass – Ethanol[e]* | *4.2* | *74.5* | *1663%* | *NE* | *NE* |
| **$CH_4$** | **668.3** | **666.5** | **0%** | **-14%** | **27%** |
| Natural Gas Systems | 189.6 | 215.4 | 14% | -20% | 61% |
| Enteric Fermentation | 133.8 | 141.3 | 6% | -14% | 30% |
| Landfills | 147.7 | 107.8 | -27% | -67% | 57% |
| Coal Mining | 84.1 | 72.6 | -14% | -29% | 9% |
| Manure Management | 31.7 | 52.0 | 64% | 25% | 114% |
| Petroleum Systems | 35.2 | 31.0 | -12% | 131% | 1136% |
| Wastewater Treatment | 15.9 | 16.3 | 3% | -63% | 24% |
| Rice Cultivation | 7.1 | 8.6 | 21% | -70% | 379% |
| Stationary Combustion | 7.5 | 6.3 | -15% | -70% | 138% |
| Abandoned Underground Coal Mines | 6.0 | 5.0 | -18% | -40% | 13% |
| Forest Land Remaining Forest Land | 2.5 | 4.8 | 92% | -69% | 1014% |
| Composting | 0.3 | 1.6 | 392% | 118% | 1023% |

| | | | | | |
|---|---|---|---|---|---|
| Petrochemical Production | 0.9 | 0.9 | 7% | -31% | 64% |
| Iron and Steel Production & Metallurgical Coke Production | 1.0 | 0.5 | -46% | -61% | -26% |
| Field Burning of Agricultural Residues | 0.2 | 0.2 | 11% | -40% | 107% |
| Ferroalloy Production | + | + | -31% | -42% | -19% |
| Silicon Carbide Production and Consumption | + | + | -67% | -71% | -62% |
| Incineration of Waste | + | + | -23% | NE | NE |
| *International Bunker Fuels*[f] | *0.2* | *0.2* | *-5%* | *NE* | *NE* |
| **$N_2O$** | **316.2** | **306.2** | **-3%** | **-31%** | **34%** |
| Agricultural Soil Management | 200.0 | 207.8 | 4% | -36% | 66% |
| Stationary Combustion | 12.3 | 22.6 | 84% | -36% | 443% |
| Mobile Combustion | 43.9 | 20.6 | -53% | -62% | -42% |
| Manure Management | 14.8 | 18.3 | 24% | -6% | 64% |
| Nitric Acid Production | 17.6 | 16.7 | -5% | -48% | 72% |
| Forest Land Remaining Forest Land | 2.1 | 4.3 | 103% | -56% | 841% |
| Wastewater Treatment | 3.5 | 5.0 | 46% | -72% | 551% |
| $N_2O$ from Product Uses | 4.4 | 4.4 | 0% | -12% | 12% |
| Adipic Acid Production | 15.8 | 2.8 | -82% | -84% | -80% |
| Composting | 0.4 | 1.7 | 392% | 121% | 994% |
| Settlements Remaining Settlements | 1.0 | 1.4 | 43% | -55% | 364% |
| Incineration of Waste | 0.5 | 0.4 | -23% | -83% | 260% |
| Field Burning of Agricultural Residues | 0.1 | 0.1 | 21% | -23% | 91% |
| Wetlands Remaining Wetlands | + | + | -5% | -72% | 205% |
| *International Bunker Fuels*[f] | *1.1* | *1.2* | *12%* | *NE* | *NE* |
| **HFCs, PFCs, and $SF_6$*** | **120.6** | **140.3** | **16%** | **12%** | **35%** |
| Substitution of Ozone Depleting Substances[g] | 30.8 | 112.2 | 265% | 232% | 302% |
| Electrical Transmission and Distribution | 26.7 | 11.8 | -56% | -68% | -39% |
| HCFC-22 Production | 36.4 | 8.1 | -78% | -80% | -75% |
| Semiconductor Manufacture | 2.9 | 5.4 | 85% | 60% | 112% |
| Aluminum Production | 18.4 | 1.6 | -92% | -95% | -85% |
| Magnesium Production and Processing | 5.4 | 1.3 | -77% | -78% | -75% |
| **Total**[h] | **6,205.3** | **6,819.1** | **10%** | **5%** | **16%** |
| **Net Emission (Sources and Sinks)** | **5,323.4** | **5,744.4** | **8%** | **2%** | **16%** |

Notes:
Totals may not sum due to independent rounding.
*Base Year is 1990 for all sources except Substitution of Ozone Depleting Substances, for which the United States has chosen to use 1995.
+ Does not exceed 0.05 Tg $CO_2$ Eq.
NE Not Estimated
[a] Emission estimates reported in this table correspond to emissions from only those source categories for which quantitative uncertainty was performed for the current inventory. Thus the totals reported in this table for 2010 exclude approximately 2.8 Tg $CO_2$ Eq. of emissions for which quantitative uncertainty was not assessed. Hence, these emission estimates do not match the final total U.S. greenhouse gas emission estimates presented in this Inventory. Emissions trends and the emission range were calculated based on the emissions estimates reported in this table and, therefore, may differ from the emissions trends reported elsewhere in this Inventory.
[b] The trend range represents a 95 percent confidence interval for the emission trend, with the lower bound corresponding to 2.5$^{th}$ percentile value and the upper bound corresponding to 97.5$^{th}$ percentile value.
[c] This source category's inventory estimates exclude $CO_2$ emissions from geothermal sources, as quantitative uncertainty analysis was not performed for that sub-source category. Hence, for this source category, the emissions reported in this table do not match the emission estimates presented in the Energy chapter of the Inventory.
[d] Sinks are only included in Net Emissions.
[e] Emissions from Wood Biomass and Ethanol Consumption are not included specifically in summing energy sector totals.
[f] Emissions from International Bunker Fuels are not included in the emission totals and emission trend estimates.
[g] This source category's inventory estimate for 2010 excludes about 2.4 Tg of $CO_2$ Eq. from several very small emission sources, as uncertainty associated with those sources was not assessed. Hence, for this source category, the emissions reported in this table do not match the emission estimates presented in the Industrial Processes chapter of the Inventory.
[h] Totals exclude emissions for which uncertainty was not quantified. The Base Year emissions correspond to 1990 estimates for all source categories, with the exception of Substitution of ODS, for which the estimates correspond to 1995. Similarly, the total for HFCs, PFCs, and $SF_6$ for the Base Year includes 1995 emission estimates for Substitution of ODS and 1990 emission estimates for all other source categories.

## 7.3. Planned Improvements

Identifying the sources of uncertainty in the emission and sink estimates of the Inventory and quantifying the magnitude of the associated uncertainty is the crucial first step towards improving those estimates. Quantitative assessment of the parameter uncertainty may also provide information about the relative importance of input parameters (such as activity data and emission factors), based on their relative contribution to the uncertainty within the source category estimates. Such information can be used to prioritize resources with a goal of reducing uncertainty over time within or among inventory source categories and their input parameters. In the current Inventory, potential sources of

model uncertainty have been identified for some emission source categories, and uncertainty estimates based on their parameters' uncertainty have been developed for all the emission source categories, with the exception of $CH_4$ from incineration of waste, which is a minor emission source category newly added to the Inventory starting with the 2008 business year, and the international bunker fuels and wood biomass and ethanol combustion source categories, which are not included in the energy sector totals. Emissions from biomass and ethanol combustion however are accounted for implicitly in the LULUCF chapter through the calculation of changes in carbon stocks. The Energy sector does provide an estimate of $CO_2$ emissions from bioenergy consumption provided as a memo item for informational purposes.

Specific areas that require further research include:

- *Incorporating excluded emission sources.* Quantitative estimates for some of the sources and sinks of greenhouse gas emissions, such as from some land-use activities, industrial processes, and parts of mobile sources, could not be developed at this time either because data are incomplete or because methodologies do not exist for estimating emissions from these source categories. See Annex 5 of this report for a discussion of the sources of greenhouse gas emissions and sinks excluded from this report. In the future, efforts will focus on estimating emissions from excluded emission sources and developing uncertainty estimates for all source categories for which emissions are estimated.
- *Improving the accuracy of emission factors.* Further research is needed in some cases to improve the accuracy of emission factors used to calculate emissions from a variety of sources. For example, the accuracy of current emission factors applied to $CH_4$ and $N_2O$ emissions from stationary and mobile combustion are highly uncertain.
- *Collecting detailed activity data.* Although methodologies exist for estimating emissions for some sources, problems arise in obtaining activity data at a level of detail in which aggregate emission factors can be applied. For example, the ability to estimate emissions of $SF_6$ from electrical transmission and distribution is limited due to a lack of activity data regarding national $SF_6$ consumption or average equipment leak rates.

In improving the quality of uncertainty estimates the following include areas that deserve further attention:

- *Refine Source Category and Overall Uncertainty Estimates.* For many individual source categories, further research is needed to more accurately characterize PDFs that surround emissions modeling input variables. This might involve using measured or published statistics or implementing rigorous elicitation protocol to elicit expert judgments, if published or measured data are not available.
- *Include GWP uncertainty in the estimation of Overall level and trend uncertainty.* The current year's Inventory does not include the uncertainty associated with the GWP values in the estimation of the overall uncertainty for the Inventory. Including this source would contribute to a better characterization of overall uncertainty and help assess the level of attention that this source of uncertainty warrants in the future.
- *Improve characterization of trend uncertainty associated with base year Inventory estimates.* The characterization of base year uncertainty estimates could be improved, by developing explicit uncertainty models for the base year. This would then improve the analysis of trend uncertainty. However, not all of the simplifying assumptions described in the "Trend Uncertainty" section above may be eliminated through this process due to a lack of availability of more appropriate data.

## 7.4. Additional Information on Uncertainty Analyses by Source

The quantitative uncertainty estimates associated with each emission and sink source category are reported in each chapter of this Inventory following the discussions of inventory estimates and their estimation methodology. This section provides additional descriptions of the uncertainty analyses performed for some of the sources, including the models and methods used to calculate the emission estimates and the potential sources of uncertainty surrounding them. These sources are organized below in the same order as the sources in each chapter of the main section of this Inventory. To avoid repetition, the following uncertainty analysis discussions of individual source categories do not include descriptions of these source categories. Hence, to better understand the details provided below, refer to the respective chapters and sections in the main section of this Inventory, as needed. All uncertainty estimates are reported relative to the 2010 Inventory estimates for the 95 percent confidence interval, unless otherwise specified.

### Energy

The uncertainty analysis descriptions in this section correspond to some source categories included in the Energy Chapter of the Inventory.

**Mobile Combustion (excluding $CO_2$)**

Mobile combustion emissions of $CH_4$ and $N_2O$ per vehicle mile traveled vary significantly due to fuel type and composition, technology type, operating speeds and conditions, type of emission control equipment, equipment age, and operating and maintenance practices.

The primary activity data for on-road vehicles, VMT, are collected and analyzed each year by government agencies. To determine the uncertainty associated with the activity data used in the calculations of $CH_4$ and $N_2O$ emissions, the agencies and the experts that supply the data were contacted. Because few of these sources were able to provide quantitative estimates of uncertainty, expert judgment was used to assess the quantitative uncertainty associated with the activity data.

The estimates of VMT for on-road vehicles by vehicle type in the U.S. were provided by the FHWA (1996 through 2012), and were generated through a cooperative process between the FHWA and the state and the local governments. These estimates are subject to several possible sources of error, such as unregistered vehicles, and measurement and estimation errors. These VMT were apportioned by fuel type, based on data from DOE (1993 through 2011), and then allocated to individual model years using temporal profiles of both the vehicle fleet by age and vehicle usage by model year in the U.S. provided by EPA (2011a) and EPA (2000). While the uncertainty associated with the total national VMT is believed to be low, the uncertainty within individual source categories was considered to be higher due to the uncertainty associated with apportioning total VMT into individual vehicle categories, by fuel type, technology type, and by equipment age. It was assumed that smaller sources had greater percentage uncertainty and vice-versa. Another source of uncertainty in the estimates occurs due to differences in the FHWA and the EPA data sources. For example, the FHWA data are used for defining vehicle types and for developing the estimates of VMT by vehicle type; whereas, the estimates of VMT by fuel types are calculated using EPA's definition of vehicle categories (which differ from those of the FHWA).

The emission factors for on-road vehicles used in the Inventory were obtained from ICF (2006b) and ICF (2004). These factors were based on laboratory testing of vehicles. While the controlled testing environment simulates real driving conditions, emission results from such testing can only approximate real world conditions and emissions. For some vehicle and control technology types, because the testing did not yield statistically significant results within the 95 percent confidence interval, expert judgment was adopted in developing the emission factors. In those cases, the missing emission factors were extrapolated based on the data available on the other emission factors and the emissions factors available for similar vehicle and control technology type. For example, if light duty trucks with an oxidation catalyst has no testing (or not significant testing) results and if light duty cars with an oxidation catalyst had testing results, the $CH_4$ and the $N_2O$ emission factors for the trucks were calculated from the corresponding emissions factors for the car based upon the ratio of $CO_2$ emissions per mile for the car to the truck.

A total of 111 highway data input variables were simulated through Monte Carlo Simulation technique using @RISK software. Variables included VMT and emission factors for individual conventional and alternative fuel vehicle categories and technologies. In developing the uncertainty estimation model, a normal distribution was assumed for all but two activity-related input variables (e.g., VMT); in the case of the two input variables, buses and percent of diesel combination trucks, triangular distributions were assumed. The dependencies and other correlations among the activity data were incorporated into the model to ensure consistency in the model specification and simulation. Emission factors were assigned uniform distributions, with the upper and the lower bounds assigned based on 95 percent confidence intervals of laboratory test data. In cases where data did not yield statistically significant results within the 95 percent confidence interval, estimates of upper and lower bounds were determined using expert judgments. For biodiesel vehicles, because no test data were available, consistent with the assumptions underlying the ANL GREET model, their $N_2O$ and $CH_4$ emissions were assumed to be same as those for diesel vehicles of similar types. For other alternative fuel vehicles (AFVs), uncertainty estimates were developed based on conventional fuel vehicle emission factors and applicable multipliers, as described in the ICF's AFV emission factors memorandum to EPA (ICF 2006a). The results of the quantitative uncertainty analysis are reported as *quantitative uncertainty estimates* following the mobile source category emissions description in the Energy Chapter of this Inventory.

Emissions from non-road vehicles account for 27 percent of $CH_4$ emissions from mobile sources and 19 percent of $N_2O$ emissions from mobile sources in 2010. A quantitative analysis of uncertainty in the inventory estimates of emissions from non-road vehicles was performed for the first time for the 2009 inventory. Sources of uncertainty for non-road vehicles were investigated by examining the underlying uncertainty of emission factors and fuel consumption data. A non-road uncertainty assessment module was developed independently and integrated with the highway mobile uncertainty model to facilitate a more comprehensive quantitative analysis of uncertainty for all mobile sources.

The fuel consumption data for non-road vehicles were obtained from several sources. Estimates of fuel consumption for non-road vehicles (i.e., equipment used for agriculture, construction, lawn and garden, railroad, airport ground support, etc., as well as recreational vehicles) were generated by the EPA's NONROAD model (EPA 2011b). This model estimates fuel consumption based on estimated equipment/vehicle use (in hours) and average fuel consumed per hour of use. Since the fuel estimates are not based upon documented fuel sales or consumption, a fair degree of uncertainty accompanies these estimates. Estimates of distillate fuel sales for ships and boats were obtained from EIA's *Fuel Oil and Kerosene Sales* (EIA 1991 through 2012). These estimates have a moderate level of uncertainty since EIA's estimates are based on survey data and reflect sales to economic sectors, which may include use by both mobile and non-mobile sources within a sector. Domestic consumption of residual fuel by ships and boats is obtained from EIA (2009a). These estimates fluctuate widely from year to year, and are believed to be highly uncertain. In addition, estimates of distillate and residual fuel sales for ships and boats are adjusted for bunker fuel consumption, which introduces an additional (and much higher) level of uncertainty. Jet fuel and aviation gasoline consumption data are obtained from EIA (2012, FAA (2012), FAA (2011), and FAA (2006). Additionally, all jet fuel consumption in the transportation sector is assumed to be consumed by aircraft. Some jet fuel may also be used for other purposes such as blending with diesel fuel or heating oil. In calculating $CH_4$ emissions from aircraft, an average emission factor is applied to total jet fuel consumption. This average emission factor takes into account the fact that $CH_4$ emissions occur only during the landing and take-off (LTO) cycles, with no $CH_4$ being emitted during the cruise cycle. However, a better approach would be to apply emission factors based on the number of LTO cycles.

Emission factors for non-road modes were taken from IPCC/UNEP/OECD/IEA (1997) and Browning (2009). These emission factors are based on laboratory test data and expert judgment, and have similar sources of uncertainty as the on-road emission factors for uncontrolled vehicles.

A total of 79 non-road data input variables were simulated in the non-road uncertainty assessment module using @RISK software. To determine the uncertainty associated with the non-road fuel consumption data, the agencies and experts that supply the data were contacted. Since few of these sources were able to provide quantitative estimates of uncertainty, expert judgment was used to assess the quantitative uncertainty associated with the fuel consumption data. A normal distribution was assumed for all non-road activity-related input (fuel use) variables, and the activity variables were assumed to be independent of each other. Uncertainty estimates for non-road emissions factors were developed based on laboratory test data and expert judgment. Beta-PERT distributions were assumed for the emissions factor variables, and correlations among the data were incorporated into the model to ensure consistency in model specification.

The results of the quantitative uncertainty analysis are reported as *quantitative uncertainty estimates* following the mobile source category emissions description in the Energy Chapter of this Inventory.

#### Incineration of Waste

The upper and lower bounds of uncertainty in the $CO_2$ emissions estimate for Incineration of Waste are 24 percent and -21 percent respectively, and in the $N_2O$ emission estimates are 320 percent and -50 percent respectively, relative to the respective 2010 emission estimates, at the 95 percent confidence interval. The uncertainties in the waste combustion emission estimates arise from both the assumptions applied to the data and from the quality of the data. Key factors include MSW combustion rate, fraction oxidized, missing data on MSW composition, average carbon content of MSW components, assumptions on the synthetic/biogenic carbon ratio, and combustion conditions affecting $N_2O$ emissions. For more information on emission estimates from MSW combustion, please refer to the Incineration of Waste section of the Energy chapter. The highest levels of uncertainty surround the variables, whose estimates were developed based on assumptions (e.g., percent of clothing and footwear composed of synthetic rubber); the lowest levels of uncertainty surround variables that were determined by quantitative measurements (e.g., combustion efficiency, carbon content of carbon black). Important sources of uncertainty are as follows:

- *MSW Combustion Rate.* A source of uncertainty affecting both fossil $CO_2$ and $N_2O$ emissions is the estimate of the MSW combustion rate. The *BioCycle* (Glenn 1999, Goldstein and Matdes 2000, Goldstein and Matdes 2001, Kaufman et al. 2004a, Kaufman et al. 2004b, Simmons et al. 2006, Arsova et al. 2008, van Haaren et al. 2010) estimate of total waste combustion was used for the $N_2O$ and $CH_4$ emissions estimates, and waste incineration rate, used for the $CO_2$ emissions estimate are based on a survey of state officials, who use differing definitions of solid waste and who draw from a variety of sources of varying reliability and accuracy. The survey methodology changed significantly in 2003 and thus the results reported for 2002 are not directly comparable to the earlier results (Kaufman et al. 2004a, 2004b), introducing further uncertainty.

- *Fraction Oxidized.* Another source of uncertainty for the $CO_2$ emissions estimate is fraction oxidized. Municipal waste combustors vary considerably in their efficiency as a function of waste type, moisture content, combustion conditions, and other factors. A value of 98 percent was assumed for this analysis.

- *Missing Data on Municipal Solid Waste Composition.* Disposal rates have been interpolated when there is an incomplete interval within a time series. Where data are not available for years at the end of a time series, they are set equal to the most recent years for which estimates are available.

- *Average Carbon Contents.* Average carbon contents were applied to the mass of "Other" plastics combusted, synthetic rubber in tires and municipal solid waste, and synthetic fibers. These average values were estimated from the average carbon content of the known products recently produced. The actual carbon content of the combusted waste may differ from this estimate depending on differences in the chemical formulation between the known and unspecified materials, and differences between the composition of the material disposed and that produced. For rubber, this uncertainty ranges from 59 to 91 percent; for plastics, it may be more significant, as their carbon contents range from 38 to 92 percent. However, overall, this is a small source of uncertainty.

- *Synthetic/Biogenic Assumptions.* A portion of the fiber and rubber in municipal solid waste is biogenic in origin. Assumptions have been made concerning the allocation between synthetic and biogenic materials based primarily on expert judgment.

- *Combustion Conditions Affecting $N_2O$ Emissions.* Because insufficient data exist to provide detailed estimates of $N_2O$ emissions for individual combustion facilities, the estimates presented exhibit high uncertainty. The emission factor for $N_2O$ from municipal solid waste combustion facilities used in the analysis corresponds to the default emission factor for continuously fed stoker units found in IPCC (2006). Using this emission factor assumes that all waste combustors in the United States use continuously fed stoker technology, which is uncertain. Due to a lack of information on the control of $N_2O$ emissions from MSW combustion facilities in the United States, the estimate of zero percent for $N_2O$ emissions control removal efficiency also exhibits uncertainty.

## Industrial Processes

The uncertainty analysis descriptions in this section correspond to some source categories included in the Industrial Processes Chapter of the Inventory.

### Ammonia Production

The uncertainty upper and lower bounds of the emission estimate for Ammonia Production were 25 percent and -10 percent, respectively, at the 95 percent confidence interval. The European Fertilizer Manufacturer's Association (EFMA) reported an emission factor range of 1.15 to 1.30 ton $CO_2$/ton $NH_3$, with 1.2 ton $CO_2$/ton $NH_3$ reported as a typical value. The actual emission factor depends upon the amount of air used in the ammonia production process, with 1.15 ton $CO_2$/ton $NH_3$ being the approximate stoichiometric minimum that is achievable for the conventional reforming process. By using natural gas consumption data for each ammonia plant, more accurate estimates of $CO_2$ emissions from ammonia production could be calculated. However, these consumption data are often considered confidential. Also, natural gas is consumed at ammonia plants both as a feedstock to the reforming process and for generating process heat and steam. Natural gas consumption data, if available, would need to be divided into feedstock use (non-energy) and process heat and steam (fuel) use, as $CO_2$ emissions from fuel use and non-energy use are calculated separately.[109]

[109] It appears that the IPCC emission factor for ammonia production of 1.5 ton $CO_2$ per ton ammonia may include both $CO_2$ emissions from the natural gas feedstock to the process and some $CO_2$ emissions from the natural gas used to generate process heat and steam for the process. Table 2-5, Ammonia Production Emission Factors, in Volume 3 of the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual* (IPCC 1997) includes two emission factors, one reported for Norway and one reported for Canada. The footnotes to the table indicate that the factor for Norway does not include natural gas used as fuel but that it is unclear whether the factor for Canada includes natural gas used as fuel. However, the factors for

Natural gas feedstock consumption data for the U.S. ammonia industry as a whole are available from the Energy Information Administration (EIA) *Manufacturers Energy Consumption Survey* (MECS) for the years 1985, 1988, 1991, 1994 and 1998 (EIA 1994, 1998). These feedstock consumption data collectively correspond to an effective average emission factor of 1.0 ton $CO_2$/ton $NH_3$, which appears to be below the stoichiometric minimum that is achievable for the conventional steam reforming process. The EIA data for natural gas consumption for the years 1994 and 1998 correspond more closely to the $CO_2$ emissions calculated using the EFMA emission factor than do data for previous years. The 1994 and 1998 data alone yield an effective emission factor of 1.1 ton $CO_2$/ton $NH_3$, corresponding to $CO_2$ emission estimates that are approximately 1.5 Tg $CO_2$ Eq. below the estimates calculated using the EFMA emission factor of 1.2 ton $CO_2$/ton $NH_3$. Natural gas feedstock consumption data are not available from EIA for other years, and data for 1991 and previous years may underestimate feedstock natural gas consumption, and therefore the EFMA emission factor was used to estimate $CO_2$ emissions from ammonia production, rather than EIA data.

Research indicates that there is only one U.S. plant that manufactures ammonia from petroleum coke. Carbon dioxide emissions from this plant are explicitly accounted for in the Inventory estimates. No data for ammonia plants using naphtha or other feedstocks other than natural gas have been identified. Therefore, all other $CO_2$ emissions from ammonia plants are calculated using the emission factor for natural gas feedstock. However, actual emissions may differ because processes other than catalytic steam reformation and feedstocks other than natural gas may have been used for ammonia production. Urea is also used for other purposes than as a nitrogenous fertilizer. Currently, urea used as a nitrogenous fertilizer is accounted for in the LULUCF chapter. Research has identified one ammonia production plant that is recovering byproduct $CO_2$ for use in EOR. Such $CO_2$ is currently assumed to remain sequestered (see the section of this chapter on $CO_2$ Consumption); however, time series data for the amount of $CO_2$ recovered from this plant are not available and therefore all of the $CO_2$ produced by this plant is assumed to be emitted to the atmosphere and allocated to Ammonia Manufacture.

**Phosphoric Acid Production**

The uncertainty upper and lower bounds of the emissions estimate for Phosphoric Acid Production were 18 percent and -18 percent, respectively, at the 95 percent confidence interval. Factors such as the composition of phosphate rock affect $CO_2$ emissions from phosphoric acid production. For more information on how emissions estimates were calculated, please refer to the Phosphoric Acid Production section of the Industrial Processes chapter. Only one set of data from the Florida Institute of Phosphate Research (FIPR) was available for the composition of phosphate rock mined domestically and imported, and data for uncalcined phosphate rock mined in North Carolina and Idaho were unavailable. Inorganic carbon content (as $CO_2$) of phosphate rock could vary ±1 percent, resulting in a variation in $CO_2$ emissions of ±20 percent.

Organic C is not included in the calculation of $CO_2$ emissions from phosphoric acid production. However, if, for example, 50 percent of the organic carbon content of the phosphate rock were to be emitted as $CO_2$ in the phosphoric acid production process, the $CO_2$ emission estimate would increase by approximately 50 percent. If it is assumed that 100 percent of the reported domestic production of phosphate rock for Idaho and Utah was first calcined, and it is assumed that 50 percent of the organic carbon content of the total production for Idaho and Utah was converted to $CO_2$ in the calcination process, the $CO_2$ emission estimate would increase on the order of 10 percent. If it were assumed that there are zero emissions from other uses of phosphate rock, $CO_2$ emissions would fall 10 percent.

**Iron and Steel & Metallurgical Coke Production**

The uncertainty upper and lower bounds of the $CO_2$ emission estimate for Iron and Steel & Metallurgical Coke Production were 17 percent and -16 percent, respectively, at the 95 percent confidence interval. Factors such as the composition of C anodes and the C content of pig iron and crude steel affect $CO_2$ emissions from Iron and Steel Production. For more information on emission estimates, please refer to the Iron and Steel Production section of the Industrial Processes chapter.

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Norway and Canada are nearly identical (1.5 and 1.6 tons $CO_2$ per ton ammonia, respectively) and it is likely that if one value does not include fuel use, the other value also does not. For the conventional steam reforming process, however, the EFMA reports an emission factor range for feedstock $CO_2$ of 1.15 to 1.30 ton per ton (with a typical value of 1.2 ton per ton) and an emission factor for fuel $CO_2$ of 0.5 tons per ton. This corresponds to a total $CO_2$ emission factor for the ammonia production process, including both feedstock $CO_2$ and process heat $CO_2$, of 1.7 ton per ton, which is closer to the emission factors reported in the *IPCC 1996 Reference Guidelines* than to the feedstock-only $CO_2$ emission factor of 1.2 ton $CO_2$ per ton ammonia reported by the EFMA. Because it appears that the emission factors cited in the *IPCC Guidelines* may actually include natural gas used as fuel, we use the 1.2 tons/ton emission factor developed by the EFMA.

It was also assumed that the C contents of all pig iron and crude steel have carbon contents of 4 percent and 1 percent, respectively. The carbon content of pig iron can vary between 3.6 and 4.4 percent, while crude steel can have a carbon content of up to 2 percent, although it is typically less than 1 percent (IPCC 2000).

#### Aluminum Production

The uncertainty upper and lower bounds of the PFCs emission estimate for Aluminum Production were 6 percent and -51 percent, respectively, at the 95 percent confidence interval. The uncertainties associated with three variables were estimated for each smelter: (1) the estimated 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 (or weight fraction). For more information on the effect of these variables on PFC emissions, please refer the Aluminum Production section of the Industrial Processes chapter. The estimated quantity of aluminum produced is assumed to be characterized by a triangular distribution with a minimum value of zero and a maximum value corresponding to the reported production capacity (USGS 2011); whereas the anode effect and slope coefficient (or weight fraction) are assumed to be characterized by a normal distribution. The uncertainty in aluminum production estimates was assumed to be 1 percent for reported data (IPCC 2006). For reported anode effect frequency and duration data, the uncertainties were assumed to be 2 percent and 5 percent, respectively (Kantamaneni et al. 2001). For calculated smelter-specific $CF_4$ and $C_2F_6$ slope coefficients the uncertainties were assumed to be 15 percent (IPCC 2006). For smelters applying technology-specific slope coefficients or weight fractions, the uncertainty in the coefficients was based on the standard deviation of the individual measurements used to determine the average value given by the IPCC guidance for technology-specific (Tier 2) slope coefficients. Consequently, the uncertainty value assigned to the technology-specific slope coefficients for $CF_4$ for CWPB was 0.036, and for $C_2F_6$ for CWPB was 0.060. (The uncertainty in the technology-specific $CF_4$ slope coefficent for CWPB is reported as 6 percent in IPCC (2006), but was increased to 50 percent in this analysis to better account for measurement uncertainty for an individual facility. The uncertainty in PFC emissions for CWPB facilities (the best behaved of the technology types) is about 50 percent for any given facility using the Tier 2 calculation.) In general, where precise quantitative information was not available on the uncertainty of a parameter, an upper-bound value was used.

#### Magnesium Production

The uncertainty information pertains to the emission estimates presented in the Magnesium Production section of the Industrial Processes chapter. Please refer to that section for more information about this source. The uncertainty upper and lower bounds of the emissions estimate for Magnesium Production were 4 percent and -4 percent, respectively, at the 95 percent confidence interval. An uncertainty of 5 percent was assigned to the data reported by each participant in EPA's $SF_6$ Emission Reduction Partnership for the Magnesium Industry. If Partners did not report emissions data during the current reporting year, $SF_6$ emissions data were estimated using available emission factor and production information reported in prior years; the extrapolation was based on the average trend for Partners reporting in the current reporting year and the year prior. The uncertainty associated with the $SF_6$ usage estimate generated from the extrapolated emission factor and production information was determined using a sum of squares method. A 5 percent uncertainty for the year the Partner last reported was assumed and a 30% uncertainty for each subsequent year was assumed. For those industry processes that are not represented in Partnership, such as permanent mold and wrought casting, $SF_6$ emissions were estimated using production and consumption statistics reported by USGS and estimated process-specific emission factors (see Table 4-73). The uncertainties associated with the emission factors and USGS-reported statistics were assumed to be 75 percent and 25 percent, respectively. Emissions associated with sand casting activities not entirely captured by the Partnership utilized a Partner-reported emission factor with an uncertainty of 75 percent. In general, where precise quantitative information was not available on the uncertainty of a parameter, a conservative (upper-bound) value was used.

#### Electrical Transmission and Distribution

The uncertainty upper and lower bounds of the emissions estimate for Electrical Transmission and Distribution at the 95 percent confidence interval were 25 percent and -22 percent, respectively. Uncertainty associated with emissions of $SF_6$ from electrical transmission and distribution stem from the following three quantities: (1) emissions from partners, (2) emissions from non-partners, and (3) emissions from manufacturers of electrical equipment. The uncertainty of partner emissions is related to whether the partner emissions are reported or estimated. For reported partner emissions, individual partner submitted $SF_6$ data was assumed to have an uncertainty of 10 percent. Based on a Monte Carlo analysis, the cumulative uncertainty of the total partner reported data was estimated to be 5.3 percent. For partner-estimated emissions, the uncertainty associated with emissions extrapolated or interpolated from reported emissions data was assumed to be 20 percent. There are two sources of uncertainty that contribute to the non-partner emissions uncertainty. The first is the uncertainty in the coefficients of the regression equations used to estimate emissions from non-partners, and the second is the uncertainty in the total transmission miles for non-partners—the independent variable in the regression equation. The uncertainty in the coefficients (as defined by the regression standard error estimate) is estimated to be ±20 percent for

small utilities and ±64 percent for large utilities, while the uncertainty in the transmission miles is assumed to be ±10 percent. For equipment manufacturers, the quantity of $SF_6$ charged into equipment by equipment manufacturers is estimated using partner reported new nameplate capacity data and the estimate for the total industry nameplate capacity. The quantity of $SF_6$ charged into equipment in 2010 is estimated to have an uncertainty of 70.3 percent, and is derived from the uncertainty in partner reported new nameplate capacity (estimated as 5.5.0 percent using error propagation) and the uncertainty in the estimate for U.S. total nameplate capacity (assumed to be 70 percent).

A Monte Carlo analysis was applied to estimate the overall uncertainty of the 2010 emission estimate for $SF_6$ from electrical transmission and distribution. For each defined parameter (i.e., regression coefficient, transmission mileage, partner-reported and partner-estimated $SF_6$ emissions data for electric power systems; and $SF_6$ emission rate and statistics for manufacturers), random variables were selected from probability density functions, all assumed to have normal distributions about the mean.

## Agriculture

The uncertainty analysis descriptions in this section correspond to some source categories included in the Agriculture Chapter of the Inventory.

### Manure Management

The uncertainty information below pertains to the emission estimates presented in the Manure Management section of the Agriculture chapter. Please refer to that section for information about various manure management systems and their effect on emissions from this source. The uncertainty upper and lower bounds of the $CH_4$ emissions estimate for Manure Management were 20 percent and -18 percent, respectively, at the 95 percent confidence interval. The primary factors that contribute to the uncertainty in the emission estimates are a lack of information on the usage of various manure management systems in each regional location and the exact $CH_4$ generating characteristics of each type of manure management system. Because of significant shifts in the swine and dairy sectors toward larger farms, it is believed that increasing amounts of manure are being managed in liquid manure management systems. The existing estimates reflect these shifts in the weighted MCFs based on 1992, 1997, and 2002 farm-size data. However, the assumption of a direct relationship between farm size and liquid system usage may not apply in all cases and may vary based on geographic location. In addition, the $CH_4$ generating characteristics of each manure management system type are based on relatively few laboratory and field measurements, and may not match the diversity of conditions under which manure is managed nationally.

Previously, IPCC published a default range of MCFs for anaerobic lagoon systems of 0 to 100 percent, reflecting the wide range in performance that may be achieved with these systems (IPCC 2000). There exist relatively few data points on which to determine country-specific MCFs for these systems. In the United States, many livestock waste treatment systems classified as anaerobic lagoons are actually holding ponds that are substantially organically overloaded and therefore not producing $CH_4$ at the same rate as a properly designed lagoon. In addition, these systems may not be well operated, contributing to higher loading rates when sludge is allowed to enter the treatment portion of the lagoon or the lagoon volume is pumped too low to allow treatment to occur. Rather than setting the MCF for all anaerobic lagoon systems in the United States based on data available from optimized lagoon systems, a MCF methodology utilizing the van't Hoff-Arrhenius equation was developed to more closely match observed system performance and account for the affect of temperature on system performance.

The MCF methodology used in the inventory includes a factor to account for management and design practices that result in the loss of VS from the management system. This factor is currently estimated based on data from anaerobic lagoons in temperate climates, and from only three systems. However, this methodology is intended to account for systems across a range of management practices.

Uncertainty also exists with the maximum $CH_4$ producing potential of VS excreted by different animal groups (i.e., $B_o$). The $B_o$ values used in the $CH_4$ calculations are published values for U.S. animal waste. However, there are several studies that provide a range of $B_o$ values for certain animals, including dairy and swine. The $B_o$ values chosen for dairy assign separate values for dairy cows and dairy heifers to better represent the feeding regimens of these animal groups. For example, dairy heifers do not receive an abundance of high energy feed and consequently, dairy heifer manure will not produce as much $CH_4$ as manure from a milking cow. However, the data available for $B_o$ values are sparse, and do not necessarily reflect the rapid changes that have occurred in this industry with respect to feed regimens.

### Rice Cultivation

The uncertainty upper and lower bounds of the emission estimate for Rice Cultivation were 153 percent and -65 percent, respectively, at the 95 percent confidence interval. Factors such as primary rice-cropped area, ratooning, and

flooding affect greenhouse gas emissions from this source. For more information on emissions estimates for Rice Cultivation, please refer to that section in the Agriculture Chapter. Uncertainty associated with primary rice-cropped area for each state was assumed to range from 1 percent to 5 percent of the mean area based on expert judgment. A normal distribution of uncertainty, truncated to avoid negative values, was assumed about the mean for areas.

Ratooned area data are an additional source of uncertainty. Although ratooning accounts for only 5 to 10 percent of the total rice-cropped area, it is responsible for about 15 to 30 percent of total emissions. For states that have never reported any ratooning, it is assumed with complete certainty that no ratooning occurred in 2010. For states that regularly report ratooning, uncertainty is estimated to be between 3 percent and 5 percent (based on expert judgment) and is assumed to have a normal distribution, truncated to avoid negative values. For Arkansas, which reported significant ratooning in 1998 and 1999 only, a triangular distribution was assumed, with a lower boundary of 0 percent ratooning and an upper boundary of 0.034 percent ratooning based on the maximum ratooned area reported in 1998 and 1999.

The practice of flooding outside of the normal rice season is also an uncertainty. According to agricultural extension agents, all of the rice-growing states practice this on some part of their rice acreage. Estimates of these areas range from 5 to 68 percent of the rice acreage. Fields are flooded for a variety of reasons: to provide habitat for waterfowl, to provide ponds for crawfish production, and to aid in rice straw decomposition. To date, however, $CH_4$ flux measurements have not been undertaken over a sufficient geographic range or under a broad enough range of representative conditions to account for this source in the emission estimates or its associated uncertainty.

#### Agricultural Soil Management

The uncertainty information below pertains to the emission estimates presented in the Agricultural Soil Management section of the Agriculture chapter. Please refer to that section for information about this source. For direct emissions calculated using DAYCENT, uncertainty in the results was attributed to model inputs (i.e., activity data, weather and soil conditions) and the structure of the model (i.e., underlying model equations and parameterization). A Monte Carlo analysis was implemented to address these uncertainties and propagate errors through the modeling process (Del Grosso et al., 2010). The analysis was conducted using probability distribution functions (PDFs) for weather, soil characteristics, and N inputs to simulate direct $N_2O$ emissions for each crop- or grassland type in a county. A joint PDF was used to address the structural uncertainty for direct $N_2O$ emissions from crops, which was derived using an empirically-based method (Ogle et al. 2007). This same Monte Carlo analysis was used to derive uncertainty for the volatilization, runoff, and leaching of N that had been estimated with DAYCENT. County-scale PDFs for weather were based on the variation in temperature and precipitation as represented in DAYMET weather data grid cells (1x1 km) occurring in croplands and grasslands in a county. The National Land Cover Dataset (Vogelman et al. 2001) provided the data on distribution of croplands and grasslands. Similarly, county-scale PDFs for soil characteristics were based on STATSGO Soil Map Units (Soil Survey Staff 2005), that occurred in croplands and grasslands. PDFs for fertilizer were derived from survey data for major U.S. crops, both irrigated and rainfed (ERS 1997; NASS 2004, 1999, 1992; Grant and Krenz 1985). State-level PDFs were developed for each crop if a minimum of 15 data points existed for each of the two categories (irrigated and rainfed). Where data were insufficient at the state-level, PDFs were developed for multi-state Farm Production Regions. Uncertainty in manure application for specific crops was incorporated into the analysis based on total manure available for application in each county, a weighted average application rate, and the crop-specific land area amended with manure for 1997 (compiled from USDA data on animal numbers, manure production, storage practices, application rates and associated land areas receiving manure amendments; see Edmonds et al. 2003). Together with the total area for each crop within a county, the result yielded a probability that a given crop in a specific county would either receive manure or not in the Monte Carlo analysis. A ratio of manure N available for application in each year of the inventory relative to 1997 was used to adjust the amount of area amended with manure, under the assumption that changing the amount of manure N available for application would lead to a proportional change in amended area (see the section on Major Crop Types on Mineral Soils for data sources on manure N availability). If soils were amended with manure, a reduction factor was applied to the N fertilization rate accounting for the interaction between fertilization and manure N amendments (i.e., producers reduce mineral fertilization rates if applying manure). Reduction factors were randomly selected from probability distribution factors based on relationships between manure N application and fertilizer rates from USDA cropping survey data (ERS 1997).

An empirically-based uncertainty estimator was developed to assess the uncertainty in model structure associated with its' algorithms and parameterization, using a method described by Ogle et al. (2007). This estimator was based on a linear mixed-effect modeling analysis comparing $N_2O$ emission estimates from eight agricultural experiments with 50 treatments. Although the dataset was relatively small, modeled emissions were significantly related to measurements with a p-value of less than 0.01. Random effects were included to capture the dependence in time series and data collected from the same experimental site, which were needed to estimate appropriate standard deviations for parameter coefficients. The model structural uncertainty estimator, accounted for bias and prediction error in the DAYCENT model

results, as well as random error associated with fine-scale emission predictions in counties over a time series from 1990 to 2010. Note that the current application only addresses structural uncertainty in cropland estimates; further development will be needed to address this uncertainty in model estimates for grasslands, which is a planned improvement as more soil $N_2O$ measurement data become available for grassland sites. In general, DAYCENT tended to underestimate emissions if the rates were above 6 g $N_2O$/ha/day (Del Grosso et al., 2010). Model structural uncertainty was not assessed for N volatilization and leaching/runoff, because sufficient data from field experiments were not available.

A simple error propagation method (IPCC 2006) was used to estimate uncertainties for direct emissions estimated with Tier 1 methods, including management of non-major crops (mineral fertilization, crop residues, organic fertilizers) and N inputs that were not addressed in the DAYCENT simulations (i.e., sewage sludge N, PRP manure N excreted on federal grasslands). Similarly, indirect emissions from N inputs that were not simulated with DAYCENT were calculated according to the IPCC methodology using the simple error propagation method (IPCC 2006). PDFs for the proportion of N subject to volatilization, leaching and runoff, as well as indirect $N_2O$ emission factors were based on IPCC (2006), and PDFs for the activity data were based on the uncertainties associated underlying survey information and calculations.[110] For lands simulated by DAYCENT, uncertainty in indirect emissions was derived using the simple error propagation approach, combining uncertainty from the DAYCENT outputs for N volatilization and leaching/runoff with uncertainty in the indirect $N_2O$ emission factors (IPCC 2006).

#### Field Burning of Agricultural Residues

The uncertainty upper and lower bounds of the $CH_4$ emission estimate for Field Burning of Agricultural Residues were 42 percent and -40 percent, respectively, and of the $N_2O$ emissions estimate were 31 percent and -29 percent respectively, at the 95 percent confidence interval. Variables such as crop production, residue/crop product ratios, and burning and combustion efficiencies affect greenhouse gas emission estimates for Field Burning of Agricultural Residues. For more information on emission estimates, please refer to the Field Burning of Agricultural Residues section of the Agriculture Chapter. The uncertainty in production for all crops considered here is estimated to be 5 percent, based on expert judgment. The uncertainty in area burned was 7 percent, based on McCarty (2009). Residue/crop product ratios can vary among cultivars. Generic residue/crop product ratios, rather than ratios specific to the United States, have been used for all crops except sugarcane. An uncertainty of 10 percent was applied to the residue/crop product ratios for all crops except for cotton, which was 55 percent. Based on the range given for measurements of soybean dry matter fraction (Strehler and Stützle 1987), residue dry matter contents were assigned an uncertainty of 3.1 percent for all crop types, except for cotton and lentils, which were 10 and 4.4 percent, respectively. Burning and combustion efficiencies were assigned an uncertainty of 5 percent based on expert judgment. The $N_2O$ emission ratio was estimated to have an uncertainty of 28.6 percent based on the range reported in IPCC/UNEP/OECD/IEA (1997). The uncertainty estimated for the $CH_4$ emission ratio was 40 percent based on the range of ratios reported in IPCC/UNEP/OECD/IEA (1997).

## Land Use, Land-Use Change, and Forestry

#### Forest Land Remaining Forest Land

##### *Changes in Forest Carbon Stocks*

Forest area data from the USDA Forest Service and C density data affect total net flux of forest C estimates. For more information on net forest C flux, please refer to the Changes in Forest Carbon Stocks section of the Land Use, Land-Use Change, and Forestry (LULUCF) chapter. The USDA Forest Service inventories are designed to be accurate within 3 percent at the 67 percent confidence level (one standard error) per 405,000 ha (1 million acres) of timberland (USDA Forest Service 2006c). For larger areas, the uncertainty in area is concomitantly less, and precision at plot levels is greater. An analysis of uncertainty in growing stock volume data for timber producing land in the Southeast by Phillips et al. (2000) found that nearly all of the uncertainty in their analysis was due to sampling rather than the regression equations used to estimate volume from tree height and diameter. The quantitative uncertainty analysis summarized here primarily focuses on uncertainties associated with the estimates of specific C stocks at the plot level and does not address error in tree diameters or volumes.

Estimates for stand-level C pools are derived from extrapolations of site-specific studies to all forest land, because survey data on these pools are not generally available. Such extrapolation introduces uncertainty because available studies may not adequately represent regional or national averages. Uncertainty may also arise due to: (1) modeling errors (e.g., relying on coefficients or relationships that are not well known); and (2) errors in converting

[110] With the exception of organic fertilizers and crop yields, which were assumed to have a default ±50 percent uncertainty.

estimates from one reporting unit to another (Birdsey and Heath 1995). An important source of uncertainty is that there is little consensus from available data sets on the effect of land-use change and forest management activities (such as harvest) on soil C stocks. For example, while Johnson and Curtis (2001) found little or no net change in soil C following harvest, on average, across a number of studies, many of the individual studies did show differences. Heath and Smith (2000) noted that the experimental design in a number of soil studies limited their usefulness for determining effects of harvesting on soil C. Because soil C stocks are large, estimates need to be very precise, since even small relative changes in soil C sum to large differences when integrated over large areas. The soil C stock and stock change estimates presented here are based on the assumption that soil C density for each broad forest type group stays constant over time. The state of information and modeling are improving in this regard (Woodbury et al. 2006, 2007); the effects of land use and of changes in land use and forest management will be better accounted for in future estimates of soil C.

Uncertainty in estimates about the HWP Contribution is based on Monte Carlo simulation of the production approach. The uncertainty analysis is based on Skog et al. (2004), with later revisions made in conjunction with overall revisions in the HWP model (Skog in preparation). The uncertainty analysis for HWP includes an evaluation of the effect of uncertainty in 13 sources including production and trade data, factors to convert products to quantities of C, rates at which wood and paper are discarded, and rates and limits for decay of wood and paper in SWDS.

#### *Direct $N_2O$ fluxes from Forest Soils*

The uncertainty upper and lower bounds of the emissions estimate for Direct $N_2O$ Fluxes from Forest Soils were 211 percent and -59 percent, respectively, at the 95 percent confidence interval. Variables such as the emission factor for synthetic fertilizer applied to soil, and the area of forest land receiving fertilizer affect Direct $N_2O$ fluxes from Forest Soils. For more information, please refer to that section of the LULUCF chapter. The uncertainty range of the IPCC (2006) default emission factor for synthetic fertilizer applied to soil, ranges from 0.3 to 3 percent. Because IPCC does not provide further information on whether this range represents the 95 percent confidence interval or the absolute minimum and maximum values, a triangular distribution was used to represent the uncertainty of the emission factor. The uncertainty in the area of forest land receiving fertilizer was conservatively estimated at ±20 percent and in fertilization rates at ±50 percent (Binkley 2004).

#### Cropland Remaining Cropland

The uncertainty information below pertains to the emission estimates presented in the Cropland Remaining Cropland section of the LULUCF chapter. Please refer to that section for information about this source. The uncertainty upper and lower bounds of the emissions estimate for Cropland Remaining Cropland were -172 percent and 167 percent, respectively, at the 95 percent confidence interval. Probability Distribution Functions (PDFs) for fertilizer were based on survey data for major U.S. crops, both irrigated and rainfed (ERS 1997; NASS 2004, 1999, 1992; Grant and Krenz 1985). State-level PDFs were developed for each crop if a minimum of 15 data points existed for each of the two categories (irrigated and rainfed). Where data were insufficient at the state-level, PDFs were developed for multi-state Farm Production Regions. Uncertainty in manure applications for specific crops was incorporated in the analysis based on total manure available for use in each county, a weighted average application rate, and the crop-specific land area amended with manure (compiled from USDA data on animal numbers, manure production, storage practices, application rates and associated land areas receiving manure amendments; see Edmonds et al. 2003). Together with the total area for each crop within a county, this yielded a probability that a given crop at a specific NRI point would either receive manure or not. A ratio of managed manure N production in each year of the inventory relative to 1997 was used to adjust the probability of an area receiving an amendment, under the assumption that greater or less managed manure N production would lead to a proportional change in amended area (see Tier 3 Methods Section for data sources on manure N production). Manure amendment areas were averaged across decades to produce the PDF for the Monte Carlo Analysis (i.e., 1980-1989, 1990-2000). If soils were amended with manure, a reduction factor was applied to the N fertilization rate accounting for the interaction between fertilization and manure N amendments (i.e., producers often reduce mineral fertilization rates if applying manure). Reduction factors were randomly selected from probability distribution factors based on relationships between manure N application and fertilizer rates (ERS 1997). For tillage uncertainty, transition matrices were constructed from CTIC data to represent tillage changes for two time periods, combining the first two and the second two management blocks (i.e., 1980-1989, 1990-2000). A Monte Carlo analysis was conducted with 100 iterations in which inputs values were randomly drawn from the PDFs to simulate the soil C stocks for each NRI cluster of points (i.e., inventory points in the same county were grouped into clusters if they had the same land-use/management history and soil type) using the Century model.

An empirically-based uncertainty estimator was developed to assess uncertainty in model structure associated with the algorithms and parameterization. The estimator was based on a linear mixed effect modeling analysis comparing modeled soil C stocks with field measurements from 45 long-term agricultural experiments with over 800 treatments, representing a variety of tillage, cropping, and fertilizer management practices (Ogle et al. 2006b). The final model

included variables for organic matter amendments, N fertilizer rates, inclusion of hay/pasture in cropping rotations, use of no-till, setting-aside cropland from production and inclusion of bare fallow in the rotation. Each of these variables were found to be significant at a 95 percent probability level, and accounted for statistically significant biases in the modeled estimates from Century. For example, Century tended to under-estimate the influence of organic amendments on soil C storage, so a variable was added to adjust the estimate from Century. Random effects captured the dependence in time series and data collected from the same long-term experimental site, which were needed to estimate appropriate standard deviations for parameter coefficients. For each C stock estimate from the Monte Carlo analysis, the structural uncertainty estimator was applied to adjust the value accounting for bias and prediction error in the modeled values. The structural uncertainty estimator was applied by randomly drawing parameter coefficients from their joint probability distribution, in addition to random draws from PDFs representing the uncertainty due to site and site by year random effects. Finally, uncertainty in the land-use and management statistics from the NRI were incorporated into the analysis based on the sampling variance for the clusters of NRI points.

The NRI has a two-stage sampling design that allowed PDFs to be constructed assuming a multivariate normal distribution accounting for dependencies in activity data. PDFs for the tillage activity data, as provided by the CTIC, were constructed on a bivariate normal distribution with a log-ratio scale, accounting for the negative dependence among the proportions of land under conventional and conservation tillage practices. PDFs for the agricultural areas receiving manure were derived assuming a normal distribution from county-scale area amendment estimates derived from the USDA Census of Agriculture (Edmonds et al. 2003). Lastly, enrollment in wetland restoration programs was estimated from contract agreements, but due to a lack of information on the margin of error, PDFs were constructed assuming a nominal ±50 percent uncertainty range.

#### *Mineral Soil Carbon Stock Changes*

##### *Tier 3 Approach*

The uncertainty information below pertains to the emission estimates presented in the Mineral Soil Carbon Stock Changes section of the LULUCF chapter. Please refer to that section for information about this source. The uncertainty analysis for the Tier 3 Century inventory had three components: 1) a Monte Carlo approach to address uncertainties in model inputs, 2) an empirically-based approach for quantifying uncertainty inherent in the structure of the Century model, and 3) scaling uncertainty associated with the NRI survey (i.e., scaling from the individual NRI points to the entire U.S. agricultural land base using the expansion factors).

For the model input uncertainty, probability distribution functions (PDFs) were developed for fertilizer rates, manure application and tillage practices. An empirically-based uncertainty estimator was developed to assess uncertainty in model structure associated with the algorithms and parameterization. The estimator was based on a linear mixed effect modeling analysis comparing modeled soil C stocks with field measurements from 45 long-term agricultural experiments with over 800 treatments, representing a variety of tillage, cropping, and fertilizer management practices (Ogle et al. 2007). The final model included variables for organic matter amendments, N fertilizer rates, inclusion of hay/pasture in cropping rotations, use of no-till, setting-aside cropland from production, and inclusion of bare fallow in the rotation. Each of these variables were found to be significant at a 0.05 alpha level, and accounted for statistically significant biases in modeled estimates from the Century model. Uncertainty in land-use and management statistics from the NRI were incorporated into the analysis based on the sampling variance for the clusters of NRI points.

##### *Tier 2 Approach*

For the Tier 2 IPCC method, a Monte Carlo approach was used (Ogle et al. 2003). PDFs for stock change factors were derived from a synthesis of 91 published studies, which addressed the impact of management on SOC storage. Uncertainties in land-use and management activity data were also derived from a statistical analysis.

##### *Additional Mineral C Stock Change Calculations*

A ±50 percent uncertainty was assumed for additional adjustments to the mineral soil C stocks between 1990 and 2006; accounting for additional C stock changes associated gains or losses in C sequestration after 1997 due to changes in Conservation Reserve Program enrollment.

#### *Organic Soil Carbon Stock Changes*

Uncertainty in C emissions from organic soils was estimated in the same manner described for mineral soil using the Tier 2 method and Monte Carlo analysis. PDFs for emission factors were derived from a synthesis of 10 studies, and combined with uncertainties in the NRI land use and management data for organic soils in the Monte Carlo analysis. Please refer to the Organic Soil C Stock Changes section of the LULUCF chapter for more information on C emissions from organic soils.

#### *$CO_2$ Emissions from Liming*

The uncertainty information below pertains to the emission estimates presented in the Mineral Soil Carbon Stock Changes section of the LULUCF chapter. Please refer to that section for information about liming activity data and the emission factors used for this source. A Monte Carlo (Tier 2) uncertainty analysis was applied to estimate the uncertainty of $CO_2$ emissions from liming. Uncertainties in the estimates of emissions from liming result from both the emission factors and the activity data. The emission factors used for limestone and dolomite take into account the fate of C following application to soils, including: dissolution of liming constituents; leaching of bicarbonates into the soil and transport to the ocean; and emissions to the atmosphere (West and McBride 2005). The C accounting behind these emission factors entails assumptions about several uncertain factors. First, it is uncertain what fraction of agricultural lime is dissolved by nitric acid ($HNO_3$)—a process that releases $CO_2$—and what portion reacts with carbonic acid ($H_2CO_3$), resulting in the uptake of $CO_2$. The fractions can vary depending on soil pH and N fertilizer use. The second major source of uncertainty is the fraction of bicarbonate ($HCO_3^-$) that leaches through the soil profile and *is transported into groundwater, which can eventually be transferred into rivers and into the ocean*. This fraction can vary depending on the soil pH and whether calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$) liming constituents that might otherwise accompany $HCO_3^-$, are taken up by crops, remain in the upper soil profile, or are transported through or out of the soil profile. Finally, the emission factors do not account for the time that is needed for leaching and transport processes to occur.

There are several sources of uncertainty in the limestone and dolomite activity data. When reporting data to the USGS (or U.S. Bureau of Mines), some producers do not distinguish between limestone and dolomite. In these cases, data are reported as limestone, so this reporting could lead to an overestimation of limestone and an underestimation of dolomite. In addition, the total quantity of crushed stone listed each year in the *Minerals Yearbook* excludes American Samoa, Guam, Puerto Rico, and the U.S. Virgin Islands.

### Land Converted to Cropland

#### *Tier 2 Approach*

The uncertainty upper and lower bounds of the emissions estimate for Land Converted to Cropland were 36 percent and -40 percent, respectively, at the 95 percent confidence interval. The uncertainty analysis for *Land Converted to Cropland* using the Tier 2 approach was based on the same method described for *Cropland Remaining Cropland*.

#### *Mineral and Organic Soil Carbon Stock Changes*

The quantitative estimates of uncertainty presented above are missing several components. This section qualitatively describes these contributors to overall uncertainty. The agricultural soil C inventory has undergone several improvements during the past few years, such as the development of the Tier 3 inventory method to estimate mineral soil C stock changes for the majority of U.S. cropland. However, some limitations remain in the analysis. First, the current agricultural soil C inventory includes some points designated as non-agricultural land-uses in the NRI if the points were categorized as cropland in either 1992 or 1997, but were urban, water, or miscellaneous non-cropland (e.g., roads and barren areas) in another year. The impact on soil organic C (SOC) storage that results from converting non-agricultural uses to cropland is not well-understood, and therefore, those points were not included in the calculations for mineral soils (emissions from organic soils, however, were computed for those points in the years that they were designated as an agricultural use). Similarly, the effect of aquaculture (e.g., rice cultivation followed by crayfish production in flooded fields) on soil C stocks has not been estimated due to a lack of experimental data. Second, the current estimates may underestimate losses of C from organic soils because the *1997 National Resources Inventory* was not designed as a soil survey and organic soils frequently occur as relatively small inclusions within major soil types. Lastly, the IPCC Tier 2 methodology does not take into account changes in SOC stocks due to pre-1982 land use and land-use change.

### Grassland Remaining Grassland

#### *Tier 2 Approach*

The uncertainty upper and lower bounds of the emissions estimate for Grassland Remaining Grassland were -32 percent and 25 percent, respectively, at the 95 percent confidence interval. The uncertainty analysis for *Grassland Remaining Grassland* using the Tier 2 approach was based on the same method described for *Cropland Remaining Cropland*.

#### *Additional Uncertainties in Mineral and Organic Soil C Stock Changes*

The quantitative estimates of uncertainty presented above are missing several components. This section qualitatively describes these contributors to overall uncertainty. Minimal data exist on where and how much sewage sludge has been applied to U.S. agricultural land and the accounting of this activity appears to be much more difficult than the related-activity of using manure to amend agricultural soils. Consequently, there is considerable uncertainty in the

application of sewage sludge, which is assumed to be applied to *Grassland Remaining Grassland*. However, some sludge may be applied to other agricultural land, but there is not sufficient information to further subdivide application among the agricultural land use/land-use change categories. Another limitation is that the current estimates may underestimate losses of C from organic soils because the *1997 National Resources Inventory* was not designed as a soil survey and organic soils frequently occur as relatively small inclusions within major soil types. Lastly, the IPCC Tier 2 methodology does not take into account changes in SOC stocks due to pre-1982 land use and land-use change.

#### Land Converted to Grassland

##### *Tier 2 Approach*

The uncertainty upper and lower bounds of the emissions estimate for Land Converted to Grassland were -15 percent and 15 percent, respectively, at the 95 percent confidence interval. The uncertainty analysis for *Land Converted to Grassland* using the Tier 2 approach was based on the same method described for *Cropland Remaining Cropland*. See the Tier 2 section under minerals soils in the *Cropland Remaining Cropland* section for additional discussion.

##### *Additional Uncertainties in Mineral and Organic Soil Carbon Stock Changes*

The quantitative estimates of uncertainty presented above are missing several components. This section qualitatively describes these contributors to overall uncertainty. The agricultural soil C inventory has undergone several improvements during the past few years, such as the development of the Tier 3 inventory method to estimate mineral soil C stock changes for the majority of U.S. grassland. However, some limitations remain in the analysis. First, the current agricultural soil C inventory includes some points designated as non-agricultural land-uses in the NRI if the points were categorized as agricultural land use in either 1992 or 1997, but were urban, water, or miscellaneous non-cropland (e.g., roads and barren areas) in another year. The impact on SOC storage that results from converting non-agricultural uses to grassland is not well-understood, and therefore, those points were not included in the calculations for mineral soils (emissions from organic soils, however, were computed for those points in the years that they were designated as grassland). Second, the current estimates may underestimate losses of C from organic soils because the *1997 National Resources Inventory* was not designed as a soil survey and organic soils frequently occur as relatively small inclusions within major soil types. Lastly, this IPCC Tier 2 methodology does not take into account changes in SOC stocks due to pre-1982 land use and land-use change.

#### Settlements Remaining Settlements

##### *$N_2O$ Fluxes from Settlement Soil*

The uncertainty information below pertains to the emission estimates presented in the $N_2O$ Fluxes from Settlement Soils section of the LULUCF chapter. Please refer to that section for information about synthetic fertilizer N, the amounts of sewage sludge applied to non-agricultural lands, and other variables that affect this source. The uncertainty upper and lower bounds of the emissions estimate for $N_2O$ fluxes from Settlement Soil were 163 percent and -49 percent, respectively, at the 95 percent confidence interval. The uncertainty range for the IPCC's default emission factor for mineral and organic N additions applied to soil ranges from 0.3 to 3 percent (IPCC 2006). Because the IPCC does not provide further information on whether this range represents the 95 percent confidence interval or the absolute minimum and maximum values, a triangular distribution was used to represent the uncertainty of the emission factor.

The uncertainty in the total amount of synthetic fertilizer N applied in the United States was estimated to be ±3 percent (Terry 2005). The uncertainty in the amount of synthetic fertilizer N applied to settlement soils was conservatively estimated to be ±50 percent, since no uncertainty was provided in Ruddy et al. (2006). The uncertainty in the amounts of sewage sludge applied to non-agricultural lands and used in surface disposal was based on the uncertainty of the following data points: (1) N content of sewage sludge; (2) total sludge applied in 2000; (3) wastewater existing flow in 1996, 2000, and 2004; and (4) the sewage sludge disposal practice distributions to non-agricultural land application and surface disposal.

(1) The value assumed for N content of sewage sludge could range from around 0.1 percent to around 17 percent (McFarland 2001). Because information was not available on the distribution, a triangular distribution was assumed based on IPCC guidelines.
(2) The uncertainty in the total amount of sludge applied in 2000 was based on a comparison with similar data available from other publications, which were all within 3 percent of the value used in the Inventory calculations (BioCycle 2000, NRC 2002, WEF 1997, Bastian 1997). The distribution was estimated to be normal based on expert opinion (Boucher 2006).
(3) The uncertainty in the wastewater existing flow values for 1996 and 2000 was estimated at 0.0625 percent with a lognormal distribution (Plastino 2006).

(4) The uncertainty in the sewage sludge disposal practice distributions was based on a comparison with similar data available from other publications, which were at most 12 percent different than the distribution for non-agricultural land application used in the Inventory calculations and at most 69 percent different than the distribution for surface disposal used in the Inventory calculations (Biocycle 2000, NRC 2002).

### Other

The uncertainty analysis descriptions in this section correspond to Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills source category included in the Other Chapter of the Inventory.

#### *Changes in Yard Trimming and Food Scrap Carbon Stocks in Landfills*

The uncertainty ranges were assigned based on expert judgment and are assumed to be normally distributed around the inventory estimate, except for the values for decomposition rate, proportion of C stored, and the decay rates. The uncertainty ranges associated with these values are highlighted separately in this section.

The uncertainty range selected for input variables for the proportions of both grass and leaves in yard trimmings was 20 to 60 percent. The initial C content for grass, leaves, and food scraps (all expressed as percentages in the calculations for the inventory) were plus or minus 10 percent. For the moisture content of branches (where the inventory estimate is 10 percent), the uncertainty range was assumed to be 5 to 30 percent, within a lognormal distribution.

The uncertainty ranges associated with the disposal of grass, leaves, branches, and food scraps were bound at 50 percent to 150 percent of the inventory estimates. The proportion of C stored in grass, leaves, branches, and food scraps was assumed to vary plus or minus 20 percent from the best estimate, with a uniform distribution. The proportion of C stored in food scraps was truncated at a lower bound of 2 percent.

Finally, the uncertainty ranges assigned to the decay rates of grass, leaves, branches, and food scraps were developed based on De la Cruz, 2010. The minimum value corresponds to projected conditions if all landfills are in a dry environment; the maximum value corresponds to bioreactor conditions. A triangular distribution is applied to each of these variables.

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