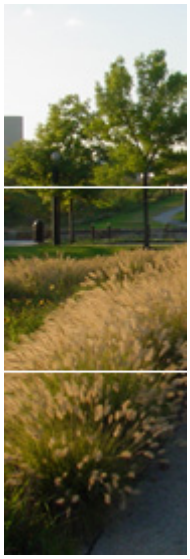
Pennsylvania Greenhouse Gas Inventory and Reference Case Projections

1990-2025





Prepared for the:

pennsylvania environmental council

Center for Climate Strategies

Alison Bailie and Alison Jamison (Lead Authors)
Tom Peterson, Stephen Roe

December 2007

Table of Contents

Acronyms and Key Terms

AEO – US DOE Energy Information Administration's *Annual Energy Outlook*
AEPS – Alternative Energy Portfolio Standard
BCF – Billion cubic feet
BLM – Bureau of Land Management
CBM – Coal-bed Methane
CH4 – Methane*
CO2 – Carbon Dioxide*
CO2e – Carbon Dioxide equivalent*
EIA – US DOE Energy Information Administration
EIIP – Emission Inventory Improvement Project
FIA – Forest Inventory Analysis (US Forest Service)
FHWA – Federal Highway Administration
GHG – Greenhouse Gases*
GNP – Gross National Product
GSP – Gross State Product
GWP - Global Warming Potential*
GWh – Gigawatt-hours (1 million kilowatt-hours)
HFCs – Hydrofluorocarbons*
IPCC – Intergovernmental Panel on Climate Change*
kWh – Kilowatt-hour
Mt - Metric ton (equivalent to 1.102 short tons)
MMt – Million Metric tons
MTBE – Methyl Tertiary Butyl Ether
MWh – Megawatt-hours (1 thousand kilowatt-hours)
N2O – Nitrous Oxide*
ODS – Ozone-Depleting Substances
PFCs – Perfluorocarbons*
PA DCNR – Pennsylvania Department of Conservation and Natural Resources
PA DEP – Pennsylvania Department of Environmental Protection
PennDOT – Pennsylvania Department of Transportation
RCI – Residential, Commercial, and Industrial
SEDS – US DOE Energy Information Administration's State Energy Data System
SGIT – US EPA State Greenhouse Gas Inventory Tool
SF6 – Sulfur Hexafluoride*
Sinks – Removals of carbon from the atmosphere, with the carbon stored in forests, soils, landfills, wood structures, or other biomass-related products.
US EPA – US Environmental Protection Agency
US DOE – US Department of Energy
USFS – US Department of Agriculture Forest Service
USGS – US Geological Survey
US MSHA – US Mine Safety and Health Administration
TWh – Terawatt-hours (1 billion kilowatt-hours)
VMT – Vehicle-miles Traveled
* - See Appendix J for more information.

Acknowledgements

We appreciate all of the time and assistance provided by numerous contacts throughout Pennsylvania and at federal agencies. Many of these contacts are listed in Appendix H – our apologies to those not listed. In particular, thanks go to the staff at several Pennsylvania state agencies for their inputs, especially to Joe Sherrick of the Pennsylvania Department of Environmental Protection and Adam Rose of Pennsylvania State University who provided key guidance for this analytical effort. Further thanks to Scott Van De Mark and Brian Hill of the Pennsylvania Environmental Council for their input during the analysis and the drafting of this document. Michael Lazarus of the Center for Climate Strategies developed the overall structure of the document and approach to presenting the data.

1. Summary of Findings

Introduction

This report presents initial estimates of historical and projected Pennsylvania anthropogenic greenhouse gas (GHG) emissions and sinks for the period from 1990 to 2025. These estimates are intended to provide an initial comprehensive understanding of past, current, and possible future Pennsylvania greenhouse gas (GHG) emissions and thereby inform the upcoming analysis and design of GHG mitigation strategies.

Historical GHG emissions estimates (1990 through 2004)[1] were developed using a set of generally-accepted principles and guidelines for state greenhouse gas emissions, as described in Section 2, relying to the extent possible on Pennsylvania-specific data and inputs.[2] The initial reference case projections out to 2025 are based on a compilation of various existing Pennsylvania and regional projections of electricity generation, fuel use, and other GHG emitting activities, along with a set of simple, transparent assumptions described later in this report.

This report covers the six types of gases included in the US Greenhouse Gas Inventory: carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). Emissions of these greenhouse gases are presented using a common metric, CO2 equivalence (CO2e), which indicates the relative contribution of each gas to global average radiative forcing on a Global Warming Potential (GWP) weighted basis. The final appendix to this report provides a fuller discussion of greenhouse gases and GWPs.

Pennsylvania Greenhouse Gas Emissions: Sources and Trends

Initial analysis suggests that in 2005, Pennsylvania produced about 317 million metric tons[3] (MMt) of *gross* carbon dioxide equivalent (CO2e) emissions, an amount equal to 4 percent of total *gross* US GHG emissions.[4] Gross emissions include all major sources and gases, most notably carbon dioxide emissions from combustion of fossil fuels in power plants, vehicles, buildings, and industries (89 percent of total State emissions), the release of methane from fossil fuel combustion, oil and gas production, coal mines, agriculture, and waste management (7

[1] For some sectors and sources, historical data are only available through 2000, 2001, 2002 or 2003.

[2] A starting point for this analysis was the Pennsylvania GHG emissions inventory prepared by the Center for Integrated Regional Assessment at Pennsylvania State University as part of *Greenhouse Gas Emissions Inventory for Pennsylvania, Phase I Report* (Rose et al, 2003). This report included two single historical years (1990 and 1999) and, like this report, used the EPA guidelines as a base for estimating the inventory. Since the PennState report was completed, both the data and the calculation approach have been adjusted for some of the components. Differences between the inventory results are discussed in Appendix I.

[3] All GHG emissions are reported here in metric tons.

[4] United States emissions estimates are drawn from Climate Analysis Indicators Tool (CAIT) version 1.5 (Washington, DC: World Resources Institute, 2003), which is based on official USEPA reports. Available at: http://cait.wri.org.

percent), and other sources such industrial processes and nitrous oxide from agricultural soils (4 percent).

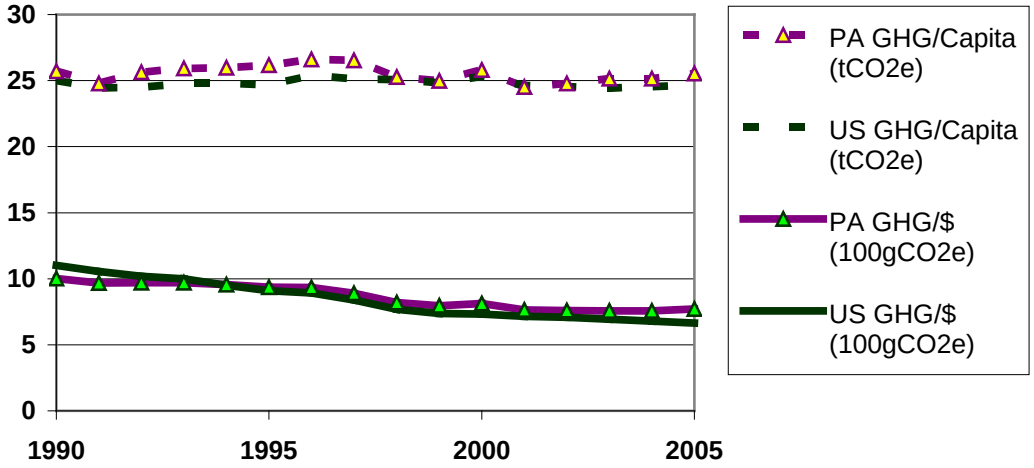
Net emissions combine gross emissions sources with carbon sequestered and released from biomass throughout the State. Preliminary estimates suggest that from the late 1980s through 2002, Pennsylvania's forest areas sequestered an average of about 17 $MMtCO_2e$ per year[5]. Applying these estimates to 2005, the State's *net* GHG emissions would be 300 $MMtCO_2e$, about 5 percent lower than the gross emissions estimate. This report provides both gross and net emissions estimates, as well as production and consumption based systems.[6]

The State's gross GHG emissions increased by about 4 percent during the previous 15 years – much more slowly than the US as a whole, where emissions rose by 16 percent.[7] This slower increase appears largely attributable to a few key factors: limited population and economic growth, a large decrease in coal consumption in industry due to a decrease in steel production, and increased capture of methane from landfills.

On a per capita basis, Pennsylvania produces approximately the same GHG emissions as the national average (about 25 tCO_2e per person). Figure 1 shows that, like the nation as a whole, per capita emissions have remained fairly flat. Economic growth outpaced emissions growth throughout the 1990-2005 period both nationally and in Pennsylvania. During this time, gross GHG emissions per unit of gross product dropped by almost 40 percent nationally, and by 26 percent in Pennsylvania.

[5] Estimate based on US Forest Service estimates as of July 2006. See Appendix F.
[6] We applied two different accounting methods for GHG emissions from the electric sector – *production-based emissions* refer to GHG emissions associated with electricity generation in the State while *consumption-based emissions* refer to GHG emissions associated with electricity consumption in the State. The emissions in this section are mostly production-based; see further description at the end of section.
[7] US EPA Emissions Inventory "Fast Facts" from 1990 through 2005. Available online at: http://www.epa.gov/climatechange/emissions/downloads/2007GHGFastFacts.pdf

Figure 1. Pennsylvania and US GHG Emissions, Per Capita and Per Unit Gross Product (2000$)



In addition to being a key facet of the State's economy, energy producing industries are the dominant feature of Pennsylvania's GHG emissions profile. Together, the production of electricity and fossil fuels accounted for 45 percent of Pennsylvania's gross GHG emissions in the year 2005, as shown in Figure 2. In comparison, these activities accounted for only 37 percent of national gross GHG emissions.[8]

Emissions of greenhouse gases by electric power plants in Pennsylvania,[9] the State's leading emission source, are relatively well understood and are for the most part (CO_2 at facilities over 25 MW) continuously monitored. Over 95 percent of these emissions occur at the State's 36 coal-fired facilities. Emissions from three plants (Bruce Mansfield, Conemaugh, and Keystone) account for about one third of the total electric sector emissions. Natural gas- and oil-fired power plants produce the remaining emissions from this sector.

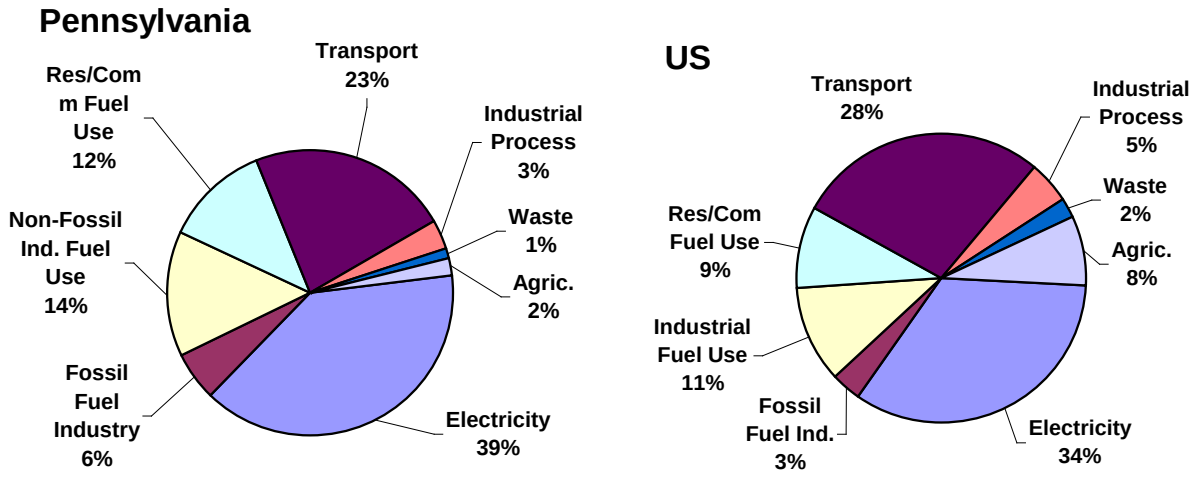
Emissions of CO_2 and methane (CH_4) occur at many stages of the fossil fuel production and delivery process (drilling, production, processing/refining, and pipeline transport) and can be highly dependent upon local resource characteristics (e.g., pressure, depth, water content, gas concentrations), technologies applied, and practices employed at individual wells sites and compressor stations. Pennsylvania has over 60,000 oil and gas wells, 9 gas processing plants, 5 oil refineries, and over 50 thousand miles of gas pipelines. Since neither the industry nor the government has regulatory requirements to track CO_2 or methane emissions, there are significant uncertainties associated with estimates of GHG emissions from the fossil fuels sector. Our

[8] Fuel use for field, processing, and pipeline operations are included in the fossil fuel industry for Pennsylvania; however, such fuel use is not disaggregated in the national inventory, and thus constitutes a fraction of the slice shown for US industrial fuel use.

[9] We applied two different accounting methods for GHG emissions from the electric sector – *production-based emissions* refer to GHG emissions associated with electricity generation in the State while *consumption-based emissions* refer to GHG emissions associated with electricity consumption in the State. The emissions in this section are production-based; see further description at the end of section.

estimates, however, suggest that fossil fuel industry emissions were about 18 $MMTCO_2e$ in 2005, or 6 percent of total State emissions.

Figure 2. Gross GHG Emissions by Sector and Gas, 2005, Pennsylvania and US



As a fraction of total GHG emissions, transportation accounted for 23 percent of Pennsylvania emissions, compared with 28 percent of national emissions. On a per capita basis, transportation emissions are about 7 percent less than the national average, possibly as a result of a relatively dense population.

The remaining use of fossil fuels – natural gas, oil products, and coal -- constitutes another 26 percent of State emissions, about half in residential and commercial buildings and the other half among non-fossil-fuel industrial sectors. GHG emissions from residential and commercial fuel use has been relatively stable from 1990 to 2005, showing an overall increase of 3% between these two years. Industrial fuel use showed much more variation – growing from 1991 through 1997 then declining by 18 percent, mostly due to reduced steel production in the State. GHG emissions since 1998 have been stable or shown modest declines.

Agricultural activities such as manure management, fertilizer use, and livestock (enteric fermentation) result in methane and nitrous oxide emissions that account for 2 percent of State GHG emissions. These emissions declined by an estimated 10 percent from 1990 to 2005, due to decreased dairy and beef stock.

Industrial process emissions (emissions that result from production processes rather than from energy consumption) comprise about 3 percent of State GHG emissions currently. Carbon dioxide released during cement production accounted for over half of these emissions. The use of hydrofluorocarbons (HFCs) as substitutes for ozone-depleting substances (ODS) such as chlorofluorocarbons and hydrochlorofluorocarbons[10] made up one third of the emissions. These emissions grew from less than 0.5 $MMTCO_2e$ in 1990 to 5.0 $MMTCO_2e$ in 2005 and are

[10] Chlorofluorocarbons and hydrochlorofluorocarbons are also potent greenhouse gases; however they are not included in GHG estimates because of concerns related to implementation of the Montreal Protocol. See final Appendix.

expected to continue their rapid growth. Perfluorocarbons (PFC) in semiconductor manufacture and sulfur hexafluoride (SF6) from electricity transmission accounted for the remaining emissions in this category.

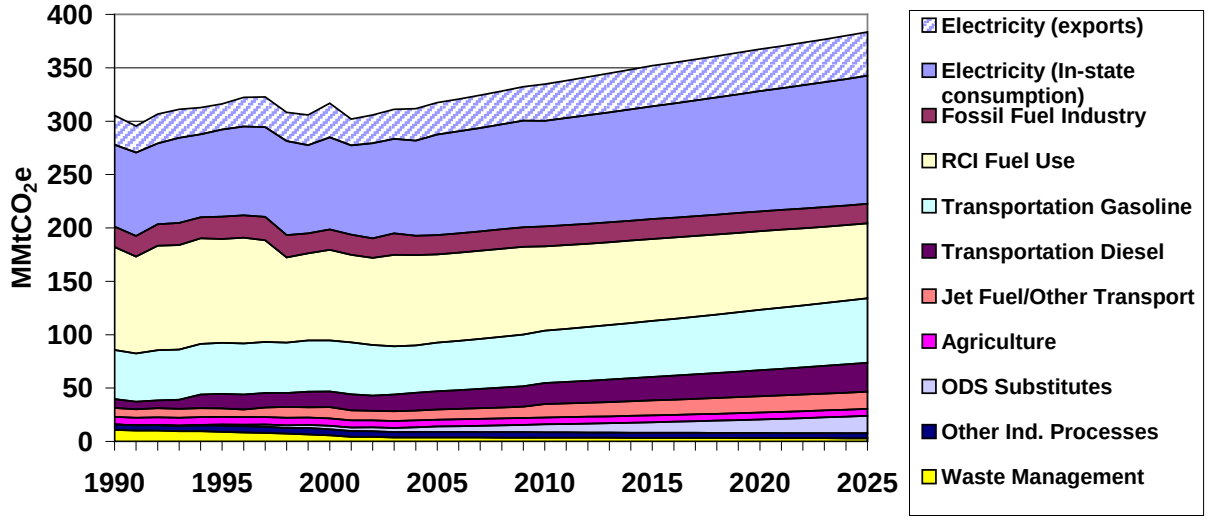
Landfills and wastewater management facilities produce methane and nitrous oxide emissions accounting for the remaining 1 percent of current State emissions in 2005. These emissions have decreased in recent years as Pennsylvania has developed several projects to capture landfill gas and either use the methane for energy production or flare it, which also reduces net GHG emissions.

Reference Case Projections

Relying on US DOE and Pennsylvania agency projections of population, employment, and electricity use plus input from State government staff and industry experts, we developed a simple reference case projection of GHG emissions through 2025.[11] The reference case assumes a continuation of current trends and but excludes the implementation of recently enacted policies, such as the State's Alternative Energy Portfolio Standard.

As illustrated in Figure 3 and shown numerically in Table 1, under the reference case projection, Pennsylvania's gross GHG emissions are projected to grow steadily from recent levels. (For more details on emissions by source, see Table 5 at the end of this section and the appendices for this document.) By 2010 GHG emissions are projected to reach 335 MMtCO2e, 5.5 percent above year 2005 levels. By 2025, gross emissions could climb to 383 $MMtCO_2e$, an increase of 21 percent above year 2005 levels. These increases are slightly greater than growth from 1990 to 2005, driven largely by projected increases in transportation activity and electric generation. Large decreases in GHG emissions from the industrial sector, such as what occurred between 1990 and 2000, are not projected in the reference case.

Figure 3. Gross GHG Emissions by Sector, 1990-2025: Historical and Projected



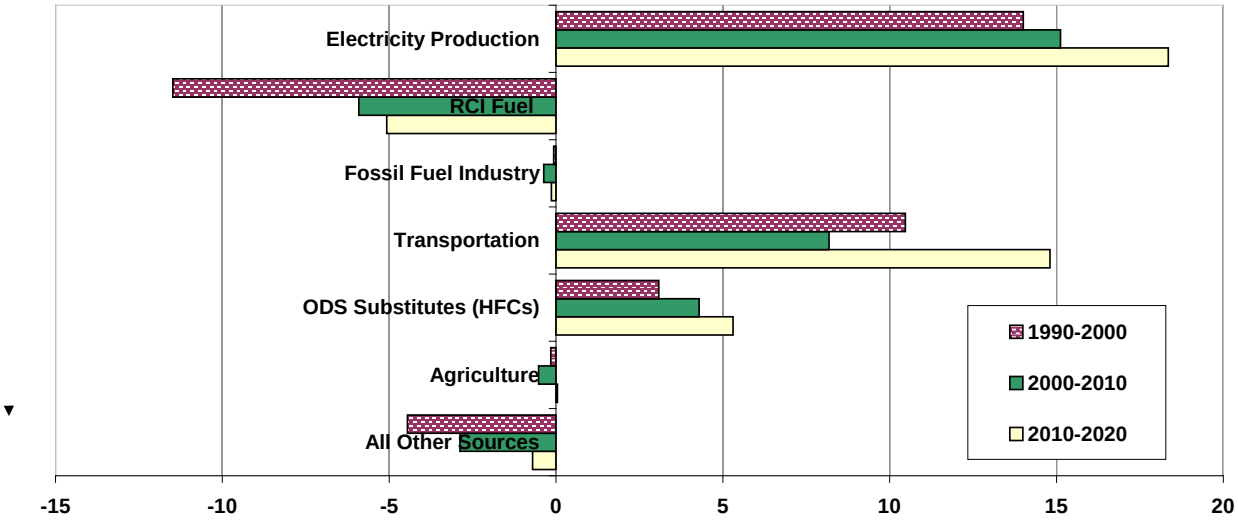
[11] Historical data is currently available through 2001 to 2005 depending on the emissions source.

Table 1. Pennsylvania GHG Emissions, Reference Case – Production Based

(Million Metric Tons CO2e)	1990	1995	2000	2005	2010	2015	2020	2025
Energy	**282**	**293**	**295**	**297**	**312**	**328**	**340**	**353**
Electricity Production	104	106	118	124	133	144	152	161
Transportation Fuel Use	63	69	73	72	81	88	96	104
Fossil Fuel Industry	19	21	19	18	19	19	19	18
Res/Comm/Other Ind. Fuel Use	96	97	85	83	79	77	74	70
Black Carbon								
Other	**23**	**23**	**22**	**20**	**22**	**24**	**27**	**31**
Industrial Processes	5	7	9	10	12	15	17	21
Agriculture	7	7	7	6	6	6	6	6
Waste Management	11	9	6	4	3	3	3	3
Gross Emissions	**305**	**316**	**317**	**317**	**335**	**352**	**367**	**383**
change relative to 1990		*+4%*	*+4%*	*+4%*	*+10%*	*+15%*	*+20%*	*+26%*
change relative to 2005					*+6%*	*+11%*	*+16%*	*+21%*
Forestry and Land Use	**-17**	**-17**	**-17**	**-17**	**-17**	**-17**	**-17**	**-17**
Net Emissions (incl. forestry*)	**288**	**299**	**300**	**300**	**318**	**335**	**350**	**366**
change relative to 1990		*+4%*	*+4%*	*+4%*	*+10%*	*+16%*	*+21%*	*+27%*
change relative to 2005					*+6%*	*+12%*	*+17%*	*+22%*
Per Capita Gross Emissions (Mt)	26	26	26	26	27	28	29	30
Per Capita Net Emissions (Mt)	24	25	24	24	25	26	27	29

These different paces of rate growth by decade can be explained by looking more closely at changes by sector, as shown in Figure 4.

Figure 4. Contributions to Emissions Growth, 1990-2020: Reference Case Projections ($MMTCO_2e$)



Electricity production emissions increased by about 14 $MMTCO_2e$ from 1990 to 2000, and this increase is expected to continue, at a slightly higher level, for the remainder of this decade. Emissions are projected to increase by a further 18 $MMTCO_2e$ from 2010 to 2020 as new plants are built using coal and waste coal. The residential, commercial, and industrial sectors (RCI) show decreases in emissions, both historically and projected. Much of this decrease is a result of drops in steel production in the past and expected continued movement away from coal consumption in the industrial sector. Note that emissions from electricity consumption are not included in the RCI fuel category; instead these emissions are part of the Electricity Production category. Emissions from the Fossil Fuel Industry did not change much between 1990 and 2000 and are projected to stay relatively constant through 2020.

Transportation emissions increased by approximately 10.5 $MMTCO_2e$ from 1990 to 2000, with diesel and jet fuel showing particularly strong increases. From 2000 to 2004, gasoline consumption decreased while diesel consumption increased but at a much lower rate than in the previous decade. However, consumption and the resulting emissions are expected to continue strong growth through 2025.

While the switch to the use of HFCs as substitutes for ozone-depleting substances (ODS) is expected to continue to increase Pennsylvania's emissions, emissions from agriculture and other sources are expected to decline or hold constant.

Consumption vs. Production-Based Emissions

As noted, emissions from Pennsylvania's electricity production play a large role in historic and projected emissions. As part of the interconnected grid connecting Pennsylvania and neighboring states, Pennsylvania exports and imports electricity daily. Overall, however, Pennsylvania

produces more electricity than is consumed in the State and thus is a *net* exporter of electricity. This situation raises an important question with respect to how these emissions should be addressed from an accounting and policy basis. In other words, should states focus on: a) all emissions produced within the State even if the electricity is exported out-of-State (*production-based emissions*), or b) the emissions associated with consumption of electricity whether produced within the State or elsewhere (*consumption-based emissions*).

Reporting production-based emissions has the advantages of simplicity and consistency with typical inventory methods. If used for policy purposes, e.g. for setting emission reduction goals and tracking progress in meeting them, production-based reporting will account for changes in emissions resulting from new in-state power plants, even if such facilities are built largely to serve out-of-state consumption. Such changes in the State's reported emissions could be very significant but may be rather difficult to predict or manage since the changes depend on factors outside of Pennsylvania. Furthermore, one could argue that these changes do not reflect "real" emissions changes, if electricity consumers would otherwise purchase their electricity from similar sources in other states or countries.

In contrast, reporting consumption-based GHG emissions can be more complex from an accounting perspective. However, the consumption-based approach may also better reflect the emissions (and emissions reductions) associated with consuming activities occurring within the State, particularly with respect to electricity use (and efficiency improvements), and thus may be useful in a policy context. Under this approach, emissions associated with electricity exported to other states would need to be covered in those states' accounts in order to avoid double counting or exclusions. The consumption-based approach also leads to projections that are likely to be less volatile (subject to major changes), and future GHG emissions are perhaps more directly influenced by state-based strategies such as energy efficiency. Nevertheless, as described in the electricity section (Appendix A), developing a robust tracking system for a consumption-based approach could be rather challenging.

For this initial inventory, we prepared simplified consumption-based estimates for electricity generation. We estimated the ratio of in-State electricity consumption to total electricity generation[12] and applied this ratio to the total GHG emissions from that sector. (See Table 2) While this method may not precisely reflect the sources of electricity used to meet in-state demands, it does provide a rough guide.

Table 2. Simplified Calculation of Consumption-Basis Emissions for Electricity and Fossil Fuel Production

	1990	2000	2005	2010	2020	2025	Units
Electricity							
Electricity Produced	172	198	215	228	257	272	TWh
In-State Electricity Needs (including transmission losses)	127	144	163	170	192	205	TWh
in-state share	*74%*	*73%*	76%	*75%*	*75%*	*75%*	
Production-Based Emissions	104	118	124	133	152	161	$MMtCO_2e$
Consumption-Based Emissions	77	86	94	100	114	121	$MMtCO_2e$

[12] See Appendix A for more information.

The result of these calculations is shown in Table 3 below. Emissions related to electricity consumption are about 25 percent lower than for electricity production, reflecting the fact that the State produces about 25 percent more electricity than it needs for its own use.

Table 3. Pennsylvania GHG Emissions, Reference Case – Consumption Based

(Million Metric Tons CO_2e)	1990	1995	2000	2005	2010	2015	2020	2025
Energy	**255**	**269**	**265**	**267**	**279**	**290**	**302**	**313**
Electricity Use	*77*	*82*	*86*	*94*	*100*	*106*	*114*	*121*
Transportation Fuel Use	63	69	73	72	81	88	96	104
Fossil Fuel Industry	19	21	21	18	19	19	18	18
Res/Comm/Other Ind. Fuel Use	96	97	85	83	79	77	74	70
Black Carbon								
Other	**23**	**23**	**22**	**20**	**22**	**24**	**27**	**31**
Industrial Processes	5	7	9	10	12	15	17	21
Agriculture	7	7	7	6	6	6	6	6
Waste Management	11	9	6	4	3	3	3	3
Gross Emissions	**278**	**292**	**287**	**288**	**301**	**315**	**329**	**344**
change relative to 1990		*+5%*	*+3%*	*+3%*	*+8%*	*+13%*	*+18%*	*+24%*
change relative to 2005					*+5%*	*+9%*	*+14%*	*+20%*
Forestry and Land Use	**-17**	**-17**	**-17**	**-17**	**-17**	**-17**	**-17**	**-17**
Net Emissions (incl. forestry*)	**261**	**275**	**269**	**270**	**284**	**298**	**311**	**327**
change relative to 1990		*+5%*	*+3%*	*+4%*	*+9%*	*+14%*	*+19%*	*+25%*
change relative to 2005					*+5%*	*+10%*	*+15%*	*+21%*
Per Capita Gross Emissions	23	25	23	24	24	26	26	28
Per Capita Net Emissions	22	23	22	23	23	25	24	27

Key Uncertainties

The greatest uncertainties in this analysis occur in the projected emissions. While uncertainties will always exist about the future, the attempt made by this work has been to use a few basic assumptions to develop a rough indication of the order of magnitude for expected emissions. The key drivers are summarized below, in Table 4, and specific assumptions are described in the following appendices. Closer review and discussion of these growth rates is planned through public and agency review and input.

Another substantial source of uncertainty involves the influence of black carbon and other aerosol emissions. Emissions of aerosols, particularly black carbon from fossil fuel and biomass combustion, could have potentially significant impacts in terms of radiative forcing (i.e. climate impacts). Methodologies for conversion of black carbon mass estimates and projections to global

warming potential involve significant uncertainty at present and have not been included in these GHG estimates.

Table 4. Key Annual Growth Rates, Historical and Projected

	Historical 1990-2004	Projected 2005-2025	Sources/Uses
Population*	0.3%	0.2%	U.S. Census Bureau, Population Division, Interim State Population Projections, 2005.
Employment*	0.7%	0.6%	Historical Data and Projections from http://www.paworkstats.state.pa.us/ 2002-2012 projection used through 2025
Manufacturing	-1.3%	-0.9%	
Non-Manufacturing	1.3%	0.9%	
Electricity sales	1.6%	1.25% from 2004 on	EIA SEDS for historic, projections based on PJM projections.
Electricity production	1.5%	1.3% from 2004 on	EIA data for historic, projections based roughly on AEO 2007 for the region; subject to uncertainties
Vehicle Miles Traveled*	1.5% (1994-2003)	1.6%	Penn DOT/PA DEP for projections (historical from HPMS Transportation Statistics, federal program administered by Penn DOT)

* Population, employment, and VMT projections for Pennsylvania were used together with US DOE's Annual Energy Outlook 2006 projections of changes in fuel use on a per capita, per employee, and per VMT, as relevant for each sector. For instance, growth in Pennsylvania residential natural gas use is calculated as the Pennsylvania population growth times the change in per capita Pennsylvania natural gas use for the Mid-Atlantic region. Pennsylvania population growth is also used as the driver of growth in cement production, soda ash consumption, solid waste generation, and wastewater generation.

Table 5. Reference Case, Production-Based GHG Emissions, Detailed Results

Source	1990	2000	2010	2020	2025	Explanatory Notes
Electricity Production	**104.3**	**118.3**	**133.4**	**151.8**	**160.9**	
Coal	98.8	113.8	123.1	139.5	147.5	See electric sector assumptions in
Natural Gas	0.7	1.1	6.0	8.0	9.0	Table 2-4
Oil	4.8	3.4	4.3	4.3	4.3	
Res/Comm/Industrial (excl. fossil fuel industry)	**96.3**	**84.8**	**78.9**	**73.8**	**70.0**	
Coal	38.9	27.9	27.2	24.7	22.9	Based on US DOE regional projections
Natural Gas	33.0	34.9	31.8	31.1	30.5	Based on US DOE regional projections
Oil	24.2	21.8	19.8	17.8	16.5	Based on US DOE regional projections
Wood (CH_4 and N_2O)	0.2	0.2	0.2	0.1	0.1	Assumes no change after 2003
Transportation	**62.7**	**73.2**	**81.4**	**96.2**	**103.6**	
Gasoline	46.1	47.9	49.1	56.5	60.5	VMT from PennDOT, constant energy/VMT
Diesel	8.3	14.7	19.8	24.4	27.2	VMT from PennDOT, constant energy/VMT
Natural Gas, LPG, other	3.4	2.9	1.8	1.8	1.8	Based on USDOE regional projections
Jet Fuel & Aviation Gasoline	4.9	7.7	10.7	13.5	14.2	Based on USDOE regional projections
Fossil Fuel Industry	**19.1**	**19.0**	**18.7**	**18.5**	**18.4**	
Natural Gas Industry *	7.9	8.3	8.8	8.9	8.8	See footnote a
Oil Industry **	2.0	1.8	1.8	1.6	1.5	See footnote b
Coal Mining (Methane)	9.2	9.0	8.1	8.1	8.1	Assumes no change after 2004
Industrial Processes	**5.1**	**9.0**	**12.5**	**17.5**	**21.1**	
ODS Substitutes	0.02	3.1	7.4	12.7	16.41	Based on national projections (State Dept.)
PFCs in Semi-conductor Ind.	0.2	0.4	0.2	0.1	0.1	Based on national projections (US EPA)
SF_6 from Electric Utilities	1.2	0.6	0.5	0.3	0.2	Based on national projections (US EPA)
Cement & Other Industry	3.7	4.8	4.4	4.4	4.4	No changes projected
CO_2 Consumption						not yet estimated
Waste Management	**10.8**	**5.6**	**3.5**	**3.1**	**2.9**	
Solid Waste Management	9.6	4.3	2.2	1.7	1.5	Based on national projections (State Dept.)
Wastewater Management	1.2	1.3	1.3	1.4	1.4	Increases with state population
Agriculture	**7.1**	**6.9**	**6.4**	**6.5**	**6.5**	
Manure Mgmt & Enteric Fermentation (CH_4)	3.7	3.4	3.4	3.4	3.5	Dairy emissions grow with population
Agricultural Soils (N_2O)	3.4	3.5	3.0	3.0	3.0	No changes projected after 2010
Total Gross Emissions	**305.5**	**316.9**	**334.8**	**367.4**	**383.4**	
Forestry and Land Use	**-17.2**	**-17.3**	**-17.3**	**-17.3**	**-17.3**	No changes projected
Total Net Emissions	**288.3**	**299.6**	**317.5**	**350.1**	**366.2**	

2. Approach

The principal goal of the inventory and reference case projections is to provide a general understanding of Pennsylvania's historical, current, and projected (expected) greenhouse gas emissions.

General Principles and Guidelines

A key part of this effort involves the establishment and use of a set of generally accepted accounting principles for evaluation of historical and projected GHG emissions, as follows:

- **Transparency:** We report data sources, methods, and key assumptions to provide open review and opportunities for additional revisions.

- **Consistency:** To the extent possible, the inventory and projections are designed to be externally consistent with current or likely future systems for state and national GHG emission reporting. We have used USEPA tools for state inventories and projections as a starting point. These initial estimates were then augmented to include local data and conditions, as informed by Pennsylvania-specific sources and experts.

- **Comprehensive Coverage of Gases, Sectors, State Activities, and Time Periods.** This analysis aims to comprehensively cover GHG emissions associated with activities in Pennsylvania. It covers all six greenhouse gases covered by US and other national inventories: carbon dioxide, (CO_2), methane (CH4), nitrous oxide (N2O), sulfur hexafluoride (SF6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

- **Priority of Significant Emissions Sources:** In general, activities with relatively small emissions levels are not reported in the same level of detail as other activities.

- **Priority of Existing State and Local Data Sources:** In gathering data and in cases where data sources may conflict, we placed highest priority on local and state data and analyses, followed by regional sources, with national data used as defaults where necessary.

- **Presentation of Production-Based and Consumption-Based Emissions Estimates:** For all sources, we present emissions produced by in-state activities, which are referred to here as production-based emissions. For electricity, which is produced in excess of Pennsylvania requirements, we also estimate consumption-based emissions, i.e. the emissions reasonably attributable to the consumption of electricity by consumers in Pennsylvania.

  For electricity, consumption-based accounting, in principle, should reflect an understanding of the electricity sources used by Pennsylvania utilities to meet consumer

demands. For this draft inventory, we took a simpler approach, estimating consumption-based emissions by multiplying total production-based emissions (from fuel combustion at all in-state power plants) times the fraction of total electricity produced (MWh) that would be needed to meet in-state electricity demands, after accounting for in-state transmission and distribution losses.

General Methodology

The overall goal of this effort was to provide simple and straightforward estimates, with an emphasis on robustness and transparency. As a result, we relied on straightforward spreadsheet analysis rather than detailed modeling.

In most cases, we followed the same approach to emissions accounting used by the US EPA in its national GHG emissions inventory[13] and its guidelines for states.[14] These inventory guidelines were developed based on the guidelines from the Intergovernmental Panel on Climate Change, the international organization responsible for developing coordinated methods for national greenhouse gas inventories.[15] The inventory methods provide flexibility to account for local conditions. In particular, the electric sector emissions expand on the US EPA inventory approach, by looking at consumption-based in addition to production-based emissions, as described above.

[13] US EPA, Feb 2005. *Draft Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2003.* *http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2005.html*.
[14] http://yosemite.epa.gov/oar/globalwarming.nsf/content/EmissionsStateInventoryGuidance.html
[15] http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm

Table 6. Key Sources for Data, Inventory Methods and Projection Growth Rates

Source	Information provided	Use of Information in this Analysis
US EPA State Greenhouse Gas Inventory Tool (SGIT)	EPA SGIT is a collection of linked spreadsheets designed to help users develop state GHG inventories. EPA SGIT contains default data for each state for most of the information required for an inventory.	Where not indicated otherwise, SGIT is used to calculate emissions from industrial processes, agriculture and forestry, and waste. We use SGIT emission factors (CO_2, CH_4, and N_2O per BTU consumed) to calculate energy use emissions.[16]
US DOE Energy Information Administration (EIA) State Energy Data System (SEDS)	EIA SEDS source provides energy use data in each state, annually to 2004.	EIA SEDS is the source for all energy use data except on-road gasoline and diesel consumption. Emission factors from EPA SGIT are used to calculate energy-related emissions.
US DOE Energy Information Administration Annual Energy Outlook 2006 and 2007 (AEO2006/7)	EIA's annual energy outlook projects energy supply and demand for the US from 2005 to 2030. Energy consumption is estimated on a regional basis. Pennsylvania is included in the Mid- Atlantic Census region (PA, DE, DC, MD, VA, WV). The AEO is updated annually to reflect new data and assumptions.	EIA AEO2006 is used to project energy demand changes in per capita (residential), per employee (commercial/industrial) consumption of natural gas, wood, and non-transportation fossil fuels. (See Table 4). The AEO2007 is used to project energy demand for the electric sector.*
Pennsylvania Department of Transportation (PennDOT)	Staff from PennDOT provided projections of VMT growth for personal and freight transportation services.	VMT growth rates provided by PennDOT were used directly to project growth in the transportation sector.

* The AEO2007 projections for energy consumption in the residential, commercial and industrial sectors did not differ significantly from the projections in the AEO2006. The electric sector projections, however, were quite different in the two versions. Given time and resources available, this document updates the 2006 version of the Inventory and Forecast and incorporates new data for the electric sector, but not the residential, commercial and industrial sectors.

[16] We did not use the EPA SGIT tool directly to calculate emissions from energy use because the data in the tool has not been updated to the most recent energy consumption data. By calculating GHG emissions directly from energy use multiplied by the emissions factors from SGIT, we are able to use most current energy data.

Appendix A. Electricity Use and Supply

Pennsylvania is an important supplier of electricity to the Mid-Atlantic US. The State's power plants have historically produced more electricity than is consumed in the State and have exported 20-25 percent of the electricity generated.[17] The Pennsylvania electricity sector is dominated by coal, which accounts for nearly 55 percent of all electricity generated in recent years. However, the share of coal-fired generation has decreased from historic levels of over 60 percent in the early 1990s. Coal-fired power plants produce as much as twice the CO_2 emissions per kilowatt-hour of electricity as natural gas-fired power plants. Nuclear generation is also significant in Pennsylvania, accounting for about 37 percent of generation recently. Nuclear generation does not produce any direct GHG emissions from electricity production. Generation from natural gas and from renewable sources has increased substantially from 1990 to 2004, with natural gas generation increasing by 7 times and renewable generation by almost 5 times. As a result of these factors, total emissions from Pennsylvania power plants have increased by about 14 percent from 1990 to 2004, but emissions per kWh produced have declined by about 5 percent in that period. GHG emissions per kWh in Pennsylvania are about the same as the US average.

As noted earlier, one of the key questions for the State to consider is how to treat GHG emissions that are produced to serve needs outside the State. In other words, should the State consider the GHG emissions associated with the State's electricity consumption or its electricity production, or some combination of the two? Since this question still needs to be resolved, this section examines electricity-related emissions from both a production and consumption basis.

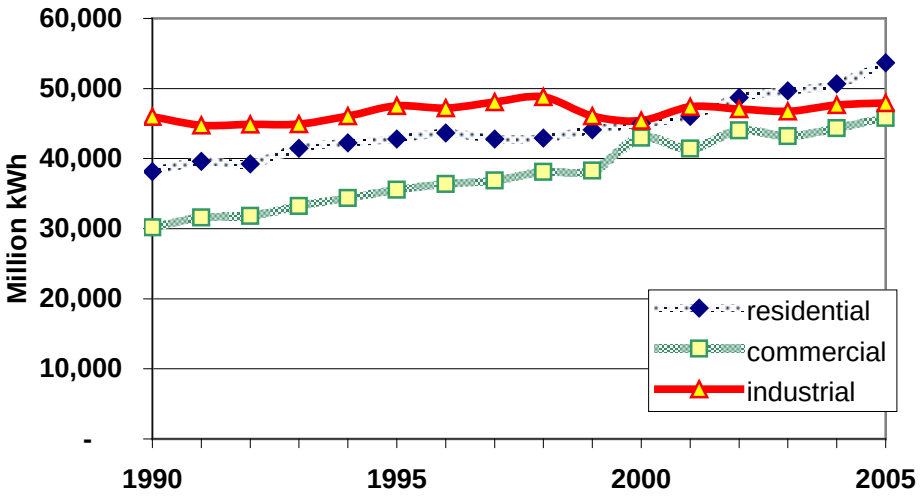
This appendix describes Pennsylvania's electric sector in terms of consumption and production, including the assumptions used to develop the reference case projections. It then describes Pennsylvania's electricity trade and potential approaches for reporting GHG emissions for the purpose of determining the State's inventory and reference case. Finally, key assumptions and results are summarized.

Electricity Consumption

At about 11,929 kWh/capita (2005 data), Pennsylvania has similar average electricity consumption per capita to neighboring states and slightly lower the US average. By way of comparison, in 2005 the per capita consumption for the US is 12,350 kWh per year, with New Jersey averaging at 9,400 kWh, Maryland at 12,200 kWh, and Virginia at 14,400 kWh.[18] As shown in Figure 5, the residential sector has the greatest electricity consumption after 2001, with continuous growth from 1990. Average annual growth for the residential sector was about 2 percent per year, despite population growth of less than 0.5 percent per year. Consumption in the industrial sector has been fairly consistent from 1990 through 2004.[19] The commercial sector consumption increased from 1990 to 2001 but has since remained relatively constant.

[17] EGRID2002 software (US EPA http://www.epa.gov/cleanenergy/egrid/whatis.htm)
[18] http://www.eia.doe.gov/cneaf/electricity/st_profiles/e_profiles_sum.html
[19] Electricity consumption figures here only include purchased electricity, and do not include electricity generated and consumed internally by specific industries.

Figure 5. Electricity Consumption by Sector, 1990-2005



The State's ten investor-owned utilities serve approximately 77 percent of the customers, and 81 percent of load, as illustrated in Table 7. The State's 36 public utilities serve 12 percent of customers and a slightly smaller fraction of the load. The remaining 12 percent of customers are served by the electric cooperatives and other energy service providers.

Table 7. Retail Electricity Sales by Pennsylvania Utilities (2002)

	Investor-Owned	Public	Cooperative	Energy Service Providers	Total
Number of Entities	10	36	13	20	79
Number of Retail Customers	4,363,782	660,382	205,487	462,446	5,692,097
Percentage of Retail Customers	77%	12%	4%	8%	100%
Retail Sales (thousand megawatthours)	113,585	13,797	2,273	11,132	140,787
Percentage of Retail Sales	81%	10%	2%	8%	100%
Revenue from Retail Sales (million 2002 dollars)	9,390	1,053	237	597	11,276

Source: EIA state electricity profiles

Overall, total electricity consumption grew at an average annual rate of 1.7 percent from 1990 to 2005, less than the rate of gross state product growth (2.2 percent per year).[20] For initial projections, future electricity consumption is projected to grow at a rate of 1.25 percent per year through 2025, compared with expected population growth of 0.2 percent per year and employment growth rate of 0.6 percent.[21]

[20] Gross State Product growth from Bureau of Economic Analysis, http://www.bea.doc.gov/bea/regional/gsp/default.cfm

[21] This electricity growth rate is from a 2005 analysis of the Advanced Energy Portfolio Standard (Black and Veatch 2004) and has been extended, at the same rate, through 2025.

Electricity Generation – Pennsylvania's Power Plants

As mentioned above and displayed in Figure 6 below, Pennsylvania's 36 coal-fired power plants figure prominently in electricity generation and GHG emissions in the State. Table 8, which reports the emissions from the 9 power plants with the greatest GHG emissions from 1996 to 2004, shows that three plants (Bruce Mansfield, Conemaugh, and Keystone) account for about one third of the total emissions.[22] All 9 plants in Table 8 use coal as the primary fuel.

Figure 6. Electricity Generation and CO_2 Emissions from Pennsylvania Power Plants, 2004

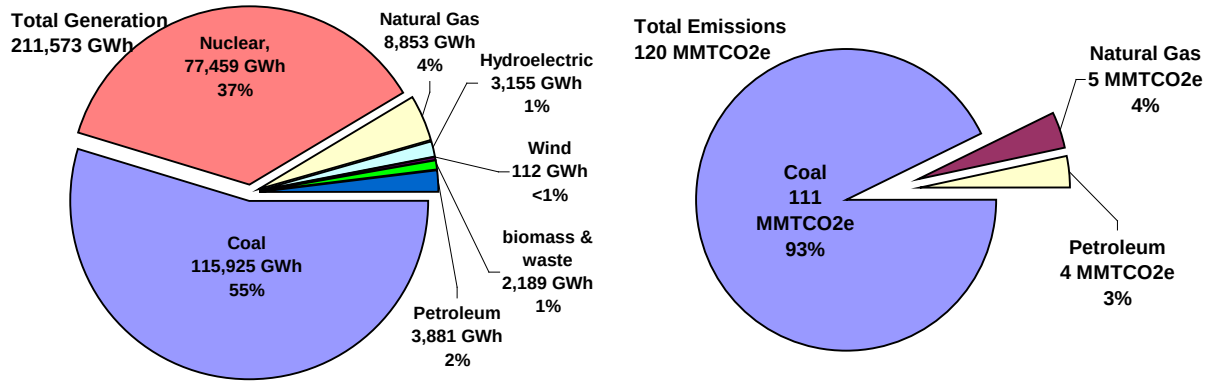


Table 8. CO_2 Emissions from Individual Pennsylvania Power Plants, 1996-2004

(Million Metric Tons CO2e)	1996	1997	1998	1999	2000	2001	2002	2003	2004
Bruce Mansfield	*14*	*13*	*14*	*12*	*15*	*12*	*14*	*14*	*16*
Brunner Island	*7*	*8*	*7*	*7*	*7*	*5*	*8*	*7*	*8*
Cheswick	*3*	*3*	*2*	*3*	*3*	*4*	*3*	*3*	*3*
Conemaugh	*11*	*12*	*13*	*12*	*11*	*11*	*11*	*12*	*11*
Eddystone Generating Sta	*4*	*4*	*4*	*3*	*4*	*5*	*3*	*4*	*4*
Hatfields Ferry Power Stat	*9*	*7*	*7*	*8*	*9*	*10*	*9*	*8*	*8*
Keystone	*12*	*12*	*12*	*11*	*10*	*11*	*10*	*11*	*11*
Montour	*7*	*8*	*9*	*8*	*8*	*8*	*8*	*8*	*8*
Shawville	*3*	*4*	*4*	*3*	*3*	*3*	*3*	*3*	*3*
Other units	*40*	*41*	*43*	*43*	*47*	*39*	*44*	*45*	*47*
Total	**110**	**112**	**114**	**110**	**118**	**108**	**113**	**116**	**120**

Source: USEPA Clean Air Markets database for named plants (http://cfpub.epa.gov/index.cfm). Other units calculated from fuel use data provided by US DOE EIA.

Future Generation and Emissions

Estimating future generation and GHG emissions from Pennsylvania power plants requires estimates of new power plant additions and production levels from new and existing power

[22] Emissions from the 9 largest power plants (based on total emissions) were obtained from the EPA Clean Air Markets database, http://cfpub.epa.gov/gdm/index.cfm. Since data from the EPA Clean Air Markets Division do not include plants under 25MW, supplemental data were required for a complete emissions estimate. Emissions for all remaining power plants were calculated by using the energy consumption for the total power plants multiplied by EPA emissions factors by fuel, accounting for combustion efficiency and changes in average carbon content of coal over time, and assigning the remaining CO2 emissions to "Other units".

plants. There are, of course, large uncertainties here, especially related to the timing and nature of new power plant construction which are influenced by many factors:

- The most recent fossil-fuel plants have been natural gas-fired; however, there are concerns that natural gas prices may increase over the next decade, which could cause a trend towards more coal-dominated construction.

- Coal plant construction could be limited by air quality requirements – both current requirements and uncertainties about future requirements will impact costs.

- Some proposed plants have applied for permits, including natural gas and biomass facilities. Permitted plants are not always built. Actual implementation depends on market conditions, adequate financing, and other factors. Permits are only valid for a specified timeframe; if construction does not begin during this period, the developer must resubmit the application, and it may or may not be granted again depending on emerging conditions.

- Pennsylvania is part of an integrated electricity supply grid and power can either be imported or exported. Economics, transmission lines, and state actions (Pennsylvania's and others) will influence the amount of electricity exports and subsequent total electricity production in the state.

Given these uncertainties and a diversity of perspectives by actors within the electricity sector, it is particularly challenging to develop a "reference case" projection for the most likely development of Pennsylvania's electricity sector. Therefore, to develop an initial projection, simple assumptions were made, relying to the extent possible on widely-reviewed modeling assessments. The reference case projections assume:

- Total generation in Pennsylvania grows at the regional growth rates forecast by the National Energy Modeling System (NEMS) developed by the US Energy Information Administration for projecting US energy supply and demand to 2030 in the US DOE's Annual Energy Outlook 2007 (AEO2007), using the Mid-Atlantic Area Council region. The growth rate average 1.2 percent per year from 2006-2025.

- Generation from existing plants remains at 2004 levels except for existing hydro-electric plants where future generation is assumed to be same as the average generation from the last ten years.

- Generation from new power plants provides the remainder of this growth. which is projected to be a mix of 71 percent coal, 18 percent natural gas, 5 percent wind, 4 percent biomass and other renewables, and 2 percent nuclear through 2015. The renewable share is projected to increase slightly over time, switching to 65 percent coal, 18 percent natural gas, 7 percent wind, 8 percent biomass and other renewables, and 2 percent nuclear from 2016 through 2025. These assumptions are based on projections from the AEO2007.

.

Electricity Trade and Allocation of GHG Emissions

Pennsylvania is part of the Eastern Interconnection region - a 30 state region extending from the Rocky Mountains in the west to the Eastern Seaboard and from Canada through the Gulf of Mexico. The inter-connected region allows electricity generators and consumers to buy and sell electricity across regions, taking advantage of the range of resources and markets. Electricity generated by any single plant enters the interconnected grid and may contribute to meeting demand throughout much of the region, depending on sufficient transmission capacity. Thus it is challenging to define which emissions should be allocated to Pennsylvania, especially when estimating these emissions both historically and into the future. Some utilities track and report electricity sales to meet consumer demand by fuel source and plant type; however, tracing sales to individual power plants may not be possible.

In 2004, electricity consumption in Pennsylvania was 143 TWh while electricity generation was 211 TWh. After accounting for losses (about 10 percent of generation), about 48 TWh was exported from the State. Thus a significant portion of the electricity generated and economic benefits may serve consumers and investors in other states.

Since almost all states are part of regional trading grids, many states that have developed GHG inventories have grappled with this problem and several approaches have been developed to allocate GHG emissions from the electric sector to individual states for inventories.
In many ways the simplest approach is *production-based* – emissions from power plants within the State are included in the state's inventory. The data for this estimate are publicly available and unambiguous. This approach has been adopted by the Regional Greenhouse Gas Initiative (RGGI) for its GHG cap-and-trade program. However, this approach is problematic for states that import or export significant amounts of electricity. Because of the State's large exports, under a production-based approach Pennsylvania's residents would be taking responsibility for emissions that they have limited ability to mitigate and that provide less of a benefit to the State.

An alternative is to estimate *consumption-based* (also called *load-based)* GHG emissions, corresponding to the emissions associated with electricity consumed in the State. The load-based approach is currently being considered by states that import significant amounts of electricity, such as California, Oregon, and Washington.[23] By accounting for emissions from imported electricity, states can account for increases or decreases in fossil-fuel consumed in power plants outside of the State due to demand growth, efficiency programs, and other actions in the State. The difficulty with this approach is properly accounting for the emissions from imports and exports. Since the electricity flowing in or out of Pennsylvania is a mix of all plants generating on the inter-connected grid, it is impossible to physically track the electrons.

The approach taken in this initial inventory is a simplification of the consumption-based approach. This approach, which one could term "*Net-Consumption-based*", estimates

[23] See for example, the reports of the Puget Sound Climate Protection Advisory Committee (http://www.pscleanair.org/specprog/globclim/), the Oregon Governor's Advisory Group On Global Warming http://egov.oregon.gov/ENERGY/GBLWRM/Strategy.shtml, and the California Climate Change Advisory Committee, Policy Options for Reducing Greenhouse Gas Emissions From Power Imports - Draft Consultant Report, http://www.energy.ca.gov/2005publications/CEC-600-2005-010/CEC-600-2005-010-D.PDF

consumption-based emissions as in-state (production-based) emissions times the ratio of total in-state electricity consumption to in-state generation (net of losses). For example, in 2004, Pennsylvania residents and businesses consumed 75 percent (143 TWh) of total in-state generation (191 TWh) net of transmission and distribution losses (10 percent).

This method does not account for differences in the type of electricity that is imported or exported from the State, and as such, it provides a simple method for reflecting the emissions impacts of electricity consumption in the State. More sophisticated methods – e.g. based on individual utility information on resources used to meet loads – can be considered for further improvements to this approach.

Summary of Assumptions and Reference Case Projections

As noted, projecting generation sources, sales, and emissions for the electric sector out to 2025 requires a number of key assumptions, including economic and demographic activity, changes in electricity-using technologies, regional markets for electricity (and competitiveness of various technologies and locations), access to transmission and distribution, the retirement of existing generation plants, the response to changing fuel prices, and the fuel/technology mix of new generation plants. The key assumptions described above are summarized in Table 9.

Table 9. Key Assumptions and Methods for Electricity Projections

Electricity Sales	1.25 percent annual growth rate, based on adjustments to projections from PJM Interconnection (Black and Veatch 2004).
Electricity Generation	1.25 percent annual growth is assumed to match sales growth from 2005-2010. 1.2 percent average annual growth is assumed from 2011 to2025, based on regional growth in EIA AEO2007 (MAAC region)
Transmission and Distribution Losses	10 percent losses are assumed, based on average statewide losses, 1994-2000, (data from EPA Emission & Generation Resource Integrated Database[24])
New Generation Sources (2006-2015)	From 2006-2015, the assumed mix is 71 percent coal, 18 percent natural gas, 5 percent wind, 4 percent biomass and other renewables, and 2 percent nuclear (MWh basis), based on the regional results from EIA AEO2007.
New Generation Sources (2016-2025)	For 2016 to 2025, the assumed mix is 65 percent coal, 18 percent natural gas, 7 percent wind, 8 percent biomass and other renewables, and 2 percent nuclear (MWh basis), based on regional results from EIA AEO2007.
Heat Rates	The assumed heat rates for new gas and coal generation are 7000 Btu/kWh and 9000 Btu/kWh, respectively, based on estimates used in similar analyses.[25]
Operation of Existing Facilities	Current sources of electricity generation produce the same amount of electricity as they did in 2004.

Figure 7 shows historical sources of electricity generation in the State by fuel source, along with projections to the year 2025 based on the assumptions described above. Natural gas generation has grown considerably during the past decade, while coal and hydro generation have stayed relatively constant. The fourth major wind project in Pennsylvania, Exelon-Community Energy Wind Farm at Waymart, came on-line in 2003 with 64.5 MW of capacity – enough energy to meet the needs of about 20,000 average homes. Wind generation is expected to grow in the next few years as utilities complete plants built to meet demand for renewable energy. Based on the above assumptions for new generation, coal dominates new generation through 2025, reflecting assumptions in the EIA AEO2007 projections.

[24] http://www.epa.gov/cleanenergy/egrid/index.htm
[25] See, for instance, the Oregon Governor's Advisory Group On Global Warming http://egov.oregon.gov/ENERGY/GBLWRM/Strategy.shtml

Figure 7. Electricity Generated by Pennsylvania Power Plants, 1990-2025

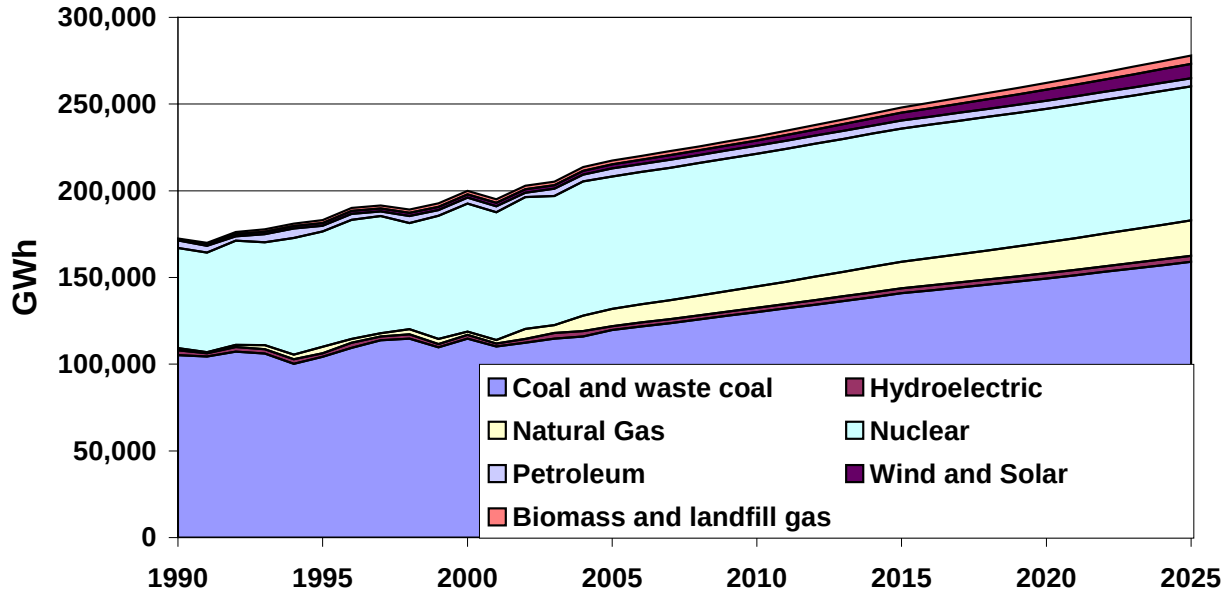


Figure 9 illustrates the GHG emissions associated with the mix of electricity generation shown in Figure 7. From 2005 to 2025, the emissions from Pennsylvania electricity generation are projected to grow at 1.31 percent per year, slightly greater than the 1.25 percent growth in electricity generation. As a result, the emission intensity (emissions per MWh) of Pennsylvania electricity is expected to increase slightly (from 0.57 $MTCO_2$/MWh in 2000 to 0.59 $MTCO_2$/MWh in 2025). Recall that the effects of Pennsylvania's Alternative Energy Portfolio Standard are not included in the reference case projections here. This new legislation is expected to decrease electric sector emissions, relative to those reported in the reference case here.

Figure 8. CO_2 Emissions Associated with Electricity Production (Production-Basis), Includes Exports

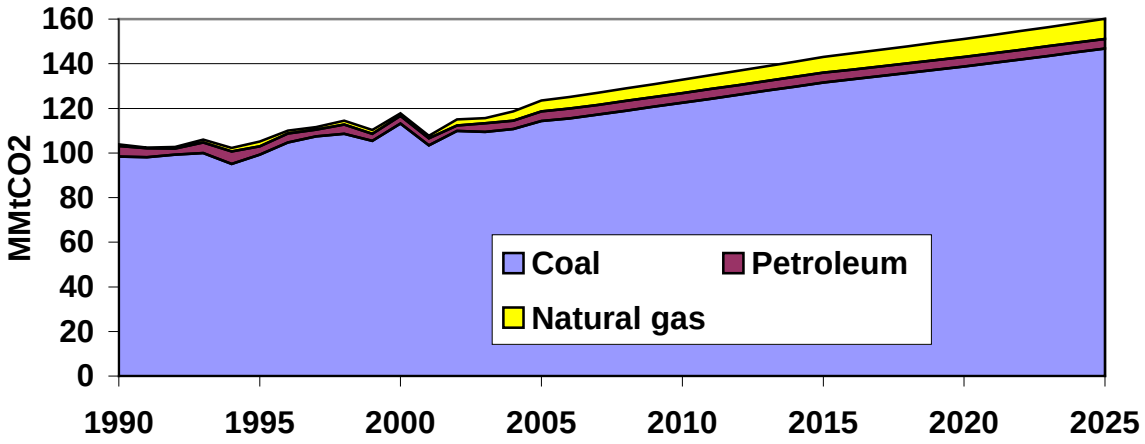


Figure 9. CO_2 Emissions Associated with Electricity Use (Consumption-Basis) and Exports

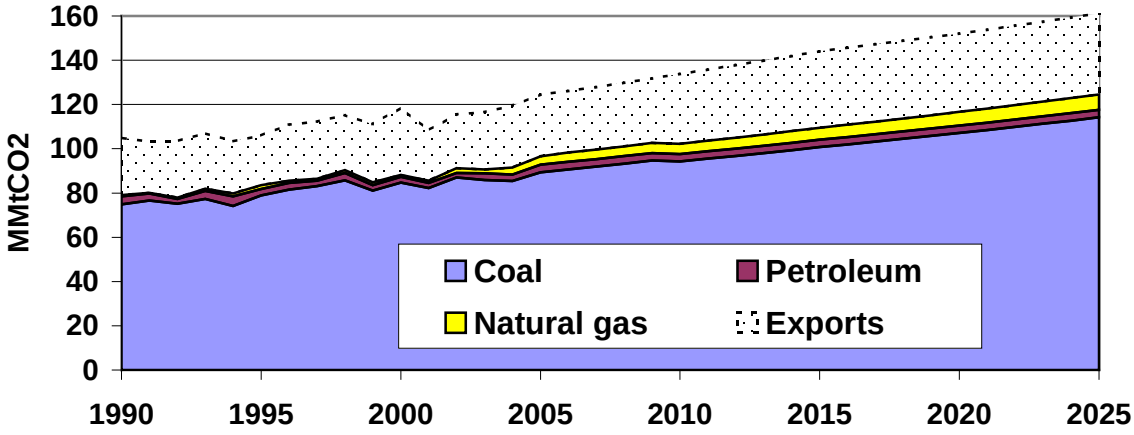


Figure 10 shows the "net-consumption-basis" emissions from 1990 to 2025. Total emissions match those shown in the previous "production-basis" chart; here, however, a significant fraction is attributed to net electricity exports as shown in the top area.

Key Uncertainties

As noted above, these estimates are subject to a number of uncertainties. Perhaps the uncertainty with the most important implications for GHG emissions is the type, size, and number of power plants built in Pennsylvania between now and 2025. As noted above, there are also significant uncertainties associated with projecting electricity consumption in the State, as well as in the estimation of consumption-based electricity emissions (i.e. which electricity sources serve Pennsylvania loads). If a consumption-based emissions approach is adopted by the State, further analysis should be directed towards the resources that utilities use to meet Pennsylvania loads and methods that can be reliably used to track them.

Appendix B. Fossil Fuel Industry Emissions

Despite Pennsylvania being credited with drilling the world's first commercial oil well in 1859, Pennsylvania currently ranks only 21st in oil production among US states, accounting for less than 1 percent of US crude oil production.[26] Pennsylvania's proved crude oil reserves sit at 13 million barrels (bbls) with most production derived from wells that produce less than ten barrels per day.[27] Pennsylvania also produces about 6% of the nation's coal.

The state's natural gas consumption has consistently been over four times higher than its production. Proved natural gas reserves are estimated at about 2.5 trillion cubic feet.[28] Until 1993 there was virtually no coal bed methane (CBM) production in Pennsylvania. From a marked jump in CBM production in 1999, there are currently over 225 CBM wells in the state, producing 1.8 billion cubic feet (Bcf) in 2004.[29] While CBM accounts for a very small portion of natural gas production in the state, state contacts suggest CBM production will grow significantly over the next ten years.[30]

Overall, future oil and gas production in the state is fairly uncertain, dependent largely on prevailing oil and gas prices.

Oil and Gas Industry Emissions

Emissions of carbon dioxide and methane occur at many stages of production, processing, transmission, and distribution. With over 60,000 oil and gas wells in the State, 9 gas processing plants, 5 oil refineries, and over 50 thousand miles of gas pipelines, there are significant uncertainties associated with estimates of the state's GHG emissions from the fossil fuels sector. This is compounded by the fact that there are no regulatory requirements to track CO_2 or methane emissions. As a result, methane emissions can only be estimated based on industry assumptions.

However, the State Greenhouse Gas Inventory Tool (SGIT) developed by the US EPA facilitates the development of an estimate of state-level greenhouse gas emissions from this source.[31] Methane emission estimates are calculated by multiplying emissions-related activity levels (e.g. miles of pipeline, number of compressor stations) by aggregate emission factors. Key information sources for the activity data, as reported in Table 10, are the Energy Information Administration (EIA) and American Gas Association's annual Gas Facts publications.[32]

[26] US DOE Energy Information Administration website.
[27] Pennsylvania Oil & Gas Association website, 2005.
[28] Pennsylvania Oil & Gas Association website, 2005.
[29] DCNR <www.dcnr.state.pa.us/topogeo/cbm>
[30] Personal communications with Toni Markowski of PADCNR and John Miller of Enervest, June 5, 2006.
[31] Methane emissions were calculated using SGIT, with reference to Emission Inventory Improvement Program, Volume VIII: Chapter. 5. "Methods for Estimating Methane Emissions from Natural Gas and Oil Systems", March 2005.
[32] Data extracted from the 1991-2003 American Gas Association publications 'Gas Facts'. Example reference for 2003 publication: "Gas Facts 2003, A Statistical Record of the Gas Industry, 2002 Data", American Gas Association. http://www.aga.org/Content/NavigationMenu/Stats_and_Studies/Gas_Facts/Gas_Facts.htm

Methane emissions were estimated using SGIT, with reference to the Emission Inventory Improvement Program (EIIP) guidance document.[33] Table 10 provides an overview of the required data, data source, and the approach to projecting future emissions.

The oil and gas industry also emits CO_2, CH_4 (methane), and N_2O during combustion of fuels, as any consumer of fossil fuels does. Neither the State nor EIA comprehensively collect data on energy consumption by this industry separately from other industries. However, the PA DEP was able to provide energy consumption from two of the major refineries and the EIA provides energy used for pipeline transportation. This information was used to roughly estimate energy consumed during oil and gas refining and transportation.

Future projections of GHG emissions from oil and gas systems are calculated based on the following key drivers:

- **Consumption:** Pennsylvania's natural gas consumption has consistently been over 4 times production. In 2004, the state consumed 690 Bcf, while producing only 160 Bcf. Residential and commercial sector consumption of natural gas (key drivers for emissions from the natural gas distribution system) is projected to increase at an average rate of 0.2 percent per year from 2004 to 2025.
- **Production:** Pennsylvania oil production peaked in the early 19th century at 31 million bbls annually, while natural gas production has shown several peaks and valleys in recent years. The highest production recently occurred in 2004 with 197 Bcf produced.[34] Both oil and gas production is assumed to increase over the short term, to 2010, then hold flat from 2010 to 2025. Pennsylvania Oil and Gas Bureau contacts suggest that given the general trend of production increases in recent years associated with higher oil and gas prices, it is reasonable to project similar rates of production growth until 2010.[35] Given the maturity of Pennsylvania's oil and gas fields, production is assumed to hold flat after 2010.
- **Projected trends in energy consumption:** The regional growth rates for consumption of refinery gas and natural gas used for pipelines from the EIA AEO2006 formed the basis of the energy consumption trends for Pennsylvania. Note that GHG emissions from the oil production industry are dominated by energy consumption in refineries.

Note that potential emission reduction improvements to production, processing, and pipeline technologies have not been accounted for in this analysis.

[33] The Emission Inventory Improvement Program (EIIP) is supported and partially sponsored by the US Environmental Protection Agency (EPA). EIIP documents are to be considered the equivalent of federal guidance.
[34] Pennsylvania Oil & Gas Association website, 2005.
[35] Assumption based on personal communication with Dave English and Ron Gilius at the Pennsylvania Oil and Gas Bureau. May 17, 2006.

Table 10. Approach to Estimating Historical and Projected Methane Emissions from Natural Gas and Oil Systems.

	Approach to Estimating Historical Emissions		**Approach to Estimating Projections**
Activity	***Required Data for SGIT***	***Data Source***	***Projection Assumptions***
Natural Gas Drilling and Field Production	Number wells	EIA	Emissions follow trend of natural gas production, which continues to grow at 3% annually until 2010, then holds flat until 2025.[36]
	Miles of gathering pipeline	Gas Facts[37]	
Natural Gas Processing	Number gas processing plants	EIA[38]	Emissions follow trend of state gas production, as above.
Natural Gas Transmission	Miles of transmission pipeline	Gas Facts[37]	Emissions assumed to remain at 2002 levels through 2025. Although emissions could increase with increased consumption, the industry has been successful recently in decreasing emissions even as consumption increases.
	Number of gas transmission compressor stations	EIIP[39]	
	Number of gas storage compressor stations	EIIP[40]	
	Number of LNG storage compressor stations	Unavailable, assumed negligible.	
Natural Gas Distribution	Miles of distribution pipeline	Gas Facts[37]	Distribution emissions grow with state gas consumption for residential and commercial sectors. Natural gas consumption for these sectors is projected to will grow at an average rate of 0.2% annually.
	Total number of services	Gas Facts	
	Number of unprotected steel services	Ratio estimated from 2002 data[41]	
	Number of protected steel services	Ratio estimated from 2002 data[41]	
Oil Production	Annual production	EIA[42]	Emissions follow trend of natural gas production, which continues to grow at 3% annually until 2010, then holds flat until 2025.[43]
Oil Refining	Annual amount refined	EIA[44]	Emissions follow trend of state oil production, as above.
Oil Transport	Annual oil transported	Assumed oil refined = oil transported	Emissions follow trend of state oil production, as above.

[36] Assumption based on personal communication with Dave English and Ron Gilius at the Pennsylvania Oil and Gas Bureau. May 17, 2006.
[37] No Gas Facts available for 1991 and 1993, so a linear relationship was assumed to extrapolate from the previous and subsequent year.
[38] EIA reported data for 1990, 1995, 1999, and 2004.
[39] Number of gas transmission compressor stations = miles of transmission pipeline x 0.006 EIIP. Volume VIII: Chapt. 5. March 2005.
[40] Number of gas storage compressor stations = miles of transmission pipeline x 0.0015 EIIP. Volume VIII: Chapt. 5. March 2005.
[41] Gas Facts reported unprotected and protected steel services for 2002, but only total services for other years. Therefore the ratio of unprotected and protected steel services in 2002 was assumed to be the ratio for all other years (0.1098 for protected services and 0.2454 for unprotected services). This yields more congruent results than the EIIP guidance of using multipliers of 0.2841 total services for protected steel services, and 0.0879 for unprotected steel services.
[42] Data extracted from the Petroleum Supply Annual for each year.
[43] Assumption based on personal communication with Dave English and Ron Gilius at the Pennsylvania Oil and Gas Bureau. May 17, 2006.
[44] Refining assumed to be equal to the total input of crude oil into PADD I times the ratio of Pennsylvania's refining capacity to PADD I's total refining capacity. No data for 1995 and 1997, so linear relationship assumed from previous and subsequent years.

Coal Bed Methane (CBM)

Until 1993 there was virtually no CBM production in Pennsylvania. From a marked jump in CBM production in 1999, there are currently over 225 CBM wells in the state, producing 1.8 billion cubic feet (Bcf) in 2004.[45]

The Pennsylvania Department of Conservation and Natural Resources (PA DCNR) reports that interest in CBM in the state continues to grow as a result of establishment and negotiation of acreage ownership, improved technology, better understanding of coal as a natural gas reservoir, higher gas prices, and the need to develop domestic energy sources.[46]

Raw gas that emerges from coal seams contains entrained CO_2, which can be a fairly significant source of GHGs from fossil fuel production. While there is huge variation in entrained CO_2 levels in various CBM wells, average levels in Pennsylvania CBM appear to range from about 0.2 percent to 6.5 percent.[47] For the purposes of this inventory, entrained CO_2 is calculated based on an average estimate of 2 percent.[48] These emissions were less than 0.002 $MMTCO_2e$ in 2004. Note that GHG emissions from coal bed methane systems and infrastructure (e.g. wells, pipelines, etc) are included in the natural gas system emissions above.[49]

CBM growth speculation by industry and government contacts see potential for annual growth rates in the next ten years to be similar to those of the recent past, with average production growth of 14 percent annually since 2001.[50] Based on this information, the forecast production for CBM in Pennsylvania includes 14% growth per year from 2005 to 2016, then constant production at 2016 levels through 2025. Since the estimated entrained emissions were low in 2004, even these high growth rates yield relatively low total emissions from entrained CO_2, 0.004 $MMTCO_2e$ in 2010 and 0.009 $MMTCO_2e$ in 2025.

Coal Production Emissions

Methane occurs naturally in coal seams and is typically vented during mining operations for safety reasons. This methane is typically referred to as "coal mine methane" in contrast to coal bed methane, which is associated with coal seams that are not expected to be mined.

Historical coal mine methane emissions by state are provided in the US EPA National GHG Emissions Inventory. The US EPA estimates annual GHG emissions based on quarterly measurements of methane from all underground coal mines, provided by the US Mines Safety and Health Administration (MSHA). MSHA also provides information on coal mines using degasification equipment and those selling methane that is recovered through degasification. The US EPA estimated the levels of methane recovery and sales on a mine-by-mine basis. Coal mine

[45] DCNR <www.dcnr.state.pa.us/topogeo/cbm>
[46] DCNR <www.dcnr.state.pa.us/topogeo/cbm>
[47] Based on CBM well testing provided by Toni Markowski of DCNR and well test data from John Miller of Enervest Management Partners. Enervest is a large CBM producer in Indiana county (the highest CBM producing county) where entrained CO2 levels range from 0.9-1.2%.
[48] Rough estimate supported by John Miller and Toni Markowski.
[49] Personal Communication with Paul Hesse, National Energy Information Center at the Energy Information Administration, July 24, 2006.
[50] Projection confirmed via phone conversation with Toni Markowski of DCNR and John Miller of Enervest.

methane emissions are considerably higher, in general, per unit of coal produced, from underground mining than from surface mining. The US EPA estimates methane emissions from surface mines based on the quantity of coal produced and the regional specific emission factors.

As of 2004, 220 coal mines were in operation in Pennsylvania (58 underground and 202 surface mines). From 1990 through 2003, methane emissions from coal mines have shown annual variation of up to 20% change from the average annual emissions of 10 $MMTCO_2e$. There was no trend of increase or decrease in that time period. Future coal mine methane emissions will depend on the extent to which new coal mining operations change in response to demands from the power market and any change in operations from surface or underground mining (which could increase emissions significantly). For this reference case, emissions from coal mining are assumed to stay constant at 2004 levels of 8.1 $MMTCO_2e$.

Energy consumption in coal mines was not available for this analysis. The energy consumed is included as part of the industrial energy consumption reported in Appendix D, *Residential, Commercial, and Industrial (non-fossil fuel production) Energy Consumption.* We were unable to separate energy consumed from coal mines from the industry total.

Results

Table 11 and Figure 11 display the estimated CO_2 and CH_4 emissions from the fossil fuel industry in Pennsylvania. As shown, total greenhouse gas emissions from the fossil fuel industry were estimated at 19 $MMTCO_2e$ in 2000, about 6 percent of total State emissions. Total emissions from the fossil fuel industry are projected to hold relatively flat through to 2025, with slight production growth in oil, gas, and coal bed methane compensated by declines in GHG emissions from fuel use in the industry.

Figure 10. GHG Emissions and Projections from the Fossil Fuel Industry

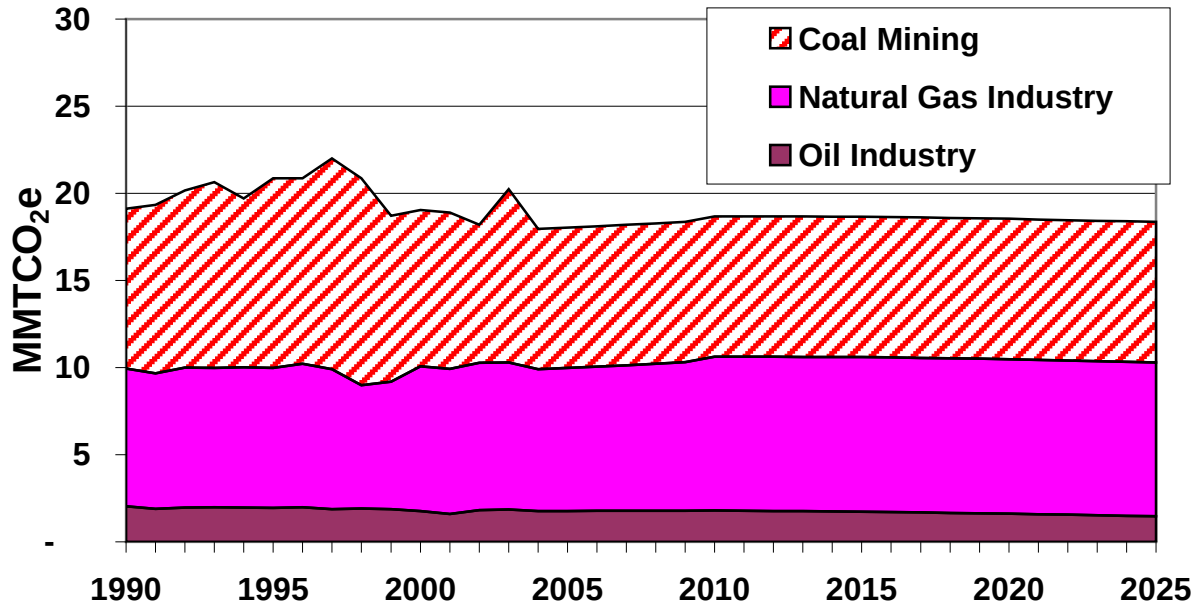


Table 11. GHG Emissions and Projections from the Fossil Fuel Industry

(Million Metric Tons CO_2e)	1990	1995	2000	2005	2010	2015	2020	2025
Fossil Fuel Industry	**19.1**	**20.9**	**19.0**	**18.0**	**18.7**	**18.7**	**18.5**	**18.4**
Natural Gas Industry	7.9	8.0	8.3	8.2	8.8	8.9	8.9	8.8
Production	2.1	2.0	2.4	2.9	3.3	3.3	3.3	3.3
Fuel Use (CO_2)	*0.32*	*0.16*	*0.28*	*0.23*	*0.23*	*0.23*	*0.23*	*0.24*
Methane Emissions (CH_4)	*1.82*	*1.86*	*2.14*	*2.66*	*3.08*	*3.08*	*3.08*	*3.08*
Processing	0.1	0.1	0.1	0.3	0.3	0.3	0.3	0.3
Fuel Use (CO_2)	*0.01*	*0.01*	*0.01*	*0.02*	*0.02*	*0.02*	*0.02*	*0.02*
Methane Emissions (CH_4)	*0.05*	*0.05*	*0.13*	*0.24*	*0.28*	*0.28*	*0.28*	*0.28*
Entrained Gas (CO_2)	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.01*	*0.01*	*0.01*
Transmission	4.0	4.2	4.0	3.2	3.5	3.5	3.5	3.4
Fuel Use (CO_2)	*1.9*	*2.1*	*2.1*	*1.6*	*1.8*	*1.8*	*1.8*	*1.8*
Methane Emissions (CH_4)	*2.2*	*2.1*	*1.9*	*1.6*	*1.6*	*1.6*	*1.6*	*1.6*
Distribution	1.7	1.7	1.7	1.8	1.7	1.8	1.8	1.8
Fuel Use (CO_2)								
Methane Emissions (CH_4)	*1.7*	*1.7*	*1.7*	*1.8*	*1.7*	*1.8*	*1.8*	*1.8*
Oil Industry	2.0	1.9	1.8	1.8	1.8	1.7	1.6	1.5
Production	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fuel Use (CO_2)	Not estimated (in RCI section)							
Methane Emissions (CH_4)	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Refineries	2.0	1.9	1.8	1.8	1.8	1.7	1.6	1.4
Fuel Use (CO_2)	2.0	1.9	1.7	1.7	1.7	1.7	1.6	1.4
Methane Emissions (CH_4)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal Mining (Methane)	9.2	10.9	9.0	8.1	8.1	8.1	8.1	8.1

Description of Sources of Methane Emissions in the Oil and Gas Industry
Excerpted from the US National GHG Inventory (USEPA, 2005)

Petroleum Systems

- *Production Field Operations*. Production field operations account for over 95 percent of total CH_4 emissions from petroleum systems. Vented CH_4 from field operations account for approximately 83 percent of the emissions from the production sector, fugitive emissions account for six percent, combustion emissions ten percent, and process upset emissions barely one percent. The most dominant sources of vented emissions are field storage tanks, natural gas-powered pneumatic devices (low bleed, high bleed, and chemical injection pumps). These four sources alone emit 79 percent of the production field operations emissions. Emissions from storage tanks occur when the CH_4 entrained in crude oil under pressure volatilizes once the crude oil is put into storage tanks at atmospheric pressure.
- *Crude Oil Transportation.* Crude oil transportation activities account for less than one percent of total CH_4 emissions from the oil industry.
- *Crude Oil Refining*. Crude oil refining processes and systems account for only three percent of total CH_4 emissions from the oil industry because most of the CH_4 in crude oil is removed or escapes before the crude oil is delivered to the refineries.

Natural Gas Systems

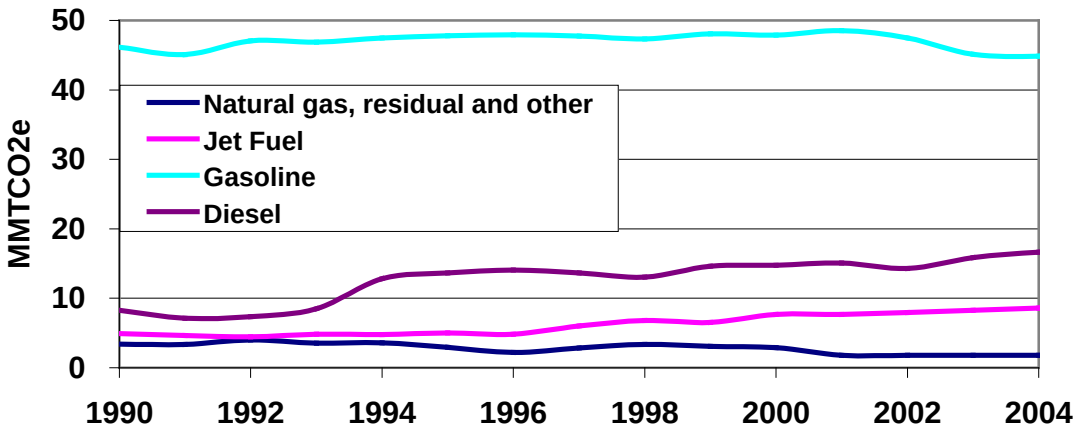
- *Field Production*. In this initial stage, wells are used to withdraw raw gas from underground formations. Emissions arise from the wells themselves, gathering pipelines, and well-site gas treatment facilities such as dehydrators and separators. Fugitive emissions and emissions from pneumatic devices account for the majority of emissions. Emissions from field production accounted for approximately 34 percent of CH_4 emissions from natural gas systems in 2003.
- *Processing*. In this stage, natural gas liquids and various other constituents from the raw gas are removed, resulting in "pipeline quality" gas, which is injected into the transmission system. Fugitive emissions from compressors, including compressor seals, are the primary emission source from this stage. Processing plants account for about 12 percent of CH_4 emissions from natural gas systems.
- *Transmission and Storage*. Natural gas transmission involves high pressure, large diameter pipelines that transport gas long distances from field production and processing areas to distribution systems or large volume customers such as power plants or chemical plants. Compressor station facilities, which contain large reciprocating and turbine compressors, are used to move the gas throughout the United States transmission system. Fugitive emissions from these compressor stations and from metering and regulating stations account for the majority of the emissions from this stage. Pneumatic devices and engine exhaust are also sources of emissions from transmission facilities. Natural gas is also injected and stored in underground formations, or liquefied and stored in above ground tanks, during periods of low demand (e.g., summer), and withdrawn, processed, and distributed during periods of high demand (e.g., winter). Compressors and dehydrators are the primary contributors to emissions from these storage facilities. Methane emissions from transmission and storage sector account for approximately 32 percent of emissions from natural gas systems.
- *Distribution*. Distribution pipelines take the high-pressure gas from the transmission system at "city gate" stations, reduce the pressure and distribute the gas through primarily underground mains and service lines to individual end users. Distribution system emissions, which account for approximately 22 percent of emissions from natural gas systems, result mainly from fugitive emissions from gate stations and non-plastic piping (cast iron, steel). An increased use of plastic piping, which has lower emissions than other pipe materials, has reduced the growth in emissions from this stage.

Appendix C. Transportation Energy Use

The transportation sector is a significant and growing source of GHG emissions in Pennsylvania. As shown in Figure 13, while gasoline consumption, which accounts for the majority of transportation GHG emissions, decreased by 3 percent from 1990 to 2004, diesel use doubled. Energy consumption and emissions from air travel increased by almost 75 percent during the 1990s, while natural gas, heavy fuel oil, and propane (together accounting for less than 5 percent of emissions) decreased during this same time period. Data for gasoline and diesel consumption were obtained from EIA's Prime Supplier tables, the same source used by Pennsylvania Department of Environmental Protection for its analyses. Data for other fuels came from EIA SEDS.

Since 1995/96, the 5-county Philadelphia region has had oxygenate requirements for their winter gasoline that may be met by mixing ethanol with gasoline. Ethanol consumption is deducted from fuel sales reported by EIA Prime Supplier data in order to calculate GHG emissions from gasoline use.[51] (Since ethanol is a biomass-derived fuel, its combustion CO_2 emissions are not typically counted in inventory assessments.[52])

Figure 11. GHG Emissions by Fuel, 1990-2004



Source: EIA Prime supplier data for gasoline and diesel and EIA SEDS for all other fuels.

GHG emissions from transportation are expected to grow strongly over the next 20 years due to increased demand on transportation services. Pennsylvania studies suggest vehicle miles traveled (VMT) will continue to grow faster than population.[53] As a simplifying assumption, it is

[51] Based on information regarding the sales of reformulated gasoline, and oxygenate requirements (7.7% by volume), ethanol consumption is estimated at 25 million gallons in 1995 and 100 million gallons in 2004. Some of this oxygenate could have been supplied by MTBE during this period.
[52] Nonetheless, ethanol, like gasoline, can require significant upstream GHG emissions in production and refining.
[53] Personal Communication, B Trowbridge, PA DEP. The information provided showed average annual growth of VMT at 1.5% per year for personal use (gasoline) and 2.3% per year for freight use (diesel). Population growth is projected to be 0.2% per year.

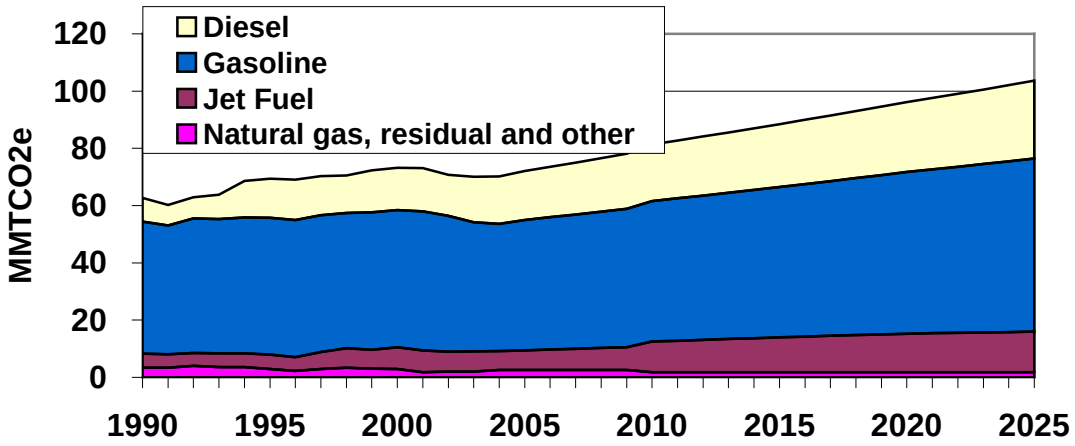
projected that energy consumption per VMT (i.e. vehicle fuel economy) will remain constant from 2004 to 2025. Other assumptions are listed in Table 12.

These assumptions combine to produce more than a 48 percent increase of transportation sector GHG emissions from 2004 to 2025. Of the various transportation fuels, jet fuel shows the greatest percentage increase in emissions from 2004 to 2025 (with emissions more than doubling over 21 years), followed by diesel consumption (64 percent increase in emissions). GHG emissions from gasoline consumption grow at 36 percent while total consumption of other fuels for transportation purposes (natural gas, residual, and propane) is expected to remain constant.

Table 12. Key Assumptions and Methods for Transportation Projections

Passenger VMT Growth	The average annual growth rate for VMT is assumed to be 1.5 percent from 2004 to 2025, based on information from PA DEP.
Gasoline Consumption	Gasoline use is assumed to grow with passenger VMT; no change in gasoline use per VMT is assumed.
Ethanol Consumption	Average annual ethanol consumption is assumed to remain at 0.3 percent of total gasoline consumption (representing Philadelphia region winter fuel requirements).
Freight VMT Growth	The average annual growth rate for VMT is assumed to be 3.0 percent from 2004 to 2010 then 2.2% from 2010 to 2025, based on information from PA DEP.
Diesel Consumption	Diesel use is assumed to grow with freight VMT; no change in diesel use per VMT is assumed.
Aviation Fuel, Jet Fuel, Natural Gas, and Propane	The average annual growth rates for these fuels are based on EIA AEO2006 growth rates for region (2.1 percent for aviation gasoline and jet fuel, -0.3 percent for natural gas, and 3.2 percent for propane). Residual consumption is projected to change by -0.2 percent per year.

Figure 12. Transportation GHG Emissions, 1990-2025



Key Uncertainties

For the historical inventory, uncertainties with respect to transportation fuel use and emissions are relatively low. Fuel use estimates are based on EIA data that PA DEP analysts have verified and used, and US EPA fuel-specific CO_2 emission factors are relatively accurate. The principal uncertainties, not surprisingly, relate to projections of future emissions, in particular the projected rate of VMT growth for freight and passenger vehicles.

Another key uncertainty is projected energy consumption per VMT. Consultants working with the Penn DOT are completing a statewide analysis (PA Mobility Plan) that may provide improved estimates of this value.

Appendix D. Residential, Commercial, and Non-Fossil Fuel Industrial Energy Use

This appendix reports GHG emissions from fuel consumption in the residential, commercial,[54] and non-fossil fuel industrial (RCI) sectors. GHG emissions from non-energy sources (such as cement production) are reported in Appendix E, while emissions from the fossil fuel industries are reported in Appendix B.[55] The RCI sectors emit carbon dioxide, methane, and nitrous oxide emissions as fuels are combusted for space heating, process heating, and other applications. Carbon dioxide accounts for over 99 percent of these emissions on a tCO_2e basis.

Direct use of coal, oil,[56] natural gas, and wood[57] in these sectors resulted in about 80 $MMTCO_2e$ of GHG emissions in 2004. Since these sectors consume electricity, one can also attribute emissions from electricity consumption to these sectors.[58] If electricity-related emissions are included, then these sectors account for nearly 172 $MMTCO_2e$ in 2004, with electricity use accounting for over half of RCI emissions. If past trends continue – constant growth in electricity use combined with slower growth or decreases in the use of gas, oil, and coal – electricity will increasingly dominate the RCI sectors in Pennsylvania both in terms of energy use and GHG emissions.

Overall electricity consumption for the three sectors increased by an average of 1.6 percent per year from 1990 to 2003; electricity-related emissions grew at a slower annual rate of 0.9 percent, as emissions per kWh declined (see Appendix A). Nearly half of direct fuel use occurs within the industrial sector, and this has declined in recent years, most likely due to decreased activity in the traditional industries.

Reference case GHG estimates depend upon projections of energy use by sector and source. As described in Appendix A, overall Pennsylvania's electricity use is projected to grow at 1.25 percent per year, only slightly slower than in the past decade. Lacking detailed projections for the State, it is further assumed, for the purposes of this initial analysis, the relative growth rates among individual RCI sectors will follow a pattern similar to recent history, as illustrated in Table 13.

---

[54] The commercial sector "consists of service-providing facilities and equipment of: businesses; Federal, State, and local governments; and other private and public organizations, such as religious, social, or fraternal groups. The commercial sector includes institutional living quarters. It also includes [energy consumed at] sewage treatment facilities" EIA 2002. *State Energy Data 2001, Technical Notes*, page 5. http://www.eia.doe.gov/emeu/states/sep_use/notes/use_intro.pdf

[55] Efforts were made to ensure that fuel use by fossil fuel industries reported in Appendix B are not included (i.e. double counted) in this section.

[56] Propane (aka LPG or liquid petroleum gas) use is included in oil consumption.

[57] Emissions from wood combustion include only N2O and CH4. Carbon dioxide emissions from biomass are assumed to be "net zero" consistent with USEPA and IPCC methodologies, and any net loss of carbon stocks due to biomass fuel use should be picked up in the land use and forestry analysis.

[58] One could similarly allocate consumption-basis GHG emissions from gas, oil, and coal production; however this would have a much smaller effect, as upstream emissions are typically only about 5-25% of combustion-related emissions on a tCO2e per BTU basis.

Growth rates for natural gas, coal, and oil consumption are based on regional projections from the EIA Annual Energy Outlook 2006 (AEO2006) and adjusted for Pennsylvania's growth rates of population and employment, resulting in the growth rates shown in Table 14. Some of the annual growth rates for natural gas are counter-intuitive because the table shows the average growth over time. For example, natural gas consumption in the commercial sector from 1990 to 2004 has grown at an average rate of 1 percent but this encompasses years of large increases (9 percent in 1999, 10 percent in 2003) and large decreases (9 percent decrease from 1997 to 1998, 5 percent decrease in 2004). Overall projections for natural gas from the AEO2006 are decreases in the commercial sector through 2010 and increases in the industrial sector. We were unable to find projections for natural gas consumption from the Pennsylvania Utilities Commission.

Table 13. Electricity Sales Annual Growth Rates, Historical and Projected

Sector	1990-2003	2004-2025
Residential	2.0%	1.4%
Commercial	2.8%	2.1%
Industrial	0.1%	0.1%
Total	**1.5%**	**1.3%**

Table 14. Projected Annual Growth in Energy Use, by Sector and Fuel, 2002-2025

	1990-current	Current-2010	2010-2015	2015-2025
Residential				
natural gas (2005)	0.1%	0.0%	0.1%	0.0%
petroleum (2001)	1.1%	-2.3%	-0.8%	-1.2%
Commercial				
natural gas (2005)	1.0%	-1.3%	0.6%	-0.1%
petroleum (2001)	-1.1%	-1.5%	-0.3%	-0.8%
Industrial				
natural gas (2005)	-1.6%	0.8%	-1.0%	-1.0%
petroleum (2001)	-0.8%	-1.4%	-1.1%	-1.7%
coal (2001)	-3.8%	-0.4%	-1.2%	-1.7%

Year value in parentheses indicate the most recent year that data was available

Figure 14, Figure 15, and Figure 16 illustrate historical and projected emissions for the residential, commercial, and industrial sectors from 1990 to 2025. Electricity consumption accounts for the largest component of each sector's emissions. Both the residential and commercial sectors show small growth in emissions from 2004 to 2025, due to assumed low growth or decreases in both electricity and fossil fuel consumption. In the residential sector energy consumption grows at a faster rate than population growth, a reflection of increased affluence and service provision (more appliances, etc.). In the commercial sector, electricity consumption outpaces employment while natural gas consumption decreases from 2004 to 2025.

Industrial sector emissions 1990 to 2004 vary from year to year, reflecting variations in business activity. The large decline in emissions from coal consumption in 1997-2000 period reflects the decline in the steel industry. From 20025to 2025, the industrial sector emissions are expected to decline, following the expected decline in employment in the manufacturing industries.[59]

Figure 13. Residential Sector GHG Emissions from Energy Use

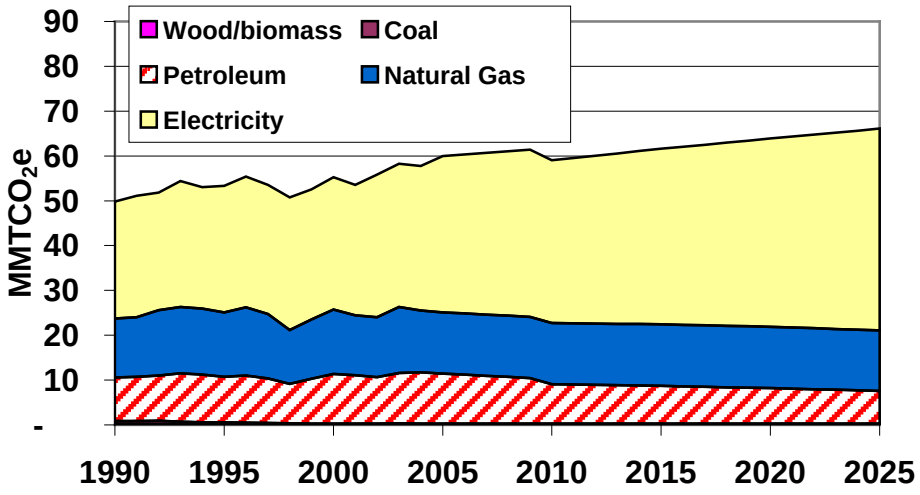
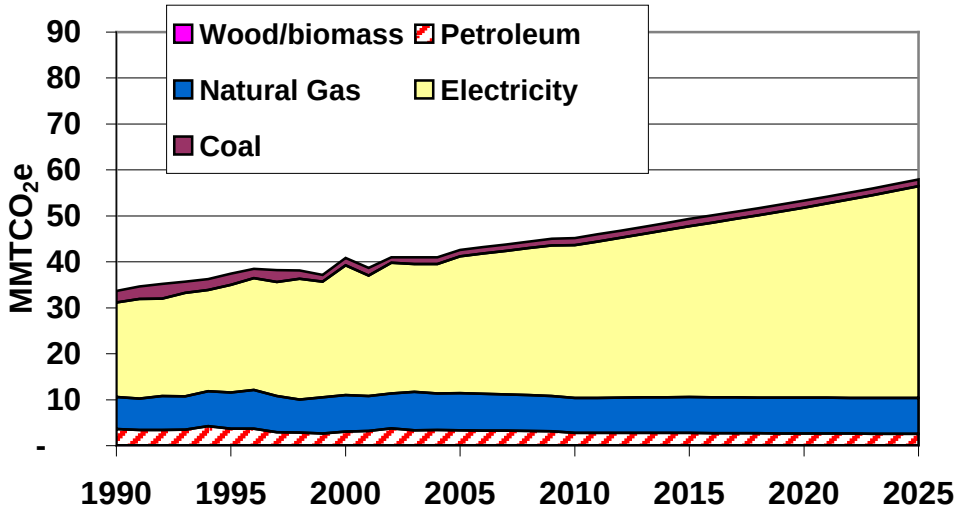
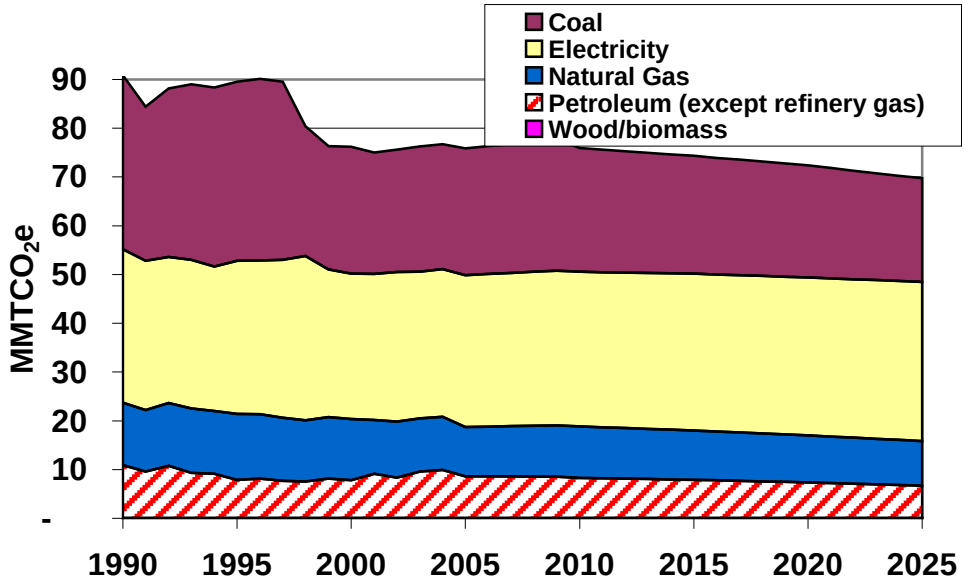


Figure 14. Commercial Sector GHG Emissions from Energy Use



[59] These estimates of growth relative to population and employment reflect expected responses – as modeled by PJM, other electric utilities and the EIA NEMS model -- to changing fuel and electricity prices and technologies, as well as structural changes within each sector (subsectoral shares, energy use patterns, etc.).

Figure 15. Industrial Sector GHG Emissions from Energy Use



Key Uncertainties

Key sources of uncertainty underlying the inventory and projections are as follows:

- Population and economic growth are the principal drivers for electricity and fuel use and are subject to significant uncertainties.
- The projections assume no large long-term changes in relative fuel and electricity prices, as compared with current levels and US DOE projections. Such changes would influence consumption levels and encourage switching among fuels.
- It is assumed that energy consumed at military bases and national laboratories are included in the energy statistics from the EIA. However, under-reporting may have occurred but estimating that impact is beyond the scope of this effort.
- Growth of major industries – the energy consumption projections assume no new large energy-consuming facilities and no major changes in industrial activity. A few large new facilities – or the decline of major industries – could significantly impact energy consumption and consequent emissions.

Appendix E. Industrial Process and Related Emissions

Emissions in this category span a wide range of activities and reflect non-combustion sources of CO_2 from industrial manufacturing (cement, lime, and soda ash production), the release of hydrofluorocarbons (HFCs) from cooling and refrigeration equipment, the use of various fluorinated gases in semiconductor manufacture (perfluorocarbons or PFCs as well as HFCs), and the release of sulfur hexafluoride (SF6) from electricity transformers.

Overall, industrial processes and related emissions as shown in Figure 17 doubled from 1990 to 2004 and are expected to continue to grow through 2025. The contributions of each sub-category are shown in Figure 18 and explained below.

Figure 16. GHG Emissions from Industrial Processes, 1990-2025

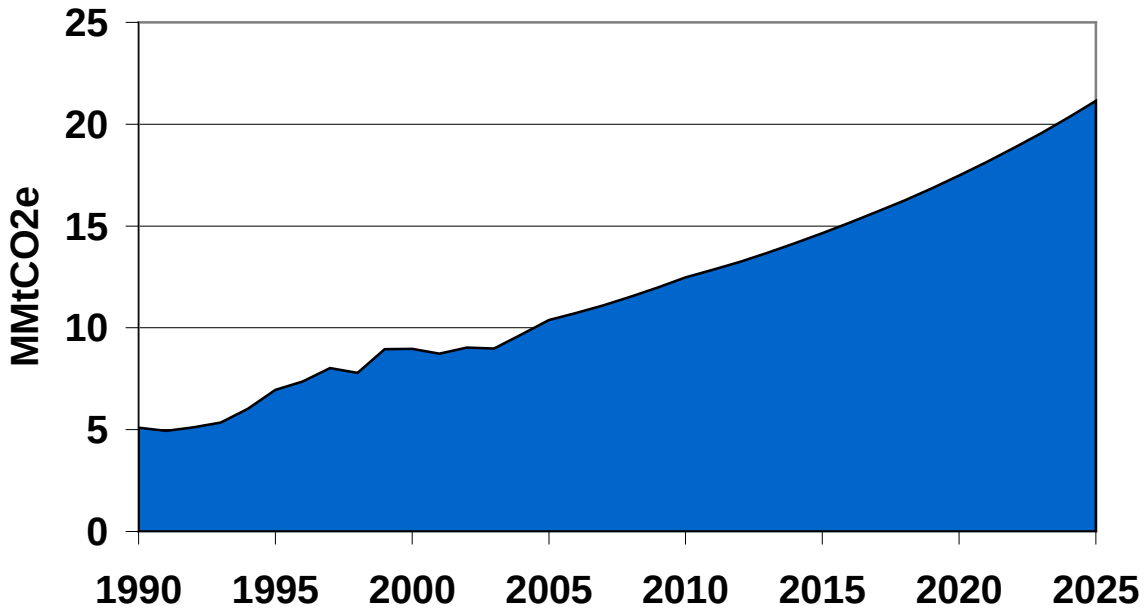
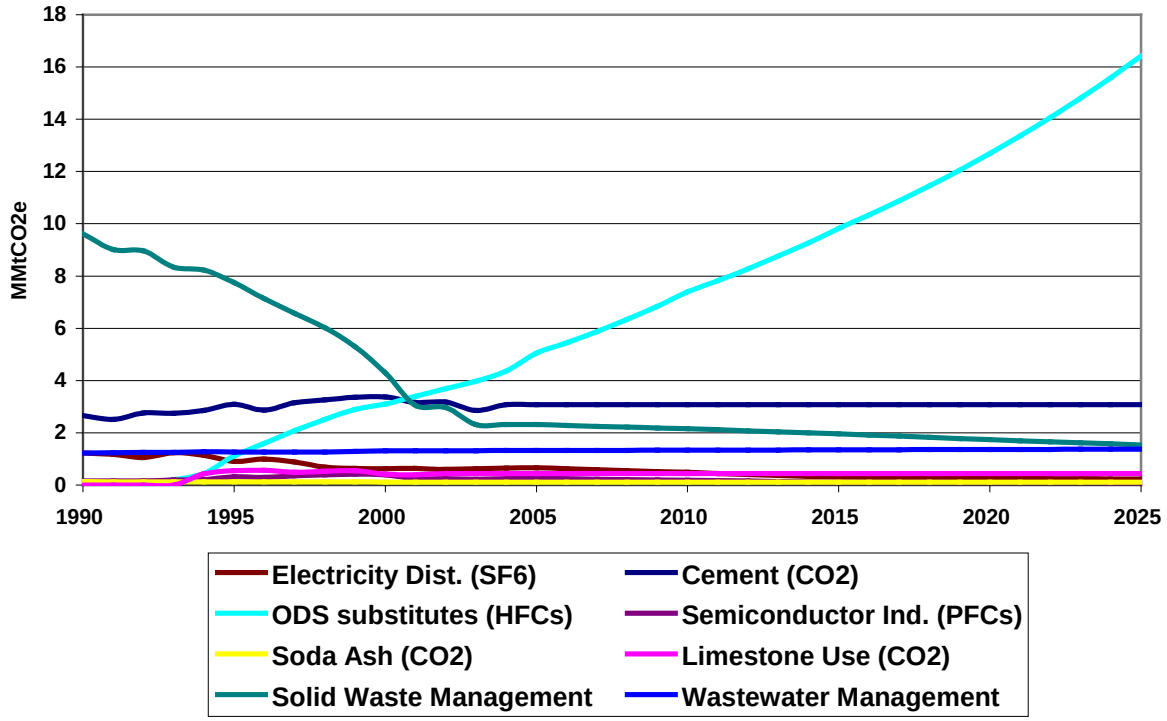


Figure 17. GHG Emissions from Industrial Processes, 1990-2025, by Source



From 1990 to 2005 the cement industry was one of the largest contributors of GHG emissions from industrial processes. Cement production emits CO_2 during the calcination process, whereby calcium carbonate (CaCO3) is converted to calcium oxide (CaO). This process also requires significant energy consumption; emissions related to fuel use at cement plants are reported in the RCI section above. The process emissions are directly related to the amount of clinker and masonry cement produced. In 2004, Pennsylvania had 10 cement plants and ranked 3rd in the country for state production of cement.[60] For 1990-2002, GHG emissions are calculated as the production from these plants multiplied by standard emission factors of 0.507 tons CO_2/ton clinker and 0.0224 tons CO_2/ton masonry cement. Cement production in Pennsylvania has varied significantly in the last 15 years with increases in 1995 (8 percent) and 1999 (3 percent) followed by similar decreases in 1996 (7 percent) and 2003 (10 percent). Since no overall trend of increases or decreases is evident in that time period, no changes in in-state cement production are assumed after 2004.

Emissions of SF6 from electrical equipment have experienced declines since the early-nineties (see Figure 18), mostly due to voluntary action by industry. Emissions for Pennsylvania from 1990 to 2003 were estimated based on the estimates of emissions per kWh from the US EPA GHG inventory (US EPA 2005 *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2003*) and the State's electricity consumption. The US Climate Action Report[61] shows expected

[60] USGS Cement Mineral Yearbook, http://minerals.usgs.gov/minerals/pubs/commodity/cement/cemenmyb04.xls

[61] U.S. Department of State, *U.S. Climate Action Report 2002*, Washington, D.C., May 2002. http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BNQ76/$File/ch5.pdf

decreases in these emissions at the national level, and the same rate of decline is assumed for emissions in Pennsylvania. The decline in emissions in the future reflects expectations of future actions by the electric industry to reduce these emissions.

After 2005, emissions from HFCs in refrigeration and air conditioning equipment dominate the category and show strong growth through 2025. HFCs are being used to substitute for ozone-depleting substances (ODS), most notably CFCs (also potent warming gases) in compliance with the *Montreal Protocol*.[62] Even low amounts of HFC emissions, from leaks and other releases under normal use of the products, can lead to high GHG emissions due to the high global warming potential (GWP) of HFCs (see Appendix J). Emissions from the ODS substitutes in Pennsylvania are estimated to have increased from 0.02 $MMTCO_2e$ in 1990 to 5 $MMTCO_2e$ in 2004, with further increases of 6.5 percent per year expected from 2004 to 2025. The estimates for the emissions in Pennsylvania are based on the State's population and estimates of emissions per capita from the US EPA national GHG inventory.[63]

Pennsylvania's semi-conductor industry, accounted for about 5 percent of national semi-conductor shipments in 1997. To estimate the historic GHG emissions, this fraction was applied to the US EPA national GHG inventory estimates of emissions from semi-conductor manufacturing. National emissions peaked in 1999 and have fallen significantly since then – largely due to voluntary actions by the industry. Emissions beyond 2004 could increase due to increases in semi-conductor manufacturing, or decrease due to process change and/or continued industry efforts to reduce emissions. Projections from the US Climate Action Report[64] shows expected decreases in PFC emissions at the national level due to a variety of industry actions to reduce emissions, and the rate of decline from that report was applied for emissions from 2004 to 2025.[65]

Emissions from lime manufacture, which also emits CO_2 from chemical conversion, are estimated based on Pennsylvania's production of high-calcium and dolomite lime.[66] EIIP

---

[62] ODS substitutes are primarily associated with refrigeration and air conditioning, but also many other uses such as fire extinguishers, solvent cleaning, aerosols, and foam production. Projections for ODS substitutes depend on technology characteristics in a range of equipment. For the US national inventory, a detailed stock vintaging model was used, but such analysis has not been completed at the state level. This report uses the EPA SGIT procedure of estimating state-level emissions based on the state's fraction of US population and the US emissions. Growth rates are based on growth in projected national emissions from recent EPA report, US EPA 2004, *Analysis of Costs to Abate International ODS Substitute Emissions*, EPA 430-R-04-006.
http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR62AS98/$File/IMAC%20Appendices%206-24.pdf

r[63] http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenter
PublicationsGHGEmissionsUSEmissionsInventory2006.html

[63] http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenter
PublicationsGHGEmissionsUSEmissionsInventory2006.html

[64] U.S. Department of State, *U.S. Climate Action Report 2002*, Washington, D.C., May 2002.
http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BNQ76/$File/ch5.pdf

[65] Similarly, the Intel data was extrapolated back to 1990, based on 1995 data from Intel and annual change in the national emissions from the US inventory (US EPA 2005 *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2003*)

[66] USGS Pennsylvania State Minerals Information. http://minerals.usgs.gov/minerals/pubs/state/pa.html

guidance provided an assumed CO_2 absorption rate of 80 percent for both types of lime production. CO_2 is emitted when limestone and dolomite are consumed at very high temperatures. Consumption data from the United States Geological Survey (USGS) suggest emissions from these sources of industrial process emissions do not show a clear trend of increases or decreases since 1990. The assumed trend is for these emissions to remain at 2002 levels through 2025.

Key Uncertainties

Since emissions from industrial processes are determined by the level of production and the production processes of a few key industries, there is relatively high uncertainty regarding future emissions, as they depend on the competitiveness of Pennsylvania manufacturers and the specific nature of their production processes.

The GHG inventory developed by Penn State in 2002 reported emissions from HCFC-22 production (1.7 $MMTCO_2e$ in 1990 and 1.3 $MMTCO_2e$ in 1999). Review of the report and discussions with the authors did not provide any details of how these emissions estimates were determined. Discussions with the US EPA similarly did not yield any information on production of HCFC-22 in Pennsylvania. Emissions from this process are excluded from this report, pending further information on production of this chemical in the State.

The projected largest source of future industrial emissions, HFCs used in cooling applications, is subject to a number of uncertainties as well. First, historical emissions are based on national estimates; Pennsylvania-specific estimates are currently unavailable. Second, emissions will be driven by future choices regarding air conditioning technologies and coolants used, for which a number of options currently exist.

Appendix F. Agriculture, Forestry, and Other Land Use

The emissions discussed in this appendix refer to non-energy emissions from agriculture, forestry, and other land uses. These emissions include emissions from livestock, agriculture soil management and field burning, CO_2 emitted and removed (sinks) due to forestry activities and land use change, and emissions linked to rangeland and forest fires.

Table 15. GHG emissions from Agriculture, Forestry, and Other Land-Use ($MMTCO_2e$)

(Million Metric Tons CO2e)	1990	1995	2000	2005	2010	2015	2020	2025
Agriculture	**7.1**	**7.0**	**6.9**	**6.4**	**6.4**	**6.4**	**6.5**	**6.5**
Manure Mgmt & Enteric Ferment. (CH4)	3.7	3.6	3.4	3.4	3.4	3.4	3.4	3.5
Agricultural Soils (N2O)	3.4	3.5	3.5	3.0	3.0	3.0	3.0	3.0
Forestry and Land Use	**-17.2**	**-17.2**	**-17.3**	**-17.3**	**-17.3**	**-17.3**	**-17.3**	**-17.3**

Agriculture

Agriculture plays a large role in Pennsylvania's economy, contributing about $4 billion in annual cash farming receipts.[67] In 2002, dairy products accounted for $1.4 billion in sales. While annual dairy stock and milk output have decreased in the last ten years, Pennsylvania still ranks as the 4th among all states in dairy production. Cattle sales accounted for $441 million while crops (including feed for stock) made up another $540 million.[68]

GHG emissions from livestock, agriculture soil management, and field burning were about 6.4 $MMTCO_2e$ in 2004. These emissions include CH4 and N2O emissions from enteric fermentation, manure management, agriculture soils, and agriculture residue burning. Data on crops and animals in the State from 1990 to 2004 were obtained from the USDA National Agriculture Statistical Service.[69] As shown in Figure 20, emissions from these sources decreased by about 10 percent from 1990 to 2004. Emissions from agricultural soils accounted for the largest fraction (almost 50 percent) of agricultural emissions throughout that time. Soil-related emissions of N2O occur as the result of activities that increase nitrogen in the soil, including fertilizer (synthetic, organic, and livestock) application and the production of nitrogen-fixing crops. These activities decreased somewhat from 1990 to 2004 and consequently emissions decreased by 11 percent between these years.

Enteric fermentation and manure management accounted for about 38 percent and 14 percent of agriculture emissions in 1990, respectively. Enteric fermentation is another term for the microbial process of breaking down food in digestive systems, which results in methane emissions that are especially large among ruminants, such as cattle and sheep. Enteric fermentation emissions decreased by 12 percent from 1990 to 2004 due to decreases in both beef

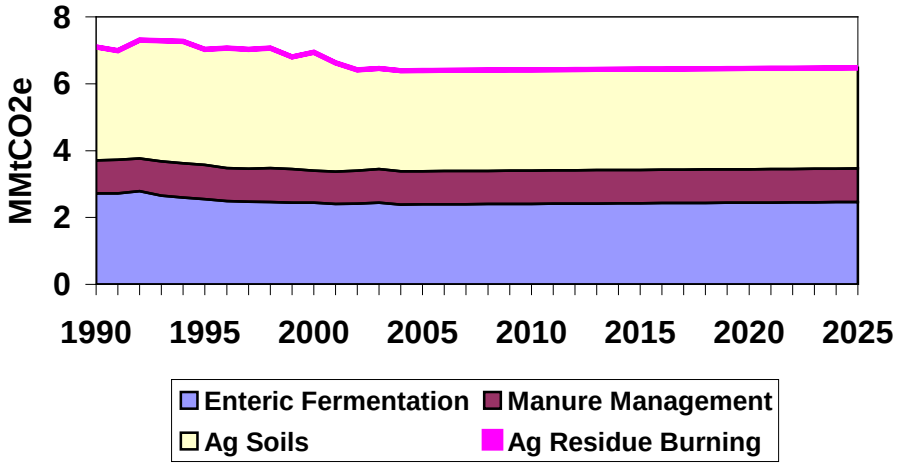
[67] http://www.marketplaceforthemind.state.pa.us/m4m/cwp/view.asp?a=3&q=150237
[68] *http://www.nass.usda.gov/census/census02/topcommodities/topcom_PA.htm*
[69] The Pennsylvania Department of Agriculture website links to the NASS website for data and statistics on agriculture stocks, data are collected in state and compiled for the NASS site.

and dairy stock. Emissions from manure management remained constant from 1990 to 2004 as the declines due to fewer cattle were countered by increases in poultry. Emissions from agriculture residue burning are very small and decreased by 34 percent from 1990 to 2004.

As a first approximation for projecting emissions from this source, the growth rate for dairy cattle is assumed to match the State population growth rate, 0.2 percent per year. For other animal stock, a simple assumption of no change from 2004 levels was applied. It is also assumed that emission rates per animal (based on animal weight, feed, and management strategies for stock and land) remain at the 2004 levels.

As illustrated in Figure 20, total GHG emissions from agriculture decreased by 13 percent from 1990 to 2004 and are projected to increase by 1 percent by 2025, relative to 2004.

Figure 18. GHG Emissions from Agriculture



Forestlands

Forest products are a key part of Pennsylvania's agriculture exports, ranking second behind food products as the most exported product group. Pennsylvania is first among the 50 United States in the production of export grade hardwood. Pennsylvania's forest products account for nearly $700 million of the State's many exports.[70]

Forest land emissions refer to the net CO_2 flux[71] from forested lands in Pennsylvania, which account for about 60% of the State's land area. These net forest and land use carbon flow estimates are based on recent improvements to US Forest Service carbon stock inventory from earlier estimates published in 1997 by Birdsey and Lewis.[72] The updated results (referred to as FORCARB2 estimates), which include a number of recent refinements by the US Forest Service, indicate that Pennsylvania forests and the use of forest productions sequestered on average 14.4

[70] http://www.agriculture.state.pa.us/agriculture/cwp/view.asp?a=3&q=125373
[71] "Flux" refers to both emissions of CO2 to the atmosphere and removal (sinks) of CO2 from the atmosphere.
[72] Thomas D. Peterson, James E. Smith and Jack D. Kartez (2005). Development of Forestry Related Climate Change Mitigation Options for the State of Maine. The Journal of Environmental Quality (available in prepublication format).

$MMTCO_2e$ each year over the period 1990 to 2000, as shown in Table 15. No changes in the net CO_2 flux are assumed in this preliminary reference case projection.

Liming of agricultural soils refers to carbon emissions from the application of limestone to soils. The emissions are calculated based on the carbon content of limestone and the quantity of limestone applied each year. These emissions did not change significantly between 1990 and 2000 and are assumed to remain constant through 2025.

These estimates are subject to uncertainty. In particular, during the survey periods used for FORCARB2 estimates, the definition of forestland changed from a minimum forest cover requirement of ten percent, to a minimum of five percent. As a result, rangelands may or may not be included in these estimates, depending on their level of tree stocking. The US Forest Service is not able to make corrections associated with these changes in forest definition, but review of the data conducted by CCS and the US Forest Service suggests that effects are likely to be small. Additionally, discussions with USFS have indicated that the soil carbon pool estimates carry a high level of uncertainty.[73] In Table 15 below, CCS provides totals with and without the soil carbon pool to recognize this uncertainty. For summary results in this report (see Table 1, Table 3, and Table 15), CCS includes the forestry estimates without the soil carbon pool

Table 16. GHG Emissions (Sinks) from Forestry and Other Activities

	1990	2000
Live and dead-standing trees and understory	-12.1	-12.1
Forest floor and coarse woody debris	-2.2	-2.2
Soil Carbon	2.8	2.8
Wood products and landfills	-3.3	-3.3
Liming of Agricultural Soils	0.4	0.4
Total	**-14.4**	**-14.4**
Totals (excluding soil carbon)	**-17.2**	**-17.3**

Note: Totals may not add due to rounding.

[73] Rich Birdsey, USFS, personal communication with CCS, May 2007.

Appendix G. Waste Management

GHG emissions from waste management are summarized in Table 16. Emissions in this category include:

- Solid waste management – methane emissions from landfills, accounting for any methane that is flared or captured for energy production, and
- Wastewater management – methane and nitrous oxide from municipal wastewater treatment facilities.

Any emissions associated with energy consumed to transport of solid waste and wastewater are included in the RCI accounting above.

Table 17. Emissions from Waste Management

(Million Metric Tons CO2e)	1990	1995	2000	2005	2010	2015	2020	2025
Waste Management	**10.8**	**9.0**	**5.6**	**3.6**	**3.5**	**3.3**	**3.1**	**2.9**
Solid Waste Management	9.6	7.8	4.3	2.3	2.2	2.0	1.7	1.5
Wastewater Management	1.2	1.3	1.3	1.3	1.3	1.3	1.4	1.4

The EPA SGIT tool was used to estimate solid waste management emissions from 1990 to 2003.[74] However, since emissions from these types of facilities are site-specific, PA DEP provided additional estimates for 2004 of methane emissions from each landfill. The information in the EPA SGIT tool was updated with these data from PA DEP and information from the US EPA Landfill Methane Outreach Program.

Between 1990 and 2004, emissions from solid waste management decreased significantly, falling from 9.6 $MMTCO_2e$ in 1990 to 2.3 $MMTCO_2e$ in 2004. Most of this decrease is due to increased levels of methane capture at landfills. The methane is then either flared or combusted in landfill gas-to-energy systems.

For emissions from 2004 to 2025, growth rates are based on national projections by the US Department of State.[75] These projections decrease over time, accounting for improved methane recovery practices.

Emissions from wastewater were also estimated using the EPA SGIT tool. These emissions increased by 1.9 percent per year from 1990 to 2003.[76] Projected emissions are assumed to increase with population growth, 0.2 percent per year from 2004 to 2025.

[74] EPA SGIT uses amount of waste in place at landfills, characteristics of landfill (size, moisture levels), amount of landfill gas recovered and flared and oxidation levels to estimate state emissions from landfills.
[75] US Department of State (2002). *US Climate Action Report 2002*. Washington DC May 2002.
[76] Emissions are calculated in EPA SGIT based on state population, assumed biochemical oxygen demand and protein consumption per capita, and emission factors for N2O and CH4.

Appendix H. List of Contacts Made

Dave English & Ron Gilius, Pennsylvania Oil and Gas Bureau
Howard Greenbery, Penn State University
Carmen La Rosa, PA DEP
Toni Markowski, DCNR
John Miller, Enervest Management Partners.
Joe Sherrick, PA DEP
Habib Sharifhossein, PA DEP
Brian Towbridge, Penn DOT
Dean Van Orden, PA DEP, Bureau of Air Quality
Brian Wall, PennDOT
Hallie Weiss, City of Philadelphia

Appendix I. Comparison of CCS GHG Inventory with Previous GHG Inventory Developed by Penn State University

In 2003, the Center for Integrated Regional Assessment at Pennsylvania State University (PennState) prepared provisional estimates of GHG emissions for two years (1990 and 1999) for Pennsylvania. These estimates along with detailed background data and description of approach and a preliminary interpretation of the results appear in the report, Greenhouse Gas Emissions Inventory for Pennsylvania Phase I Report (Rose et al 2003). As with the CCS approach reported in this document, the PennState analysis drew on the standardized inventory approach developed by US EPA. The PennState work provides an excellent starting point, but some differences in GHG estimates have occurred.

Table 17 presents the GHG emission estimates from the two sources and indicates reasons for differences that have been identified. Overall, the total net GHG emissions differ by less than 2.5% in 1990 and less than 0.5% in 1999. However, differences in individual categories are larger. Note that the reporting categories differ slightly from the categories used in the rest of this report in order to provide a relevant comparison to the Penn State analysis. Most of the differences reflect updates to data, including updated data on activity levels (e.g. energy consumption) and updates to emission factors or inventory approaches.

One omission in the CCS inventory is emissions from HCFC-22 production. The GHG inventory developed by Penn State reported emissions from HCFC-22 production (1.7 $MMTCO_2e$ in 1990 and 1.3 $MMTCO_2e$ in 1999). Review of the report and discussions with the authors did not provide any indication of how these emissions estimates were determined. Discussions with the US EPA similarly did not yield any information on production of HCFC-22 in Pennsylvania. Emissions from this process are excluded from this report, pending further information on production of this chemical in the State.

Table 18. Comparison of CCS and Penn State GHG Inventories, 1990 and 1999

Emission Source	1990		1999		Comments
	PennState	CCS	PennState	CCS	
CO_2 from Fossil Fuels	262.4	264.4	264.8	265.6	
Residential	*22.0*	*23.4*	*23.4*	*23.4*	CCS estimates use updated EIA data for energy consumption
Commercial	*12.5*	*13.0*	*11.9*	*11.9*	CCS estimates use updated EIA data for energy consumption
Industrial	*68.5*	*61.4*	*54.9*	*47.8*	CCS estimates use updated EPA guildelines, which account for non-energy use of industrial energy such as asphalt and road oil.
Transportation	*58.8*	*62.7*	*68.6*	*72.2*	CCS estimates use gasoline and diesel consumption data from PennDOT source
Electricity	*100.6*	*103.8*	*106.0*	*110.3*	CCS estimates use updated EIA data for energy consumption
GHGs from Non-Energy Industrial Processes	7.0	5.1	10.8	9.0	CCS estimates do not include emissions from production of HCFC22
CH_4 from Oil and Natural Gas	5.2	5.7	5.4	5.1	CCS estimates use updated emissions factors from US EPA guidelines (March 2005 updates)
CH_4 from Coal Mining	7.3	9.2	8.3	9.5	CCS estimates use updated US EPA estimates for methane emissions by mine
GHGs from Municipal Waste Management	4.6	9.6	4.3	5.3	CCS estimates based on information provided by PA DEP
CH_4 from Domestic Animals	0.3	2.7	0.3	2.4	PennState values appear to be miscalculated
GHGs from Manure Management	2.9	1.0	3.0	1.0	PennState values appear to be miscalculated
GHGs from Agricultural Soils	Not estimated	3.4	Not estimated	3.4	Values not estimated in PennState inventory, assumed to be low
GHGs from Municipal Waste Water	0.6	1.2	0.6	1.3	CCS estimates use updated emission factors from US EPA guidelines
CH_4 & N_2O from Mobile Combustion	1.5	2.2	1.6	2.3	CCS estimates include emissions from non-road travel and greater refinement on VMT use by vintage of vehicle
CH_4 & N_2O from Stationary Combustion	0.9	1.0	0.9	0.9	CCS estimates use updated EIA data for energy consumption
CO_2 from Forestry and Land-use Change	-8.8	-14.4	-7.4	-14.5	CCS estimates based on updated estimates of carbon stocks from US Forestry Service
Total	283.9	291.1	292.6	291.3	

Appendix J. Greenhouse Gases and Global Warming Potential Values: Excerpts from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000

Original Reference: All material taken from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2000*, U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-02-003, April 2002. www.epa.gov/globalwarming/publications/emissions The preparation of this document was directed by Michael Gillenwater.

Introduction

The *Inventory of U.S. Greenhouse Gas Emissions and Sinks* presents estimates by the United States government of U.S. anthropogenic greenhouse gas emissions and removals for the years 1990 through 2000. The estimates are presented on both a full molecular mass basis and on a Global Warming Potential (GWP) weighted basis in order to show the relative contribution of each gas to global average radiative forcing.

The Intergovernmental Panel on Climate Change (IPCC) has recently updated the specific global warming potentials for most greenhouse gases in their Third Assessment Report (TAR, IPCC 2001). Although the GWPs have been updated, estimates of emissions presented in the U.S. *Inventory* continue to use the GWPs from the Second Assessment Report (SAR). The guidelines under which the *Inventory* is developed, the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines for national inventories[77] were developed prior to the publication of the TAR. Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. This excerpt of the U.S. *Inventory* addresses in detail the differences between emission estimates using these two sets of GWPs. Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends.

Additional discussion on emission trends for the United States can be found in the complete Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000.

What is Climate Change?

Climate change refers to long-term fluctuations in temperature, precipitation, wind, and other elements of the Earth's climate system. Natural processes such as solar-irradiance variations, variations in the Earth's orbital parameters, and volcanic activity can produce variations in climate. The climate system can also be influenced by changes in the concentration of various gases in the atmosphere, which affect the Earth's absorption of radiation.

The Earth naturally absorbs and reflects incoming solar radiation and emits longer wavelength terrestrial (thermal) radiation back into space. On average, the absorbed solar radiation is balanced by the outgoing terrestrial radiation emitted to space. A portion of this terrestrial radiation, though, is itself absorbed by gases in the atmosphere. The energy from this absorbed terrestrial radiation warms the Earth's surface and atmosphere, creating what is known as the "natural greenhouse effect." Without the natural heat-trapping properties of these atmospheric gases, the average surface temperature of the Earth would be about 33°C lower (IPCC 2001).

Under the UNFCCC, the definition of climate change is "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." Given that definition, in its Second Assessment Report

[77] See FCCC/CP/1999/7 at <www.unfccc.de>.

of the science of climate change, the IPCC concluded that:

> *Human activities are changing the atmospheric concentrations and distributions of greenhouse gases and aerosols. These changes can produce a radiative forcing by changing either the reflection or absorption of solar radiation, or the emission and absorption of terrestrial radiation (IPCC 1996).*

Building on that conclusion, the more recent IPCC Third Assessment Report asserts that "[c]oncentrations of atmospheric greenhouse gases and their radiative forcing have continued to increase as a result of human activities" (IPCC 2001).

The IPCC went on to report that the global average surface temperature of the Earth has increased by between 0.6 ± 0.2°C over the 20th century (IPCC 2001). This value is about 0.15°C larger than that estimated by the Second Assessment Report, which reported for the period up to 1994, "owing to the relatively high temperatures of the additional years (1995 to 2000) and improved methods of processing the data" (IPCC 2001).

While the Second Assessment Report concluded, "the balance of evidence suggests that there is a discernible human influence on global climate," the Third Assessment Report states the influence of human activities on climate in even starker terms. It concludes that, "[I]n light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations" (IPCC 2001).

Greenhouse Gases

Although the Earth's atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide, and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 1996). Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the atmosphere, space, land, and the oceans. A gauge of these changes is called radiative forcing, which is a simple measure of changes in the energy available to the Earth-atmosphere system (IPCC 1996). Holding everything else constant, increases in greenhouse gas concentrations in the atmosphere will produce positive radiative forcing (i.e., a net increase in the absorption of energy by the Earth).

Climate change can be driven by changes in the atmospheric concentrations of a number of radiatively active gases and aerosols. We have clear evidence that human activities have affected concentrations, distributions and life cycles of these gases (IPCC 1996).

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). Because CFCs, HCFCs, and halons are stratospheric ozone depleting substances, they are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. The UNFCCC defers to this earlier international treaty; consequently these gases are not included in national greenhouse gas inventories. Some other fluorine containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)—do not deplete stratospheric ozone but are potent greenhouse gases. These latter substances are addressed by the UNFCCC and accounted for in national greenhouse gas inventories.

There are also several gases that, although they do not have a commonly agreed upon direct radiative forcing effect, do influence the global radiation budget. These tropospheric gases—referred to as ambient air pollutants—include carbon monoxide (CO), nitrogen dioxide (NO_2),

sulfur dioxide (SO_2), and tropospheric (ground level) ozone (O_3). Tropospheric ozone is formed by two precursor pollutants, volatile organic compounds (VOCs) and nitrogen oxides (NO_x) in the presence of ultraviolet light (sunlight). Aerosols—extremely small particles or liquid droplets—often composed of sulfur compounds, carbonaceous combustion products, crustal materials and other human induced pollutants—can affect the absorptive characteristics of the atmosphere. However, the level of scientific understanding of aerosols is still very low (IPCC 2001).

Carbon dioxide, methane, and nitrous oxide are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities, however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes—except when directly or indirectly perturbed out of equilibrium by anthropogenic activities—generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1.

Table 1: Global atmospheric concentration (ppm unless otherwise specified), rate of concentration change (ppb/year) and atmospheric lifetime (years) of selected greenhouse gases

Atmospheric Variable	CO_2	CH_4	N_2O	SF_6[a]	CF_4[a]
Pre-industrial atmospheric concentration	278	0.700	0.270	0	40
Atmospheric concentration (1998)	365	1.745	0.314	4.2	80
Rate of concentration change[b]	1.5[c]	0.007[c]	0.0008	0.24	1.0
Atmospheric Lifetime	50-200[d]	12[e]	114[e]	3,200	>50,000

Source: IPCC (2001)
[a] Concentrations in parts per trillion (ppt) and rate of concentration change in ppt/year.
[b] Rate is calculated over the period 1990 to 1999.
[c] Rate has fluctuated between 0.9 and 2.8 ppm per year for CO_2 and between 0 and 0.013 ppm per year for CH4 over the period 1990 to 1999.
[d] No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes.
[e] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

A brief description of each greenhouse gas, its sources, and its role in the atmosphere is given below. The following section then explains the concept of Global Warming Potentials (GWPs), which are assigned to individual gases as a measure of their relative average global radiative forcing effect.

Water Vapor (H_2O). Overall, the most abundant and dominant greenhouse gas in the atmosphere is water vapor. Water vapor is neither long-lived nor well mixed in the atmosphere, varying spatially from 0 to 2 percent (IPCC 1996). In addition, atmospheric water can exist in several physical states including gaseous, liquid, and solid. Human activities are not believed to directly affect the average global concentration of water vapor; however, the radiative forcing produced by the increased concentrations of other greenhouse gases may indirectly affect the hydrologic cycle. A warmer atmosphere has an increased water holding capacity; yet, increased concentrations of water vapor affects the formation of clouds, which can both absorb and reflect solar and terrestrial radiation. Aircraft contrails, which consist of water vapor and other aircraft emittants, are similar to clouds in their radiative forcing effects (IPCC 1999).

Carbon Dioxide (CO_2). In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO_2. Atmospheric carbon dioxide is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 367 ppmv in 1999, a 31 percent increase (IPCC 2001). The IPCC notes that "[t]his concentration has not been exceeded during the past 420,000 years, and likely not during the past 20 million years. The rate of increase over the past century is unprecedented, at least during the past 20,000 years." The IPCC definitively states that "the present atmospheric CO_2 increase is caused by anthropogenic emissions of CO_2" (IPCC 2001). Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of carbon dioxide.

In its second assessment, the IPCC also stated that "[t]he increased amount of carbon dioxide [in the atmosphere] is leading to climate change and will produce, on average, a global warming of the Earth's surface because of its enhanced greenhouse effect—although the magnitude and significance of the effects are not fully resolved" (IPCC 1996).

Methane (CH_4). Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH_4, as does the decomposition of municipal solid wastes. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a by-product of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of methane have increased by about 150 percent since pre-industrial times, although the rate of increase has been declining. The IPCC has estimated that slightly more than half of the current CH_4 flux to the atmosphere is anthropogenic, from human activities such as agriculture, fossil fuel use and waste disposal (IPCC 2001).

Methane is removed from the atmosphere by reacting with the hydroxyl radical (OH) and is ultimately converted to CO_2. Minor removal processes also include reaction with Cl in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of methane reduce the concentration of OH, a feedback which may increase methane's atmospheric lifetime (IPCC 2001).

Nitrous Oxide (N_2O). Anthropogenic sources of N_2O emissions include agricultural soils, especially the use of synthetic and manure fertilizers; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste combustion; and biomass burning. The atmospheric concentration of nitrous oxide (N_2O) has increased by 16 percent since 1750, from a pre industrial value of about 270 ppb to 314 ppb in 1998, a concentration that has not been exceeded during the last thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere.

Ozone (O_3). Ozone is present in both the upper stratosphere, where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere, where it is the main component of anthropogenic photochemical "smog." During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as chlorofluorocarbons (CFCs), have depleted stratospheric ozone concentrations. This loss of ozone in the stratosphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 1996). The depletion of stratospheric ozone and its radiative forcing was expected to reach a maximum in about 2000 before starting to recover, with detection of such recovery not expected to occur much before 2010 (IPCC 2001).

The past increase in tropospheric ozone, which is also a greenhouse gas, is estimated to provide the third largest increase in direct radiative forcing since the pre-industrial era, behind CO_2 and CH_4. Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds mixing with nitrogen oxides (NO_x) in the presence of sunlight. Ozone, carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and particulate matter are included in the category referred to as "criteria pollutants" in the United States under the Clean Air Act and its subsequent amendments. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable.

Halocarbons, Perfluorocarbons, and Sulfur Hexafluoride (SF_6). Halocarbons are, for the most part, man-made chemicals that have both direct and indirect radiative forcing effects. Halocarbons that contain chlorine—chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl chloroform, and carbon tetrachloride—and bromine—halons, methyl bromide, and hydrobromofluorocarbons (HBFCs)—result in stratospheric ozone depletion and are therefore controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer. Although CFCs and HCFCs include potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which is itself an important greenhouse gas in addition to shielding the Earth from harmful levels of ultraviolet radiation. Under the Montreal Protocol, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the Protocol, a cap was placed on the production and importation of HCFCs by non-Article 5 countries beginning in 1996, and then followed by a complete phase-out by the year 2030. The ozone depleting gases covered under the Montreal Protocol and its Amendments are not covered by the UNFCCC.

Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are not ozone depleting substances, and therefore are not covered under the Montreal Protocol. They are, however, powerful greenhouse gases. HFCs—primarily used as replacements for ozone depleting substances but also emitted as a by-product of the HCFC-22 manufacturing process—currently have a small aggregate radiative forcing impact; however, it is anticipated that their contribution to overall radiative forcing will increase (IPCC 2001). PFCs and SF_6 are predominantly emitted from various industrial processes including aluminum smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. Currently, the radiative forcing impact of PFCs and SF_6 is also small; however, they have a significant growth rate, extremely long atmospheric lifetimes, and are strong absorbers of infrared radiation, and therefore have the potential to influence climate far into the future (IPCC 2001).

Carbon Monoxide (CO). Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH_4 and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying CH_4 and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO_2. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.

Nitrogen Oxides (NO_x). The primary climate change effects of nitrogen oxides (i.e., NO and NO_2) are indirect and result from their role in promoting the formation of ozone in the troposphere and, to a lesser degree, lower stratosphere, where it has positive radiative forcing effects. Additionally, NO_x emissions from aircraft are also likely to decrease methane concentrations, thus having a negative radiative forcing effect (IPCC 1999). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning – both natural and anthropogenic fires – fuel combustion, and, in the stratosphere, from the photo-degradation of nitrous oxide (N_2O). Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

Nonmethane Volatile Organic Compounds (NMVOCs). Nonmethane volatile organic compounds include compounds such as propane, butane, and ethane. These compounds participate, along with NO_x, in the formation of tropospheric ozone and other photochemical oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents. Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

Aerosols. Aerosols are extremely small particles or liquid droplets found in the atmosphere. They can be produced by natural events such as dust storms and volcanic activity, or by anthropogenic processes such as fuel combustion and biomass burning. They affect radiative forcing in both direct and indirect ways: directly by scattering and absorbing solar and thermal infrared radiation; and indirectly by increasing droplet counts that modify the formation, precipitation efficiency, and radiative properties of clouds. Aerosols are removed from the atmosphere relatively rapidly by precipitation. Because aerosols generally have short atmospheric lifetimes, and have concentrations and compositions that vary regionally, spatially, and temporally, their contributions to radiative forcing are difficult to quantify (IPCC 2001).

The indirect radiative forcing from aerosols are typically divided into two effects. The first effect involves decreased droplet size and increased droplet concentration resulting from an increase in airborne aerosols. The second effect involves an increase in the water content and lifetime of clouds due to the effect of reduced droplet size on precipitation efficiency (IPCC 2001). Recent research has placed a greater focus on the second indirect radiative forcing effect of aerosols.

Various categories of aerosols exist, including naturally produced aerosols such as soil dust, sea salt, biogenic aerosols, sulphates, and volcanic aerosols, and anthropogenically manufactured aerosols such as industrial dust and carbonaceous aerosols (e.g., black carbon, organic carbon) from transportation, coal combustion, cement manufacturing, waste incineration, and biomass burning.

The net effect of aerosols is believed to produce a negative radiative forcing effect (i.e., net cooling effect on the climate), although because they are short-lived in the atmosphere—lasting days to weeks—their concentrations respond rapidly to changes in emissions. Locally, the negative radiative forcing effects of aerosols can offset the positive forcing of greenhouse gases (IPCC 1996). "However, the aerosol effects do not cancel the global-scale effects of the much longer-lived greenhouse gases, and significant climate changes can still result" (IPCC 1996).

The IPCC's Third Assessment Report notes that "the indirect radiative effect of aerosols is now understood to also encompass effects on ice and mixed-phase clouds, but the magnitude of any such indirect effect is not known, although it is likely to be positive" (IPCC 2001). Additionally, current research suggests that another constituent of aerosols, elemental carbon, may have a positive radiative forcing (Jacobson 2001). The primary anthropogenic emission sources of elemental carbon include diesel exhaust, coal combustion, and biomass burning.

Global Warming Potentials

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 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 roughly ±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 2).

> *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. (FCCC/CP/1996/15/Add.1)*

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. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, other ambient air pollutants (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and black carbon), however, 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 2: Global Warming Potentials (GWP) and Atmospheric Lifetimes (Years) Used in the Inventory

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-125	32.6	2,800	4,600	920
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-4310mee	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_4F_{10}	2,600	7,000	4,800	10,100
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 here 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 3 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.

Table 3: 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)

* 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 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*. The effects of these compounds on radiative forcing are not addressed here.

The IPCC recently published its Third Assessment Report (TAR), providing the most current and comprehensive scientific assessment of climate change (IPCC 2001). Within that report, the GWPs of several gases were revised relative to the IPCC's Second Assessment Report (SAR) (IPCC 1996), and new GWPs have been calculated for an expanded set of gases. Since the SAR, the IPCC has applied an improved calculation of CO_2 radiative forcing and an improved CO_2 response function (presented in WMO 1999). The GWPs are drawn from WMO (1999) and the SAR, 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 12 percent lower than that in the SAR, 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. The changes are described in the TAR as follows:

New categories of gases include fluorinated organic molecules, many of which are ethers that are proposed as halocarbon substitutes. Some of the GWPs have larger uncertainties

than that of others, particularly for those gases where detailed laboratory data on lifetimes are not yet available. The direct GWPs have been calculated relative to CO_2 using an improved calculation of the CO_2 radiative forcing, the SAR response function for a CO_2 pulse, and new values for the radiative forcing and lifetimes for a number of halocarbons.

Table 4 compares the lifetimes and GWPs for the SAR and TAR. As can be seen in Table 4, GWPs changed anywhere from a decrease of 15 percent to an increase of 49 percent.

References

FCCC (1996) 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. Revised Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention, p18. Geneva 1996.

IPCC (2001) *Climate Change 2001: A 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, U.K.

IPCC (2000) *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.* IPCC National Greenhouse Gas Inventories Programme Technical Support Unit, Kanagawa, Japan. Available online at <http://www.ipcc-nggip.iges.or.jp/gp/report.htm>.

IPCC (1999) *Aviation and the Global Atmosphere*. Intergovernmental Panel on Climate Change; Penner, J.E., et al., eds.; Cambridge University Press. Cambridge, U.K.

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, U.K.

IPCC/UNEP/OECD/IEA (1997) *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories.* Paris: Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Co-Operation and Development, International Energy Agency.

Jacobson, M.Z. (2001) Strong Radiative Heating Due to the Mixing State ofBlack Carbon in Atmospheric Aerosols. Nature. In press.

UNEP/WMO (2000) *Information Unit on Climate Change*. Framework Convention on Climate Change (Available on the internet at <http://www.unfccc.de>.)

WMO (1999) *Scientific Assessment of Ozone Depletion, Global Ozone Research and Monitoring Project-Report No. 44*, World Meteorological Organization, Geneva, Switzerland.