DRAFT Minnesota Greenhouse Gas Inventory and Reference Case Projections 1990-2020

Center for Climate Strategies
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Executive Summary

The Center for Climate Strategies (CCS) prepared this report for the Minnesota Climate Change Advisory Group (MCCAG) of the Office of the Governor of Minnesota. The inventory and forecast estimates serve as a starting point to assist the MCCAG and Technical Work Groups with an initial comprehensive understanding of Minnesota's current and possible future greenhouse gas (GHG) emissions, and thereby inform the upcoming identification and analysis of policy options for mitigating GHG emissions. The MCCAG and Technical Working Groups will review, discuss, and evaluate alternative approaches to the underlying assumptions for improving this draft GHG inventory and forecast. The inventory and forecast as well as this report will be revised to address the comments approved by the MCCAG. In addition, the forecast will be extended to the year 2025 to comport with the *Next Generation Energy Act of 2007* recently adopted by the State legislature and signed into law by the Governor of Minnesota.[1]

Minnesota's anthropogenic GHG emissions and anthropogenic sinks (carbon storage) were estimated for the period from 1990 to 2020. Historical GHG emission estimates (1990 through 2005, or most recent historical year) were developed using a set of generally accepted principles and guidelines for state GHG emissions estimates (both historical and forecasted), with adjustments by CCS as needed to provide Minnesota-specific data and inputs when it was possible to do so. The Minnesota Pollution Control Agency's (MPCA) GHG inventory for 1990 through 2004 provides state-specific estimates for all of the source sectors located within Minnesota. Therefore, historical emissions are based on the MPCA inventory. The initial reference case projections (2006-2020) are based on a compilation of various existing projections of electricity generation, fuel use, and other GHG-emitting activities, along with a set of transparent assumptions.

Table ES-1 provides a summary of historical (1990 to 2005) and reference case projection (2010 and 2020) GHG emissions for Minnesota. Activities in Minnesota accounted for approximately 151 million metric tons (MMt) of *gross*[2] carbon dioxide equivalent (CO_2e) emissions in 2005, an amount equal to about 2.1% of total US gross GHG emissions. Minnesota's gross GHG emissions are rising faster than those of the nation as a whole (gross emissions exclude carbon sinks, such as forests). Minnesota's gross GHG emissions increased about 31% from 1990 to 2005, while national emissions rose by only 16%. The growth in Minnesota's emissions from 1990 to 2005 is primarily associated with the electricity supply and transportation sectors.

Figure ES-1 illustrates the State's emissions per capita and per unit of economic output. On a per capita basis, Minnesotans emitted from 26 to 29 metric tons (Mt) of CO_2e annually from 1990 through 1995, which is higher than the national average of 24 MtCO_2e/yr. Per capita emissions increased to about 29 MtCO_2e/yr by 2005, while the per capita emissions for the US have remained relatively constant at 24 to 25 MtCO_2e/yr. As with the nation as a whole, economic growth exceeded emissions growth throughout the 1990 to 2005 period (leading to declining

[1] Minnesota Session Laws 2007 - Chapter 136, S.F. No. 145, http://www.revisor.leg.state.mn.us/bin/getbill.php?number=SF145&session=ls85&version=list&session_number=0&session_year=2007.
[2] Excluding GHG emissions removed due to forestry and other land uses and excluding GHG emissions associated with exported electricity. No emission sinks were identified for MN; therefore, gross emissions equal net emissions.

estimates of GHG emissions per unit of state product). From 1990 to 2005, emissions per unit of gross product dropped by 27% nationally and 25% in Minnesota.[3]

The principal source of Minnesota's GHG emissions is electricity consumption, accounting for 33% of Minnesota's gross GHG emissions in 2005. The next largest contributors are the transportation and the residential, commercial, and industrial (RCI) fuel use sectors that accounted for 25% and 21% of gross GHG emissions in 2005, respectively. The agriculture and waste sectors accounted for 13% and 3% of total gross GHG emissions in 2005, respectively. The fossil fuel production, industrial non-fuel use processes, and forestry categories together accounted for the remaining 4% of gross emissions in 2005.

Forestland emissions refer to the net carbon dioxide (CO_2) flux[4] from forested lands in Minnesota, which account for about 32% of the state's land area.[5] Minnesota's forests are estimated to be net sources of CO_2 emissions contributing about 3.3 $MMtCO_2e$ per year to total GHG emissions in Minnesota, accounting for about 2.2% of total gross GHG emissions in 2005. Changes in soil carbon due to cultivation practices are also estimated to be net GHG emissions sources of 4.1 $MMtCO_2e$ per year, accounting for about 2.7% of total gross GHG emissions in 2005.

As illustrated in Figure ES-2 and shown numerically in Table ES-1, under the reference case projections, Minnesota's gross GHG emissions continue to grow, and are projected to climb to about 184 $MMtCO_2e$ by 2020, reaching 59% above 1990 levels. As shown in Figure ES-3 emissions associated with electricity generation and imports to in-state demand is projected to be the largest contributor to future emissions growth, followed by emissions associated with the transportation and RCI fuel use sectors in Minnesota.

Some data gaps exist in this analysis, particularly for the reference case projections. Key tasks include review and revision of key emissions drivers that will be major determinants of Minnesota's future GHG emissions (such as the growth rate assumptions for electricity generation and consumption, transportation fuel use, and fossil fuel). Appendices A through H provide the detailed methods, data sources, and assumptions for each GHG sector. Also included are descriptions of significant uncertainties in emission estimates or methods and suggested next steps for refinement of the inventory.

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[3] Based on real gross domestic product by state (millions of chained 2000 dollars), available from the US Bureau of Economic Analysis, http://www.bea.gov/regional/gsp/. The national emissions used for these comparisons are based on 2004 emissions, http://www.epa.gov/climatechange/emissions/usinventoryreport.html.

[4] "Flux" refers to both emissions of CO_2 to the atmosphere and removal (sinks) of CO_2 from the atmosphere.

[5] Total forested acreage is 16.2 million acres in 2003; J. Smith, USFS, personal communication with S. Roe, CCS, April 2007. Acreage by forest type available from the USFS at: http://www.fs.fed.us/ne/global/pubs/books/epa/states/MN.htm. The total land area in Minnesota is 51 million acres http://www.50states.com/minnesot.htm.

Table ES-1. Minnesota Historical and Reference Case GHG Emissions, by Sector[a]

(Million Metric Tons CO_2e)	1990	2000	2005	2010	2020	Explanatory Notes for Projections
Electricity Consumption	**35.0**	**43.4**	**50.5**	**55.8**	**66.4**	
Coal	28.1	33.0	33.8	36.1	43.6	See electric sector assumptions
Natural Gas	0.5	0.6	1.0	0.3	0.6	in Appendix A
Oil	0.6	0.6	0.6	0.7	0.8	
MSW/Landfill Gas	0.8	0.8	0.8	0.8	0.8	
Biomass and Nuclear (CH_4 and N_2O)	0.005	0.006	0.008	0.008	0.006	
Net Imported Electricity	5.0	8.4	14.3	17.9	20.6	
Residential/Commercial/Industrial (RCI)	**25.6**	**31.3**	**32.0**	**35.0**	**38.6**	
Coal	2.0	3.3	2.5	2.7	2.9	US DOE regional projections
Natural Gas	14.3	17.6	17.5	19.9	22.7	US DOE regional projections
Oil	9.2	10.2	11.7	12.2	12.9	US DOE regional projections
Wood (CH_4 and N_2O)	0.2	0.2	0.2	0.2	0.2	US DOE regional projections
Transportation	**28.7**	**35.4**	**37.2**	**38.2**	**42.6**	
Onroad Gasoline	17.3	21.7	22.7	23.3	24.9	MNDOT VMT projections
Onroad Diesel	4.5	5.8	6.7	7.7	10.1	MNDOT VMT projections
Jet Fuel and Aviation Gasoline	3.4	5.0	5.0	4.6	5.2	FAA aircraft operations projections
Marine Vessels	2.7	2.0	1.9	1.8	1.8	Historical trends (1990-2004)
Rail and Other	*0.8*	*0.9*	*1.0*	*0.7*	*0.7*	US DOE regional projections
Fossil Fuel Industry	**1.4**	**2.1**	**2.2**	**2.6**	**3.5**	
Natural Gas Industry	1.4	2.1	2.2	2.6	3.5	US DOE projections and historic production
Industrial Processes	**0.6**	**1.4**	**1.6**	**1.8**	**2.5**	
Lime Manufacture (CO_2)	0.00	0.04	0.02	0.02	0.02	MN employment forecast for 2004-2014
Limestone Use (CO_2)	0.01	0.02	0.02	0.02	0.02	MN employment forecast for 2004-2014
Taconite Production (CO_2)	0.31	0.58	0.58	0.61	0.67	Historic production from 1999-2004
Peat Mining and Use (CO_2)	0.04	0.07	0.06	0.06	0.06	Assumed no growth
Ammonia Manufacture (CO_2)	0.03	0.00	0.00	0.00	0.00	No activity after 1996
ODS Substitutes (HFC, PFC, and SF_6)	0.00	0.41	0.65	0.93	1.60	EPA 2004 ODS cost study report
Semiconductor Manuf. (HFC, PFC)	0.00	0.03	0.02	0.01	0.01	National projections (US State Dept.)
Electric Power T & D (SF_6)	0.21	0.21	0.20	0.14	0.08	National projections (US State Dept.)
Medical (N_2O)	0.01	0.01	0.01	0.01	0.01	MN population growth
Waste Management	**5.5**	**5.0**	**5.0**	**4.9**	**4.7**	
Solid Waste Management	5.3	4.6	4.6	4.5	4.2	Historical trends (1995-2004)
Wastewater Management	0.3	0.3	0.3	0.4	0.4	MN population growth
Agriculture	**15.5**	**19.5**	**19.7**	**20.5**	**22.2**	
Enteric Ferment. and Manure Mgmt	5.5	6.2	6.2	6.0	5.9	Historical trends (1990-2004)
Agricultural Soils	5.6	9.0	9.2	10.0	11.8	Historical trends (1990-2004)
Ag. Burning, Rice Cult.	0.1	0.2	0.2	0.3	0.4	Historical trends (1990-2004)
Residential Fertilizer	0.06	0.08	0.09	0.10	0.11	Historical trends (1990-2004)
Urea Application and Liming	0.3	0.0	0.0	0.0	0.0	
Changes in Cultivation Practices**	4.1	4.1	4.1	4.1	4.1	All years held constant at 1997 levels
Forestry and Land Use**	3.3	3.3	3.3	3.3	3.3	All years based on current (2005) estimates from the USFS
Total Gross Emissions**	**115.7**	**141.4**	**151.5**	**162.0**	**183.8**	
increase relative to 1990		*22%*	*31%*	*40%*	*59%*	

[a] Totals may not equal exact sum of subtotals shown in this table due to independent rounding.
** Forest lands and changes in cultivation practices related to agricultural soils are net sources rather than sinks of emissions; therefore, gross and net emissions are the same.

Figure ES-1. Historical Minnesota and US Gross GHG Emissions, Per Capita and Per Unit Gross Product

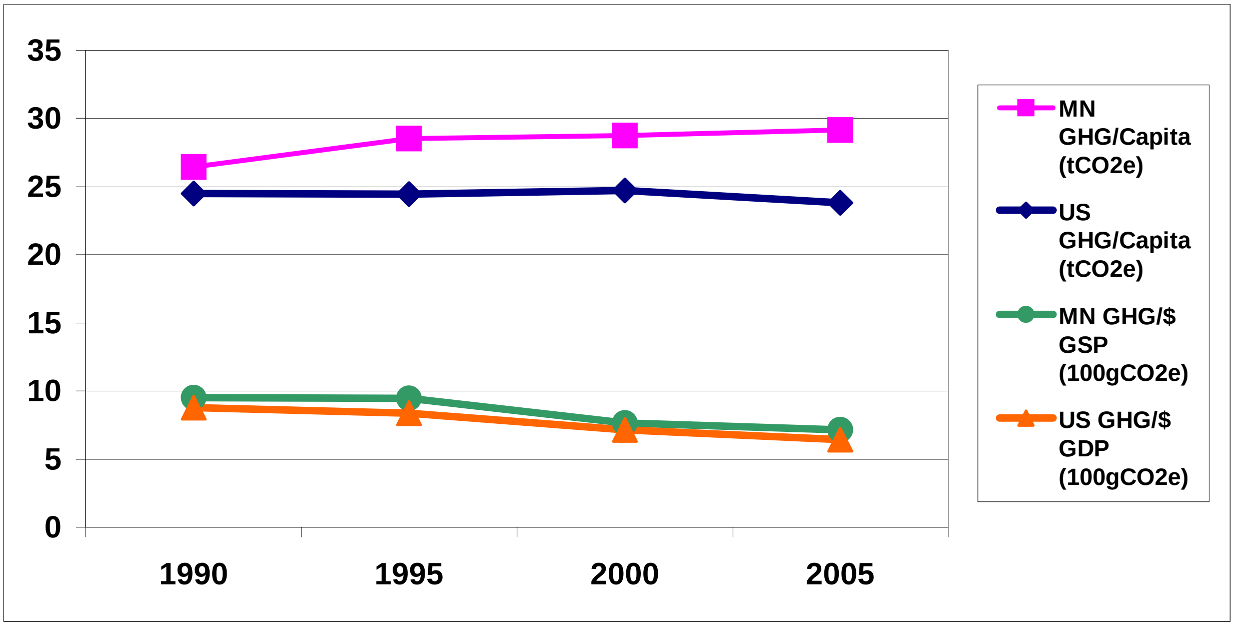
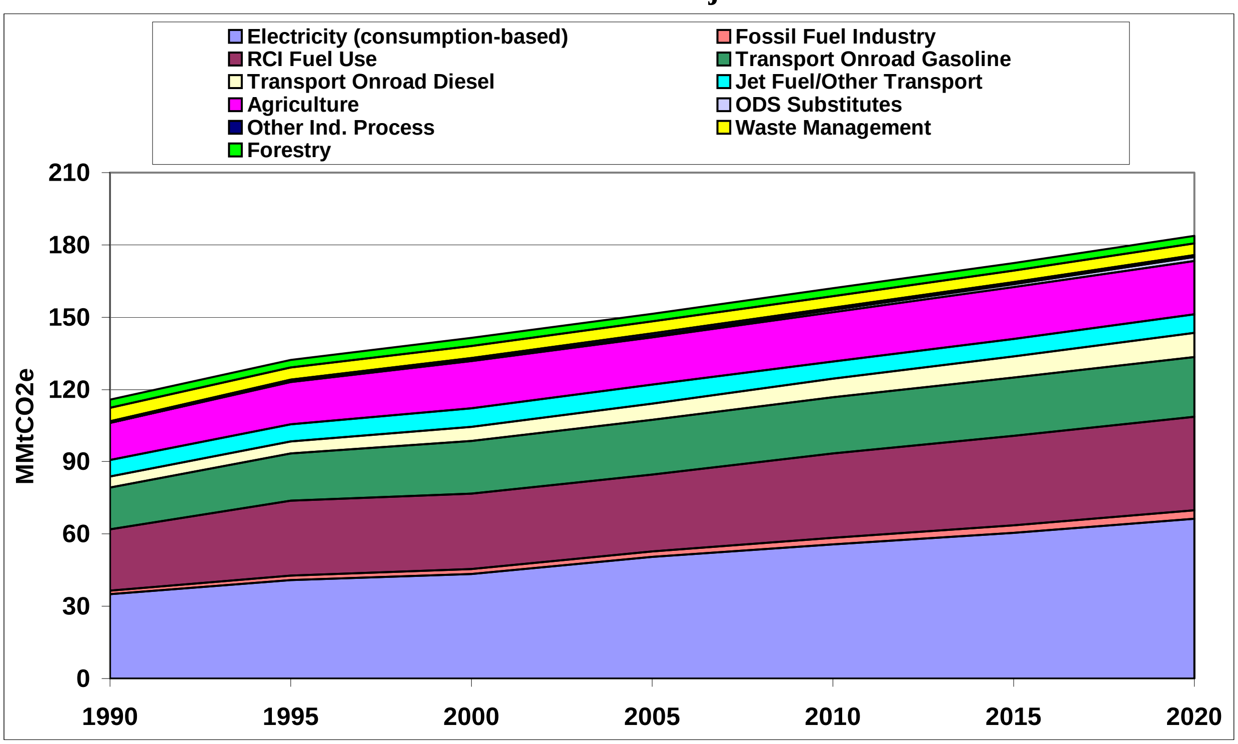
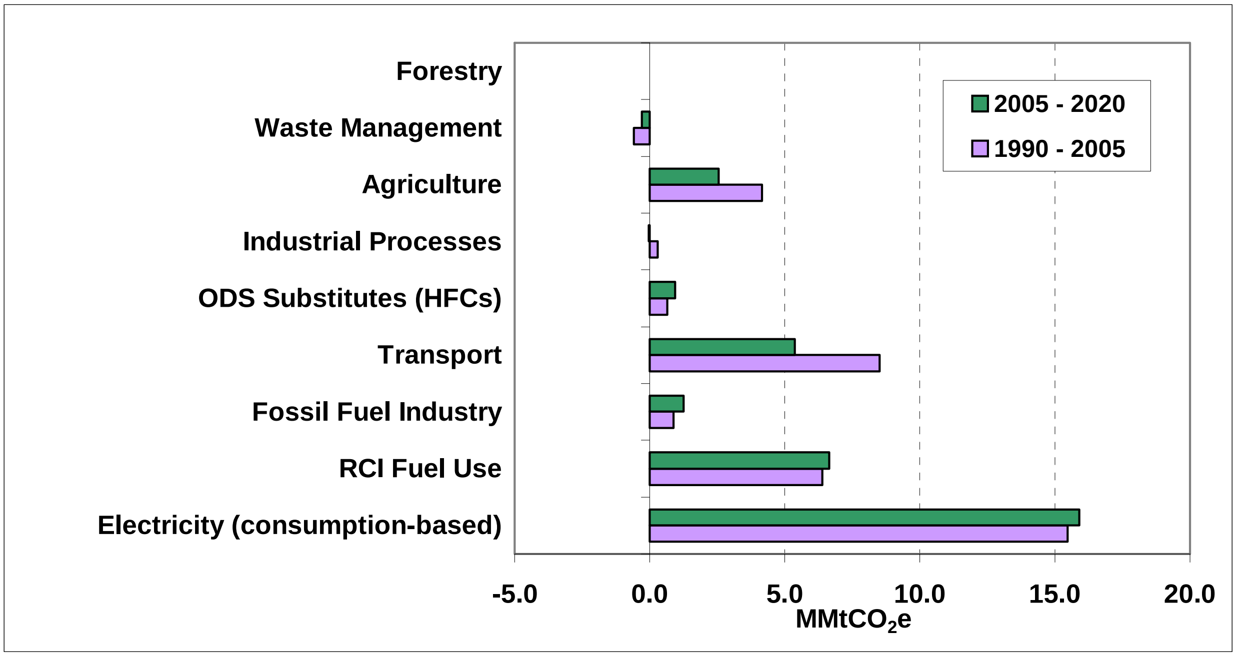


Figure ES-2. Minnesota Gross GHG Emissions by Sector, 1990-2020: Historical and Projected



* RCI – direct fuel use in residential, commercial, and industrial sectors. ODS – ozone depleting substance.

Figure ES-3. Sector Contributions to Gross Emissions Growth in Minnesota, 1990-2020: Reference Case Projections (MMtCO$_2$e Basis)



* RCI – direct fuel use in residential, commercial, and industrial sectors. ODS – ozone depleting substance. HFCs – hydrofluorocarbons.

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Acronyms and Key Terms

AEO2006 – EIA's Annual Energy Outlook 2006

Ag – Agriculture

bbls – Barrels

BC – Black Carbon*

Bcf – Billion cubic feet

BLM – United States Bureau of Land Management

BOC – Bureau of Census

BOD – Biochemical Oxygen Demand

BTU – British thermal unit

C – Carbon*

$CaCO_3$ – Calcium Carbonate

CCS – Center for Climate Strategies

CEC – Commission for Environmental Cooperation in North America

CFCs – chlorofluorocarbons*

CH_4 – Methane*

CO – Carbon Monoxide*

CO_2 – Carbon Dioxide*

CO_2e – Carbon Dioxide equivalent*

CRP – Federal Conservation Reserve Program

EC – Elemental Carbon*

EEZ – Exclusive Economic Zone

eGRID – US EPA's Emissions & Generation Resource Integrated Database

EIA – US DOE Energy Information Administration

EIIP – Emissions Inventory Improvement Program

FAA – Federal Aviation Administration

FAPRI – Food and Agricultural Policy Research Institute

FERC – Federal Energy Regulatory Commission

FIA – Forest Inventory Analysis

GHG – Greenhouse Gases*

GWh – Gigawatt-hour

GWP – Global Warming Potential*

HFCs – Hydrofluorocarbons*

IPCC – Intergovernmental Panel on Climate Change*

kWh – kilowatt-hour

LandGEM – Landfill Gas Emissions Model (US EPA)

LNG – Liquefied Natural Gas

LPG – Liquefied Petroleum Gas

MAPP – Mid-Continent Area Power Pool

MCCAG – Minnesota Climate Change Advisory Group

MDOC – Minnesota Department of Commerce

MN – Minnesota

MNDOT – Minnesota Department of Transportation

MPCA – Minnesota Pollution Control Agency

MSW – Municipal Solid Waste

Mt – Metric ton (equivalent to 1.102 short tons)

MMt – Million Metric tons

MW – Megawatt

MWh – Megawatt-hour

N – Nitrogen*

N_2O – Nitrous Oxide*

NO_2 – Nitrogen Dioxide*

NO_x – Nitrogen Oxides*

NEI – National Emissions Inventory

NEMS – National Energy Modeling System

NMVOCs – Nonmethane Volatile Organic Compounds*

O_3 – Ozone*

ODS – Ozone-Depleting Substances*

OM – Organic Matter*

PFCs – Perfluorocarbons*

PM – Particulate Matter*

ppb – parts per billion

ppm – parts per million

ppt – parts per trillion

PV – Photovoltaic

RCI – Residential, Commercial, and Industrial

RPA – Resources Planning Act Assessment

RPS – Renewable Portfolio Standard

SAR – Second Assessment Report*

SED – State Energy Data

SF_6 – Sulfur Hexafluoride*

SGIT – State Greenhouse Gas Inventory Tool

Sinks – Removals of carbon from the atmosphere, with the carbon stored in forests, soils, landfills, wood structures, or other biomass-related products.

TAR – Third Assessment Report*

T&D – Transmission and Distribution

TOG – Total Organic Gas

TWh – Terawatt-hours

UNFCCC – United Nations Framework Convention on Climate Change

US EPA – United States Environmental Protection Agency

US DOE – United States Department of Energy

USDA – United States Department of Agriculture

USFS – United States Forest Service

USGS – United States Geological Survey

VIUS – Vehicle Inventory and Use Survey

VMT – Vehicle-Miles Traveled

W/m^2 – Watts per Square Meter

WMO – World Meteorological Organization*

WW – Wastewater

* – See Appendix I for more information.

Acknowledgements

We appreciate all of the time and assistance provided by numerous contacts throughout Minnesota and at federal agencies. Thanks go to in particular the many staff at several Minnesota State Agencies for their inputs, and in particular to David Thornton and Peter Ciborowski of the Minnesota Pollution Control Agency (MPCA) and Edward Garvey of the Minnesota Department of Commerce (MDOC) who provided key guidance for this analytical effort.

The authors would also like to express their appreciation to Katie Bickel, Will Schroeer, Katie Pasko, and David Von Hippel of the Center for Climate Strategies (CCS) who provided valuable review comments during development of this report.

Summary of Preliminary Findings

Introduction

The Center for Climate Strategies (CCS) prepared this report for the Minnesota Climate Change Advisory Group (MCCAG) of the Office of the Governor of Minnesota. The inventory and forecast estimates serve as a starting point to assist the MCCAG and Technical Working Groups with an initial comprehensive understanding of Minnesota's current and possible future GHG emissions, and thereby inform the upcoming identification and analysis of policy options for mitigating GHG emissions. The MCCAG and Technical Working Groups will review, discuss, and evaluate alternative approaches to the underlying assumptions for improving this draft GHG inventory and forecast. The inventory and forecast as well as this report will be revised to address the comments approved by the MCCAG. In addition, the forecast will be extended to the year 2025 to comport with the *Next Generation Energy Act of 2007* recently adopted by the State legislature and signed into law by the Governor of Minnesota.[6]

This report presents initial estimates of base year and projected anthropogenic greenhouse gas (GHG) emissions and anthropogenic sinks (carbon storage) for the period from 1990 to 2020. These estimates are intended to assist the State with an initial, comprehensive understanding of current and possible future GHG emissions for Minnesota.

Historical GHG emission estimates (1990 through 2005, or most recent historical year)[7] were developed using a set of generally accepted principles and guidelines for State GHG emissions inventories, as described in the "Approach" section below, relying to the extent possible on Minnesota-specific data and inputs. The Minnesota Pollution Control Agency's (MPCA) GHG inventory for 1990 through 2004 provides state-specific estimates for all of the source sectors located within Minnesota. Therefore, historical emissions are based on the MPCA inventory. The initial reference case projections (2006-2020) are based on a compilation of various existing projections of electricity generation, fuel use, and other GHG-emitting activities, along with a set of simple, transparent assumptions described in the appendices of this report.

This report covers the six gases included in the US Greenhouse Gas Inventory: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Emissions of these GHGs are presented using a common metric, CO_2 equivalence (CO_2e), which indicates the relative contribution of each gas to global average radiative forcing on a Global Warming Potential- (GWP-) weighted basis.

It is important to note that the preliminary emissions estimates reflect the *GHG emissions associated with the electricity sources used to meet Minnesota's demands*, corresponding to a consumption-based approach to emissions accounting (see "Approach" section below). Another way to look at electricity emissions is to consider the *GHG emissions produced by electricity*

[6] Minnesota Session Laws 2007 - Chapter 136, S.F. No. 145, http://www.revisor.leg.state.mn.us/bin/getbill.php?number=SF145&session=ls85&version=list&session_number=0&session_year=2007.
[7] The last year of available historical data varies by sector; ranging from 2000 to 2005.

generation facilities in the State. This report covers both methods of accounting for emissions, but for consistency, all total results are reported as *consumption-based*.

Minnesota Greenhouse Gas Emissions: Sources and Trends

Table 1 provides a summary of GHG emissions estimated for Minnesota by sector for the years 1990, 2000, 2005, 2010, and 2020. Details on the methods and data sources used to construct these draft estimates are provided in the appendices to this report**.** In the sections below, we discuss GHG emission sources (positive, or *gross*, emissions) and sinks (negative emissions) separately in order to identify trends, projections, and uncertainties clearly for each.

This next section of the report provides a summary of the historical emissions (1990 through 2005) followed by a summary of the reference-case projection-year emissions (2006 through 2020) and key uncertainties. We also provide an overview of the general methodology, principles, and guidelines followed for preparing the inventories. Appendices A through H provide the detailed methods, data sources, and assumptions for each GHG sector.

Appendix I provides background information on GHGs and climate-forcing aerosols.

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(Million Metric Tons CO_2e)	1990	2000	2005	2010	2020	Explanatory Notes for Projections
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Historical Emissions

Overview

Preliminary analyses suggest that in 2005, activities in Minnesota accounted for approximately 151 million metric tons (MMt) of CO_2e emissions, an amount equal to about 2.1% of total US GHG emissions. Minnesota's gross GHG emissions are rising faster than those of the nation as a whole (gross emissions exclude carbon sinks, such as forests). Minnesota's gross GHG emissions increased 31% from 1990 to 2005, while national emissions rose by only 16% during the same period.

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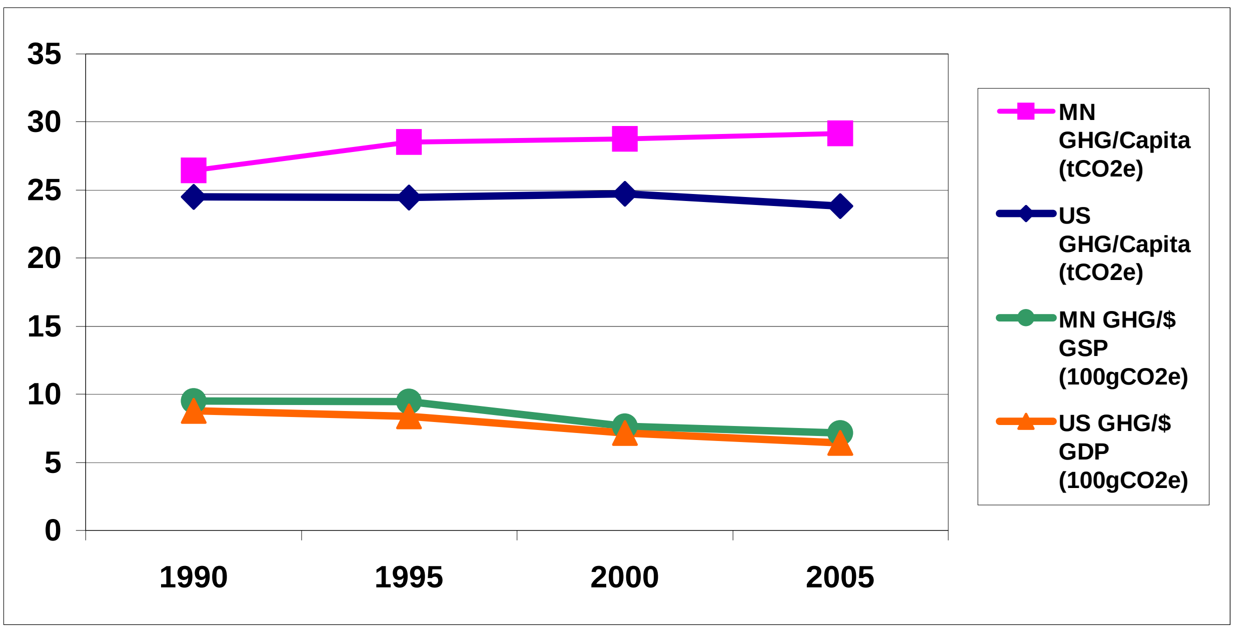
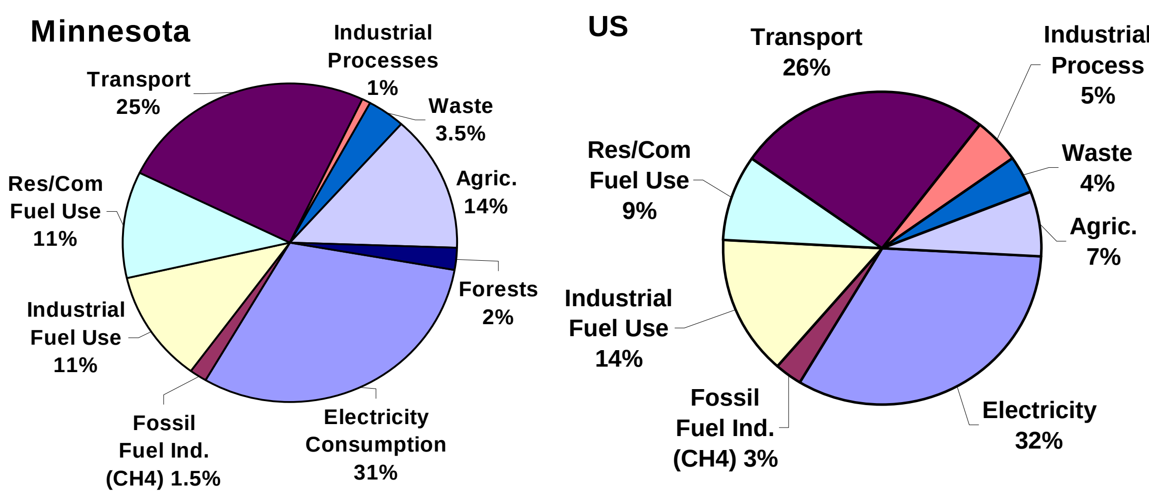
Figure 1. Historical Minnesota and US Gross GHG Emissions, Per Capita and Per Unit Gross Product



[8] Based on real gross domestic product by state (millions of chained 2000 dollars), available from the US Bureau of Economic Analysis, http://www.bea.gov/regional/gsp/. The national emissions used for these comparisons are based on 2004 emissions, http://www.epa.gov/climatechange/emissions/usinventoryreport.html.

As shown in Figure 2, the electricity supply and transportation sectors are the principle sources of Minnesota's GHG emissions, accounting for 31% and 25% of Minnesota's gross GHG emissions in 2000, respectively. The next largest contributor is the residential, commercial, and industrial (RCI) fuel use sector, accounting for 22% of gross GHG emissions in 2000. The agriculture sector, which includes emissions from enteric fermentation, manure management, fertilizer, crops, agricultural burning, and soil carbon fluxes due to changes in cultivation practices, contributed 14% of gross GHG emissions in 2000. The forestry and land use sector is a net sink in many states, but this sector is a net emitter in Minnesota, accounting for 2% of gross GHG emissions in 2000. The fossil fuel production, waste, and industrial non-fuel use processes categories together accounted for the remaining 6% of gross emissions in 2000.

Figure 2. Gross GHG Emissions by Sector, 2000: Minnesota and US



Note: At a national level, forests act as a net sink of CO_2; therefore, they do not show up in the above graph of gross US emissions sources.

Forestland emissions refer to the net carbon dioxide (CO_2) flux[9] from forested lands in Minnesota, which account for about 32% of the state's land area.[10] The dominant forest type in Minnesota is Aspen-Birch which makes up about 41% of forested lands. Another common forest type is Spruce-Fir at 27% of forested land. All other forest types make up less than 10% each of the State's forests.

Based on US Forest Service (USFS) data, Minnesota's forests are estimated to be a net source of CO_2 emissions contributing about 3.3 MMtCO_2e per year to total GHG emissions in Minnesota, which accounts for about 2% of Minnesota's total gross GHG emissions in 2000. Soil carbon fluxes resulting from changes in cultivation practices are also estimated to be a net GHG emissions source of 4.1 MMtCO_2e per year, accounting for about 2.9% of total gross GHG

[9] "Flux" refers to both emissions of CO_2 to the atmosphere and removal (sinks) of CO_2 from the atmosphere.
[10] Total forested acreage is 16.2 million acres in 2003; J. Smith, USFS, personal communication with S. Roe, CCS, April 2007. Acreage by forest type available from the USFS at: http://www.fs.fed.us/ne/global/pubs/books/epa/states/MN.htm. The total land area in Minnesota is 51 million acres (http://www.50states.com/minnesot.htm).

emissions in 2005. Due to uncertainties in projecting the future levels of net CO_2 emissions from the State's forests and agricultural lands, the projected emissions were held constant at current levels for both of these sources.

A Closer Look at the Two Major Sources: Electricity Supply and Transportation

Electricity Supply Sector

Minnesota's electricity has been characterized primarily by a mix of coal and nuclear fuels. From 1990 through 2005, electricity generated by coal-fired power plants in Minnesota accounted for 64% to 68% of total in-state generation. Nuclear power accounted for 25% to 30% of total in-state generation (depending on the year) from 1990 through 2005. The remaining in-state generation came from a mix of natural gas, oil, refuse derived fuel, and hydroelectric facilities. The consumption of imported electricity has increased from 12% of total Minnesota demand in 1990 to 27% of total Minnesota demand in 1995.[11]

As shown in Figure 2, electricity consumption accounted for about 31% of Minnesota's gross GHG emissions in 2000 (about 43.4 $MMtCO_2e$), which is similar to the national average share of emissions from electricity consumption (32%).[12] The GHG emissions associated with Minnesota's electricity sector increased by 15.5 $MMtCO_2e$ between 1990 and 2005, accounting for about 43% of the state's net growth in gross GHG emissions in this time period.

In 2005, emissions associated with Minnesota's electricity consumption (50.5 $MMtCO_2e$, see Table 1) were higher than those associated with electricity production (36.2 $MMtCO_2e$, see Appendix A). The higher level for consumption-based emissions reflects GHG emissions associated with net imports of electricity to meet the State's electricity demand.[13] Electricity sales for 2005 through 2020 indicate that Minnesota will remain a net importer of electricity. For the period covering 2005 through 2020, the reference case projection assumes that production-based emissions associated with electricity generated in-state will increase by about 9.6 $MMtCO_2e$, while emissions associated with imported electricity will increase by about 6.3 $MMtCO_2e$.

It is important to note that these GHG emissions estimates reflect the *GHG emissions associated with the electricity sources used to meet Minnesota demands,* corresponding to a consumption-based approach to emissions accounting. Another way to look at electricity emissions is to consider the *GHG emissions produced by electricity generation facilities in the State* (see "Approach" section below). While we estimate emissions associated with both electricity production and consumption, unless otherwise indicated, tables, figures, and totals in this report reflect electricity consumption-based emissions. The consumption-based approach can better reflect the emissions (and emissions reductions) associated with activities occurring in the State,

[11] Percentages are based on gross generation (including plant fuel use and line losses) associated with imports relative to total gross generation to meet Minnesota demand.
[12] For the US as a whole, there is relatively little difference between the emissions from electricity use and emissions from electricity production, as the US imports only about 1% of its electricity, and exports far less. Minnesota's situation is different, since it is a net electricity importer.
[13] Estimating the emissions associated with electricity use requires an understanding of the electricity sources (both in-state and out-of-state) used by utilities to meet consumer demand. The current estimates reflect some very simple assumptions, as described in Appendix A.

particularly with respect to electricity use (and efficiency improvements), and is particularly useful for policy-making. Under this approach, emissions associated with electricity imported from other States would need to be excluded in those States' accounts in order to avoid double-counting.

Transportation Sector

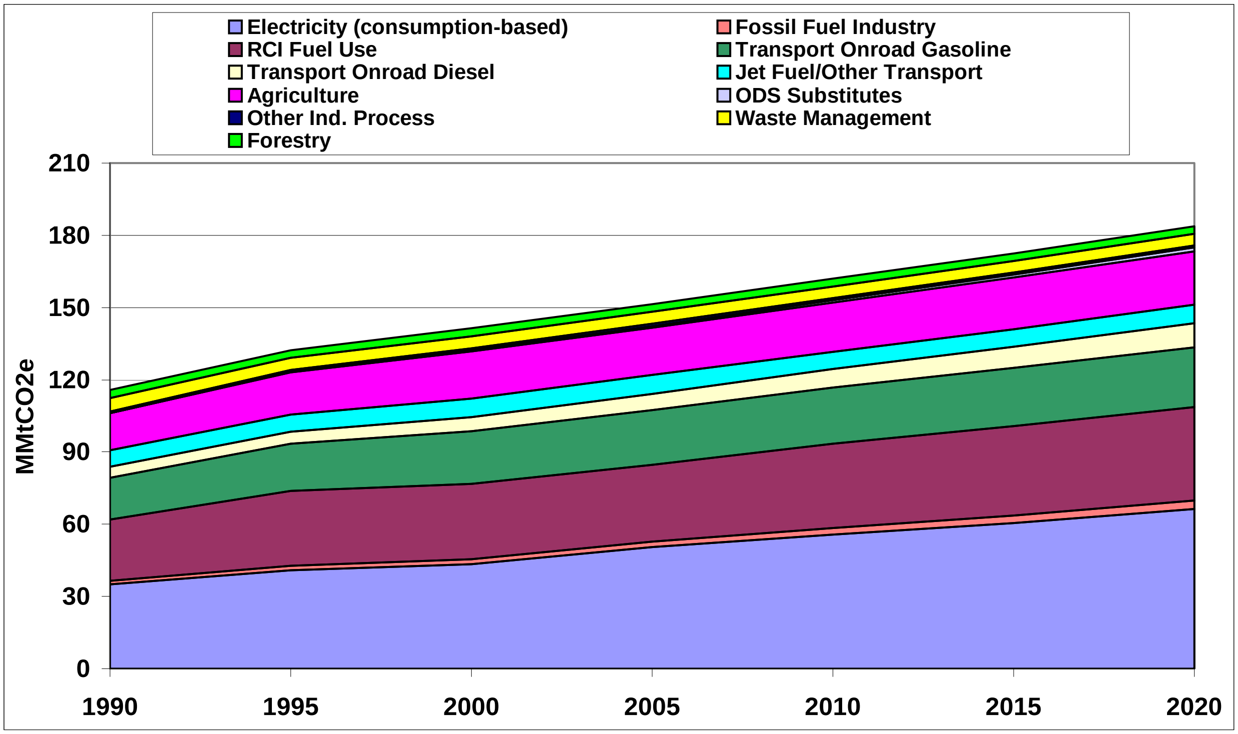
As shown in Figure 2, the transportation sector accounted for about 25% of Minnesota's gross GHG emissions in 2000 (about 35.4 $MMtCO_2e$), which was just slightly lower than the national average share of emissions from transportation fuel consumption (26%). The GHG emissions associated with Minnesota's transportation sector increased by 8.5 $MMtCO_2e$ between 1990 and 2005, accounting for about 24% of the State's net growth in gross GHG emissions in this time period.

From 1990 through 2005, GHG emissions from transportation fuel use have risen steadily at an average rate of about 1.7% annually. In 2005, onroad gasoline vehicles accounted for about 61% of transportation GHG emissions. Onroad diesel vehicles accounted for another 18% of emissions, and aviation fuels for roughly 13%. Emissions associated with marine vessels accounted for 5% of transportation emissions in 2005. Rail and other sources (natural gas- and liquefied petroleum gas- (LPG-) fueled-vehicles used in transport applications) accounted for the remaining 3% of transportation emissions. As a result of Minnesota's population and economic growth and an increase in total vehicle miles traveled (VMT) during the 1990s, onroad gasoline use grew 31% between 1990 and 2005. Meanwhile, onroad diesel use rose 49% during that period, suggesting an even more rapid growth in freight movement within or across the State. Aviation fuel use grew by about 30% from 1990-2005.

Reference Case Projections

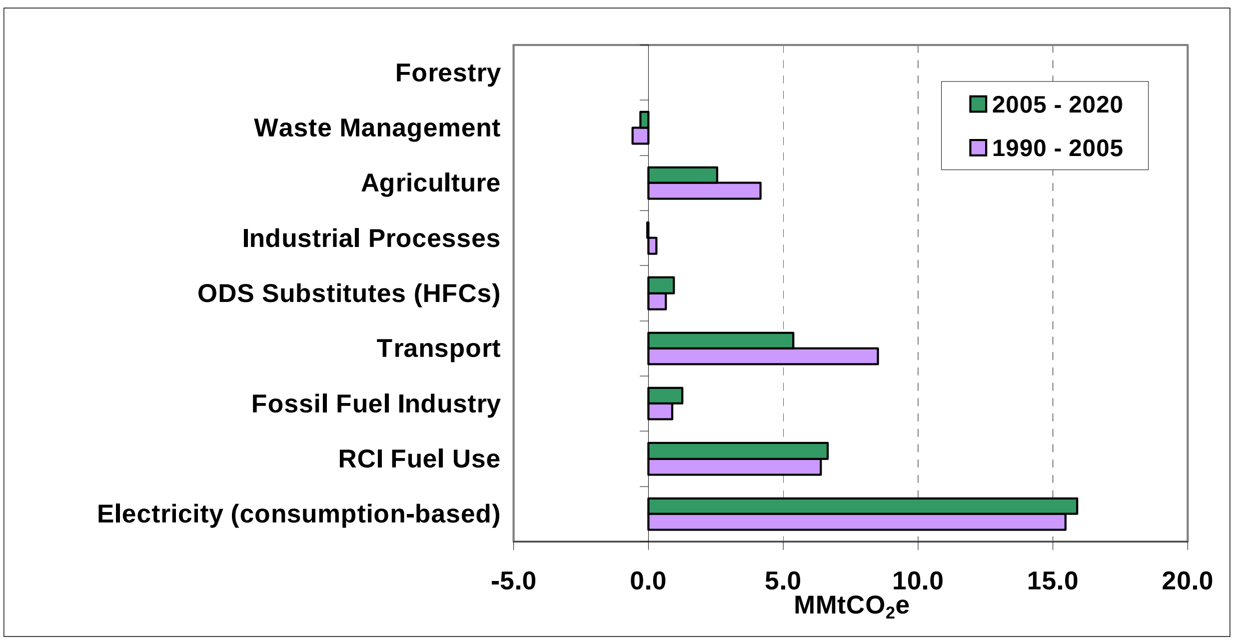
Relying on a variety of sources for projections, as noted below and in the appendices, we developed a simple reference case projection of GHG emissions through 2020. As illustrated in Figure 3 and shown numerically in Table 1, under the reference case projections, Minnesota's gross GHG emissions continue to grow steadily, climbing to about 184 $MMtCO_2e$ by 2020, 59% above 1990 levels. Emissions associated with electricity generation and imports to meet in-state demand is projected to be the largest contributor to future emissions growth, followed by emissions associated with the transportation and RCI fuel use sectors (see Figure 4). Table 2 summarizes the growth rates that drive the growth in the Minnesota reference case projections as well as the sources of these data.

Figure 3. Minnesota Gross GHG Emissions by Sector, 1990-2020: Historical and Projected



* RCI – direct fuel use in residential, commercial, and industrial sectors. ODS – ozone depleting substance.

Figure 4. Sector Contributions to Gross Emissions Growth in Minnesota, 1990-2020: Historic and Reference Case Projections (MMtCO$_2$e Basis)



RCI – direct fuel use in residential, commercial, and industrial sectors. ODS – ozone depleting substance.
HFCs – hydrofluorocarbons.

Table 2. Key Annual Growth Rates for Minnesota, Historical and Projected

	1990-2005	2005-2020	Sources
Population[a]	1.15%	0.9%	Minnesota Department of Administration, Office of Geographic and Demographic Analysis, State Demographic Center
Employment[a] **Goods** **Services**	 NA[b] NA	 0.4% 1.5%	Minnesota Department of Employment and Economic Development
Electricity Sales	2.27%	1.72%	Inventory: EIA's Electric Utility Sales data (http://www.eia.doe.gov/cneaf/electricity/page/sales_revenue.xls) Forecast: Averaged projected sales growth as per Certificate of Need Applications for six Minnesota utilities (Xcel Energy, Otter Tail Power, Central Minnesota Municipal Power Agency, Great River Energy, Missouri River Energy Services, and Southern Minnesota Municipal Power Agency)
Vehicle Miles Traveled	2.7%	2.0%	Minnesota Department of Transportation.

[a] For the RCI fuel consumption sectors, population and employment projections for Minnesota were used together with US DOE EIA's Annual Energy Outlook 2006 (AEO2006) projections of changes in fuel use for the EIA's US West North Central region on a per capita basis for the residential sector, and on a per employee basis for the commercial and industrial sectors. For instance, growth in Minnesota's residential natural gas use is calculated as the Minnesota population growth times the change in per capita natural gas use for the West North Central region.

[b] NA – Not available; historical employment data for South Carolina for the goods producing and services providing sectors could not be identified during development of this report.

Approach

The principle goal of compiling the inventories and reference case projections presented in this document is to provide the State of Minnesota with a general understanding of Minnesota's historical, current, and projected (expected) GHG emissions. The following explains the general methodology and the general principles and guidelines followed during development of these GHG inventories for Minnesota.

General Methodology

We prepared this analysis in close consultation with Minnesota agencies, in particular, with the MPCA staff. The overall goal of this effort is to provide simple and straightforward estimates, with an emphasis on robustness, consistency, and transparency. As a result, we rely on reference forecasts from best available State and regional sources where possible. Where reliable existing forecasts are lacking, we use straightforward spreadsheet analysis and constant growth-rate extrapolations of historical trends rather than complex modeling.

In most cases, we follow the same approach to emissions accounting for historical inventories used by the US EPA in its national GHG emissions inventory[14] and its guidelines for States.[15]

[14] 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.
[15] http://yosemite.epa.gov/oar/globalwarming.nsf/content/EmissionsStateInventoryGuidance.html.

These inventory guidelines were developed based on the guidelines from the IPCC, the international organization responsible for developing coordinated methods for national GHG inventories.[16] The inventory methods provide flexibility to account for local conditions. The key sources of activity and projection data used are shown in Table 3. Table 3 also provides the descriptions of the data provided by each source and the uses of each data set in this analysis.

Table 3. Key Sources for Minnesota Data, Inventory Methods, and Growth Rates

Source	Information provided	Use of Information in this Analysis
Minnesota Pollution Control Agency (MPCA)	In-state GHG inventory for all sectors from 1990 through 2004.	Basis for in-state (production-based) GHG inventory.
US EPA	The US EPA methods provided in the Volume VIII document series published by the Emissions Inventory Improvement Program (EIIP) (http://www.epa.gov/ttn/chief/eiip/techreport/volume08/index.html), and the US EPA's State Greenhouse Gas Inventory Tool (SGIT)	Where not indicated otherwise, US EPA methods and emission factors were used to calculate historical emissions.
US DOE Energy Information Administration (EIA) State Energy Data (SED)	EIA SED provides energy use data in each State, annually to 2004 for all fuels.	EIA SED is the source for most energy use data. We also use the more recent data for electricity and natural gas consumption (including natural gas for vehicle fuel) from EIA website for years after 2004. Emission factors from US EPA SGIT are used to calculate energy-related emissions.
EIA AEO2006	EIA AEO2006 projects energy supply and demand for the US from 2003 to 2030. Energy consumption is estimated on a regional basis. Minnesota is included in the West North Central Census region (IA, KS, MN, MO, ND, NE, and SD).	EIA AEO2006 is used to project changes in per capita (residential), per employee (commercial/industrial).
US Forest Service	Data on forest carbon stocks for multiple years.	Data are used to calculate CO_2 flux over time (terrestrial CO_2 sequestration in forested areas).
USDS National Agricultural Statistics Service (NASS)	USDA NASS provides data on crops and livestock.	Crop production data used to estimate agricultural residue and agricultural soils emissions; livestock population data used to estimate manure and enteric fermentation emissions.

[16] http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

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 allow open review and opportunities for additional revisions later based on input from others. In addition, we will report key uncertainties where they exist.
- **Consistency:** To the extent possible, the inventory and projections will be designed to be externally consistent with current or likely future systems for State and national GHG emission reporting. We have used the EPA tools for State inventories and projections as a starting point. These initial estimates were then augmented and/or revised as needed to conform with State-based inventory and base-case projection needs. For consistency in making reference case projections, we define reference case actions for the purposes of projections as those *currently in place or reasonably expected to be put in place over the time period of analysis*.
- **Priority of Existing State and Local Data Sources:** In gathering data and in cases where data sources conflicted, we placed highest priority on local and State data and analyses, followed by regional sources, with national data or simplified assumptions such as constant linear extrapolation of trends used as defaults where necessary.
- **Priority of Significant Emissions Sources:** In general, activities with relatively small emissions levels may not be reported with the same level of detail as other activities.
- **Comprehensive Coverage of Gases, Sectors, State Activities, and Time Periods.** This analysis aims to comprehensively cover GHG emissions associated with activities in Minnesota. It covers all six GHGs covered by US and other national inventories: CO_2, CH_4, N_2O, SF_6, HFCs, PFCs, and BC. The inventory estimates are for the year 1990, with subsequent years included up to most recently available data (typically 2002 to 2005), with projections to 2010 and 2020.
- **Use of Consumption-Based Emissions Estimates:** To the extent possible, we estimated emissions that are caused by activities that occur in Minnesota. For example, we reported emissions associated with the electricity consumed in Minnesota. The rationale for this method of reporting is that it can more accurately reflect the impact of State-based policy strategies such as energy efficiency on overall GHG emissions, and it resolves double-counting and exclusion problems with multi-emissions issues. This approach can differ from how inventories are compiled, for example, on an in-state production basis, in particular for electricity.

For electricity, we estimate, in addition to the emissions due to fuels combusted at electricity plants in the State, the emissions related to electricity *consumed* in Minnesota. This entails accounting for the electricity sources used by Minnesota utilities to meet consumer demands. As this analysis is refined in the future, one could also attempt to estimate other sectoral emissions on a consumption basis, such as accounting for emissions from transportation fuel used in Minnesota, but purchased out-of-state. In some cases, this can require venturing into the relatively complex terrain of life-cycle analysis. In general, we recommend considering a consumption-based approach where it will significantly improve the estimation of the emissions impact of potential mitigation strategies. For example re-use, recycling, and source reduction can lead to emission reductions resulting from lower energy requirements for material production (such as paper, cardboard, and aluminum), even though production of those materials, and emissions associated with materials production, may not occur within the State.

Details on the methods and data sources used to construct the inventories and forecasts for each source sector are provided in the following appendices:

- Appendix A. Electricity Use and Supply
- Appendix B. Residential, Commercial, and Industrial (RCI) Fuel Combustion
- Appendix C. Transportation Energy Use
- Appendix D. Industrial Processes
- Appendix E. Fossil Fuel Production Industry
- Appendix F. Agriculture
- Appendix G. Waste Management
- Appendix H. Forestry

Appendix I provides additional background information from the US EPA on GHGs and global warming potential values.

Appendix A. Electricity Supply

This appendix describes the data sources, key assumptions, and the methodology used to develop an inventory of greenhouse gas (GHG) emissions over the 1990-2005 period associated with meeting electricity demand in Minnesota. It also describes the data sources, key assumptions, and methodology used to develop a forecast of GHG emissions over the 2006-2020 period associated with meeting electricity demand in the state. Specifically, the following topics are covered in this Appendix:

- *Data sources:* This section provides an overview of the data sources that were used to develop the inventory and forecast, including publicly accessible websites where this information can be obtained and verified.
- *Greenhouse Gas Inventory methodology:* This section provides an overview of the methodological approach used to develop of the MN GHG inventory for the electric supply sector.
- *Greenhouse Gas Forecast Methodology – Reference Case:* This section provides an overview of methodological approach used to develop the MN GHG Reference Case forecast for the electric supply sector. This forecast does not include the impact of RPS (Renewable Portfolio Standard) legislation.
- *Greenhouse Gas Forecast Methodology – Alternative Reference Case:* This section provides an overview of methodological approach used to develop the MN GHG Alternative Reference Case forecast for the electric supply sector. This forecast includes the impact of RPS legislation.
- *Greenhouse Gas Inventory Results:* This section provides an overview of key results of the MN GHG inventory for the electric supply sector.
- *Greenhouse Gas Forecast Results:* This section provides an overview of key results of the MN GHG forecast for the electric supply sector. The results of both Reference Cases are presented.

Data Sources

We considered several sources of information in the development of the inventory and forecast of carbon dioxide equivalent (CO_2e) emissions from MN power plants. These are briefly summarized below:

- *GHGemitsum07.xls:* This is an inventory of GHG emissions in Minnesota for all sectors over the period 1965 through and including 2005. Electric sector data is provided in worksheets "Energy Use and CO_2" and "Electric sector indicators".[17] The information in these worksheets provides a production-based estimate of GHG emissions (i.e., associated with electric generation from electric power stations located in MN) from the electric sector. A consumption-based estimate of GHG emissions (i.e., associated with electricity consumption in MN) was not prepared.

[17] This spreadsheet was prepared by Peter Ciborowski of the MPCA.

- *2005 EIA-906/920 Monthly Time Series data.* This is a database file available from the Energy Information Administration (EIA) of the US Department of Energy. The information in the database is based on information collected from utilities in Forms EIA-906/920 and EIA-860 for the forecast Base Year of 2005. Data was extracted for MN as well as neighboring states IA, ND, NE, SD, and MT. Data from these forms provide, among other things, fuel consumption and net generation in power stations located in these states for 2005 by plant type. This information can be accessed from http://www.eia.doe.gov/cneaf/electricity/page/eia906_920.html.

- *MN Certificate of Need applications.* These are submissions by major utilities in MN concerning the construction of Transmission Lines in Western Minnesota. These sources provide electricity sale and net generation forecasts up through and including 2020 for the following utilities operating in MN: Central Minnesota Municipal Power Agency, Great River Energy, Missouri River Energy Services, Otter Tail Power, Southern Minnesota Municipal Power Agency, and Xcel (note that the Certificate of Need for Excel was in reference to the Chisago County 115/161 KV transmission line). This information can be accessed directly from http://www.puc.state.mn.us/.

- *Annual Energy Outlook 2007.* This is an output of an EIA analysis using the National Energy Modeling System (NEMS), a model that forecasts electric expansion/electricity demand in the USA. In particular, regional outputs for Mid-Continent Area Power Pool (MAPP) region was used. The MAPP region is the one in which MN is located (see map at right). The MAPP results include forecasts of gross generation, net generation, combustion efficiency, total sales, and exports/imports through the year 2025. This information is available in supplemental tables that can be accessed directly from http://www.eia.doe.gov/oiaf/aeo/supplement/index.html. The sources of the above map is http://www.bydesign.com/fossilfuels/crisis/html/NERC_regions_map.html.

North American Electric Reliability Council Region Map—(US)

- *Monthly Cost and Quality of Fuels for Electric Plants.* This information is available from the Federal Energy Regulatory Commission (FERC). The database relies on information collected from utilities in the FERC-423 form. It was used to determine the share of coal type (i.e., whether bituminous, sub-bituminous, anthracite, or lignite) as well as the coal quantity consumed in MN power plants over the period 1990-2005. It can be accessed directly from http://www.eia.doe.gov/cneaf/electricity/page/ferc423.html.

- *State Electricity Profiles.* This information is available from the EIA. The database compiles capacity, net generation, and total retail electricity sales by state. It was used to determine total sales of electricity across all sectors in the Base Year 2005. It can be accessed directly from http://www.eia.doe.gov/cneaf/electricity/st_profiles/e_profiles_sum.html.

- *Energy conversion factors.* This is based on Table Y-2 of Appendix Y in the USEPA's 2003 GHG Inventory for the USA. The table is entitled "Conversion Factors to Energy Units (Heat Equivalents)". This information can be accessed directly from the following website: http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/LHOD5MJTCL/$File/2003-final-inventory_annex_y.pdf.
- *Fuel combustion oxidation factors:* This is based on Appendix A of the USEPA's 2003 US GHG inventory for the USA. This information can be accessed directly from: http://www.epa.gov/climatechange/emissions/downloads06/06_Annex_Chapter2.pdf.
- *Carbon dioxide, methane, and nitrous oxide emission factors.* For all fuels except MSW, these emission factors are based on Appendix A of the USEPA's 2003 GHG inventory for the USA. This information can be accessed directly from: http://www.epa.gov/climatechange/emissions/downloads06/06_Annex_Chapter2.pdf. For MSW, emission factors are based on the Energy Information Administration, Office of Integrated Analysis and Forecasting, Voluntary Reporting of Greenhouse Gases Program, Table of Fuel and Energy Source: Codes and Emission Coefficients. This information can be accessed directly from http://www.eia.doe.gov/oiaf/1605/coefficients.html.
- *Global warming potentials:* These are based on values proposed by the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report. This information can be accessed directly from http://www.ipcc.ch/pub/reports.htm.

Greenhouse Gas Inventory Methodology

The methodology used to the develop the MN inventory of GHG emissions associated with electricity production and consumption is based on methods developed by the IPCC and used by the USEPA in the development of the US GHG inventory. There are four fundamental premises of the GHG inventory developed for MN, as briefly described below:

- The GHG inventory should be estimated based on both the production and consumption of electricity. Developing the production estimate involves tallying up the GHG emissions associated with the operation of power plants physically located in MN, regardless of ownership. Developing the consumption estimate involves tallying up the GHG emissions associated with consumption of electricity in MN, regardless of where the electricity is produced. As MN is a net importer of electricity, these estimates will be different.
- The GHG inventory should be estimated based on emissions at the point of electric generation only. That is, GHG emissions associated with upstream fuel cycle process such as primary fuel extraction, transport to refinery/processing stations, refining, beneficiation, and transport to the power station are not included.
- As an approximation, it was assumed that all power generated in MN was consumed in MN. In fact, some of the power generated in MN is exported. However, given the similarity in the average carbon intensity of MN power stations and that of power stations in the surrounding MAPP region, the potential error associated with this simplifying assumption is small, on the order of 2%, plus or minus.

- Several key assumptions were used for making projections of CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions for the electric sector out to 2020. These are summarized in Table A1.

Table A1. Key Assumptions used in the MN GHG Forecast

Key Assumptions	2005	2020	Average Annual Growth / Change (%)
MN electricity demand (GWh)	66,019	85,206	1.72%
MN Gross generation (GWh)	50,625	66,372	1.82%
MN utility sales to meet MN demand (GWh)	48,164	60,613	1.54%
Import sales from MAPP region (GWh)	17,855	24,593	2.16%
Gross generation from MAPP imports (GWh)	18,767	26,930	2.44%
Power plant heat rate (BTU/kWh)			
Coal	10,942	10,348	-0.37%
Nuclear	10,351	10,351	0.00%
Natural Gas	11,190	7,487	-2.64%
Oil	10,379	9,743	-0.42%
Municipal Solid Waste (MSW)	18,505	18,505	0.00%
Biomass	17,763	20,715	1.03%
Landfill Gas (LFG)	11,928	7,981	-2.64%
Wind	9,916	9,916	0.00%
Hydroelectric	9,916	9,916	0.00%
Losses (%)			
From on-site usage	0.83%	0.29%	-6.88%
From T&D and on-site usage	4.86%	8.68%	3.94%

There were several steps in the methodology for the development of the electric sector GHG inventory for the period 1990-2005. These are briefly outlined below:

- Determine the coal quality used in MN power stations (i.e., share of anthracite, bituminous, lignite, sub-bituminous, and coal wastes used).
- Determine gross annual primary energy consumption by MN power stations by plant and fuel type.
- Determine gross annual generation associated with net power imports to satisfy MN electricity demand.
- Multiply gross annual primary energy consumption by MN power stations by CO_2e emission factors. This provides an estimate of the MN GHG inventory on a production basis.
- Multiply annual gross generation associated with net power imports by the carbon emission intensity (in units of tonnes CO_2-equivalent per megawatt-hour [CO_2e/MWh]) of the MAPP region. This provides an estimate of the additional GHG emissions associated with meeting MN electricity demand in excess of generation from local power plants.
- Add the emissions associated with net power imports to the production-based emissions. This provides an estimate of the GHG inventory on a consumption basis.

Greenhouse Gas Forecast Methodology – Reference Case

We consider that the most useful methodology for constructing a GHG forecast is one that attempts to build information from the bottom-up. That is, the GHG forecast in developed using detailed State-specific data regarding projected sales, gross in-state generation, supply side efficiency improvements, planned capacity additions and retirements by plant type/vintage, and changes over time regarding losses associated with on-site use and transmission and distribution.

While some of this information was available in MN, some key data was not available at the time the forecast was prepared. Therefore, it was necessary to use a top-down approach. A top-down approach uses proxy information regarding future gross in-state generation, supply side efficiency improvements, and changes over time regarding losses. This approach, while less satisfactory for representing state-specific conditions, nonetheless offers an acceptable starting point for exploring projections of GHG emissions from the electric sector in MN. The methodological steps used for forecasting CO_2e emissions are described below.

Coal quality. An overview of the methodology applied to forecast annual gross electricity generation by MN power stations is briefly summarized below:

- For the Base Year of 2005, determine the coal quality used in MN power stations (i.e., share of anthracite, bituminous, lignite, sub-bituminous, and coal wastes used).
- For the period 2006 through and including 2020, assume that the coal quality is the same for the Base year.

Total Sales. An overview of the methodology applied to forecast annual sales of electricity to MN consumers is briefly summarized below:

- For the Base Year of 2005, establish total retail sales in MN (i.e. 66,019 gigawatt-hour (GWh)).
- For the period 2006 through and including 2020, obtain in-state electricity sale projections from MN-based utilities (Note: this was obtained from Certificates of Need but corresponded only to about 74% of total sales in MN for the Base Year 2005).
- For the period 2006 through and including 2020, compute the annual growth rate associated with electricity sales by MN-based utilities to MN consumers and apply this growth rate to the 2005 retail sale level to forecast annual sales.

Gross Generation. An overview of the methodology applied to forecast annual gross electricity generation by MN power stations is briefly summarized below:

- For the Base Year of 2005, estimate losses associated with on-site usage of electricity by plant type for MN power plants. On-site usage losses were assumed to be equal to the MAPP regional average of 0.8% of gross generation.
- For the Base Year of 2005, combine actual net electric generation data (i.e., from the inventory) and assumed average on-site losses (i.e., from the MAPP region) to estimate gross generation by plant type.

- For the period 2006 through and including 2020, estimate total gross generation of MN power stations by multiplying the 2005 value of MN total gross generation by plant type by the annual growth rate of gross generation in the MAPP region.
- For the period 2006 through and including 2020, multiply plant type-specific gross generation by the annual growth rate of total gross generation in the MAPP region. Then benchmark the plant type-specific totals pro-rata to match the control total of gross generation.

Combustion efficiency. An overview of the methodology applied to forecast annual heat rates at MN power stations is briefly summarized below:

- For the Base Year of 2005, estimate gross heat rate of MN power stations by dividing the plant type-specific 2005 gross generation estimate by the plant type-specific 2005 gross primary energy consumption estimate.
- For the period 2006 through and including 2020, estimate the annual average gross plant type-specific heat rate for the MAPP region.
- For the period 2006 through and including 2020, estimate annual average gross plant type-specific heat rate of MN power stations by multiplying the 2005 value of the annual average gross plant type-specific heat rate of MN power plants by the annual rate of improvement of gross heat rate in the MAPP region.

Energy use. An overview of the methodology applied to forecast annual primary energy use at MN power stations is briefly summarized below:

- For the Base Year of 2005, establish the actual primary energy consumption for MN power plants as reported by the databases used to develop the inventory.
- For the period 2006 through and including 2020, multiply annual gross generation by annual heat rate for each plant type in MN.

Electricity imports. An overview of the methodology applied to forecast annual net electricity imports to meet MN demand is briefly summarized below:

- For the Base Year of 2005, establish actual total sales of electricity in MN.
- For the period 2006 through and including 2020, estimate annual electricity sales in MN by multiplying the previous year’s sales by the annual growth rate of the MAPP region.
- For the Base Year of 2005 through and including 2020, estimate the sales associated with imports as the difference between total sales in MN and the total sales by MN power stations.
- For the Base Year of 2005 through and including 2020, estimate the gross generation associated with imports by dividing sales from imports by one minus the percent losses from on-site usage and transmission and distribution in the MAPP region.

Carbon dioxide-equivalent emissions from MN power stations. An overview of the methodology applied to forecast annual CO_2e emissions is briefly summarized below:

- For the Base Year of 2005 through and including 2020, estimate total CO_2 emissions from MN power stations by multiplying total primary energy use by the CO_2 emission factor and the global warming potential.
- For the Base Year of 2005 through and including 2020, estimate total CH_4 emissions from MN power stations by multiplying total primary energy use by the CH_4 emission factor and the global warming potential.
- For the Base Year of 2005 through and including 2020, estimate total N_2O emissions from MN power stations by multiplying total primary energy use by the N_2O emission factor and the global warming potential.
- For the Base Year of 2005 through and including 2020, estimate total CO_2e emissions from MN power stations by adding the CO_2e of CO_2, CH_4, and N_2O.

Carbon dioxide-equivalent emissions from imported electricity. An overview of the methodology applied to forecast annual CO_2e emissions is briefly summarized below:

- For the Base Year of 2005 through and including 2020, estimate the average annual GHG emission intensity (i.e., tonnes of CO_2, CH_4, and N_2O per MWh of gross generation) for the MAPP region from the data sources described earlier.
- For the Base Year of 2005 through and including 2020, estimate total CO_2 emissions associated with imported electricity by multiplying the gross generation associated with these imports by the CO_2 emission intensity and the global warming potential.
- For the Base Year of 2005 through and including 2020, estimate total CH_4 emissions associated with imported electricity by multiplying the gross generation associated with these imports by the CH_4 emission intensity and the global warming potential.
- For the Base Year of 2005 through and including 2020, estimate total N_2O emissions associated with imported electricity by multiplying the gross generation associated with these imports by the N_2O emission intensity and the global warming potential.
- For the Base Year of 2005 through and including 2020, estimate total CO_2e emissions associated with imported electricity by adding the CO_2e of CO_2, CH_4, and N_2O.

Greenhouse Gas Forecast Methodology – Alternative Reference Case

We also considered an alternative Reference Case that integrates renewable energy objectives from a Renewable Portfolio Standard as represented in amended Minnesota Statutes 2006, Section 216b.1691. This statute calls for each electric utility in MN to either generate or procure sufficient electricity generation to provide retail/wholesale customers in Minnesota with the following percentages of total retail electric sales:

- 7% of retail sales in MN met be renewable energy sources by the year 2010.
- 12% of retail sales in MN met be renewable energy sources by the year 2012
- 17% of retail sales in MN met be renewable energy sources by the year 2016
- 20% of retail sales in MN met be renewable energy sources by the year 2020

The methodology for forecasting gross generation and CO_2e emissions from imports is described below. The methodology for forecasting combustion efficiency, primary energy use, electricity imports, and CO_2e emissions from MN power stations is the same as described above.

Gross Generation. An overview of the methodology applied to forecast annual gross electricity generation in the Alternative Reference Case by MN power stations is briefly summarized below:

- For the Base Year of 2005 through 2006 (i.e., the period before the RPS takes effect), assume the same gross generation as determined in the Reference Case forecast.
- For the period 2007 through and including 2020, decrease the gross generation of fossil stations in MN by the prorata share of 20% of Reference Case sales.
- For the period 2007 through and including 2020, increase the gross generation of renewable stations (i.e., biomass, solar, hydro, and wind) in MN by the prorata share of 20% of Reference Case sales.

Carbon dioxide-equivalent emissions from imported electricity. An overview of the methodology applied to forecast annual CO_2e emissions in the Alternative Reference Case is briefly summarized below:

- For the Base Year of 2005 through and including 2006 (i.e., the period before the RPS takes effect), assume the CO_2e intensity of imported electricity is as determined in the Reference Case forecast.
- For the period 2007 through and including 2020, decrease the CO_2e emission intensity of imported electricity by 20% of the Reference Case emission intensity.

Greenhouse Gas Inventory Results

Figure A1 and Table A2 summarize the characteristics of the electric generation system in MN, together with a breakdown in generation and emissions for MN power stations for 2005.

Figure A1. Breakdown of MN Generation, Capacity and CO_2 Emissions – 2005 Base Year

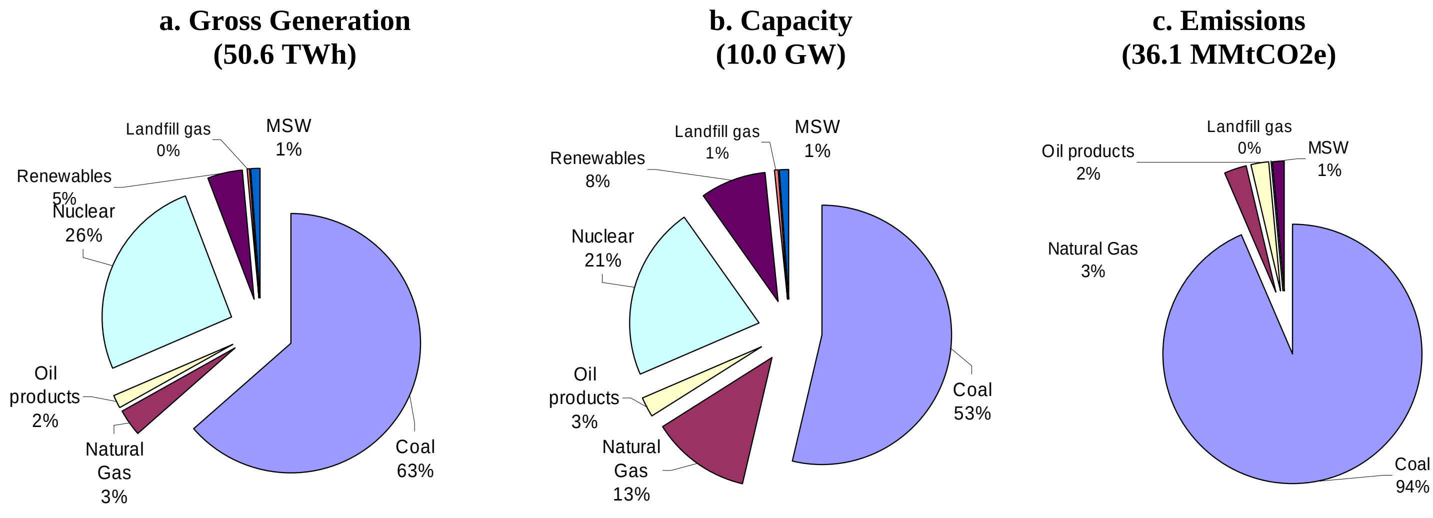


Table A2. Summary of MN Electric Generator Characteristics for the 2005 Base Year

Type	Fuel	Gross Generation (GWh)	Capacity (MW)	Fuel use (Billion Btu)	Heat rate (Btu/KWh)	Emissions (MMtCO2e)
Steam plants	Non-lignite coal	32,193	5,367	352,272	10,942	33.79
	Lignite coal	0	0	0	0	0.00
	Natural Gas	165	28	1,974	11,960	0.11
	Residual oil	43	7	462	10,633	0.04
	Diesel oil	26	4	270	10,552	0.02
	Petroleum coke	617	103	6,137	9,945	0.62
	LFG	0	0	0	0	0.00
	Refuse derived fuel/MSW	617	103	11,413	18,505	0.49
	Biomass	18	3	323	17,763	0.00
	Nuclear	12,943	2,158	133,974	10,351	0.00
	Subtotal:	*46,622*	*7,772*	*506,826*		*35.05*
Turbines	Natural Gas	844	1,059	10,732	12,710	0.58
	Diesel	63	79	899	14,273	0.07
	Landfill Gas	0	0	0	0	0.00
	Waste oils/solvents	0	NA	0	0	0.00
	Subtotal:	*907*	*1,138*	*11,631*		*0.64*
Combined Cycle	Natural Gas	681	0	5,913	8,683	0.32
	Diesel	2	0	23	10,721	0.00
	Landfill Gas	44	0	534	12,164	0.03
	Subtotal:	*727*	*0*	*6,470*		*0.35*
Engines	Natural Gas	30	166	632	21,085	0.03
	Diesel	11	63	125	10,965	0.01
	Landfill Gas	12	68	136	11,087	0.01
	LPG	0	0	0	0	0.00
	subtotal:	*54*	*296*	*892*		*0.05*
Renew	Wind	1,596	634	15,823	9,916	0.00
	Solar PV	0	0	0	0	0.00
	Hydroelectric	719	164	7,130	9,916	0.00
	Subtotal:	*2,315*	*798*	*22,954*		*0.00*
All	***Total***	**50,625**	**10,005**	**548,772**		**36.10**

Greenhouse Gas Forecast Results

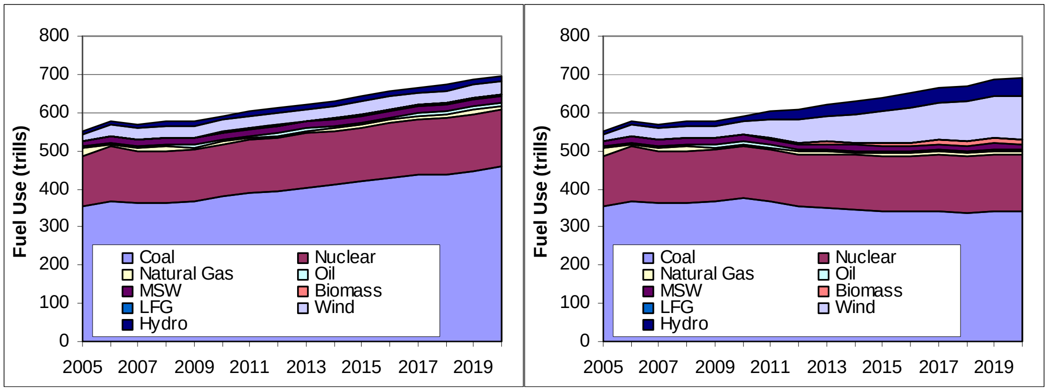
The following subsections provide an overview of the results obtained after applying the methodological approach described above.

Primary Energy Consumption

Total primary energy consumption associated with electricity generation in MN is summarized in Figure A2 for both Reference Cases. In the Reference Case without the RPS, primary energy consumption in MN is dominated by coal and nuclear resources. In the Reference Case with the RPS, primary energy consumption in MN, while still dependent on coal and nuclear resources, has a sharply increased share of wind and hydro resources.

Figure A2. Primary Energy Use at MN Power Stations

a. RPS Excluded **b. RPS Included**

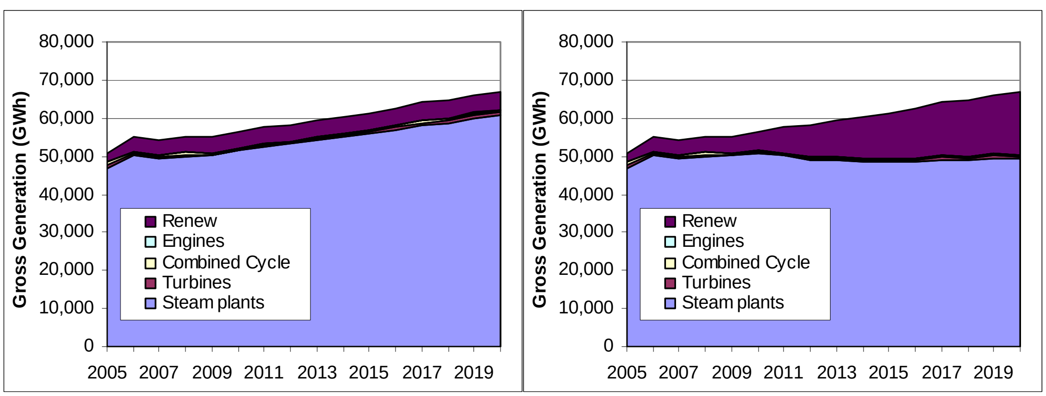


Gross Generation

Total gross generation by MN power plants is summarized in Figure A3 for both Reference Cases. In the Reference Case without the RPS, gross generation in MN is dominated by steam units, which are primarily based on coal and nuclear fuel. In the Reference Case with the RPS, renewable energy accounts for a substantially increased share of wind and hydro resources.

Figure A3. Gross Generation at MN Power Stations

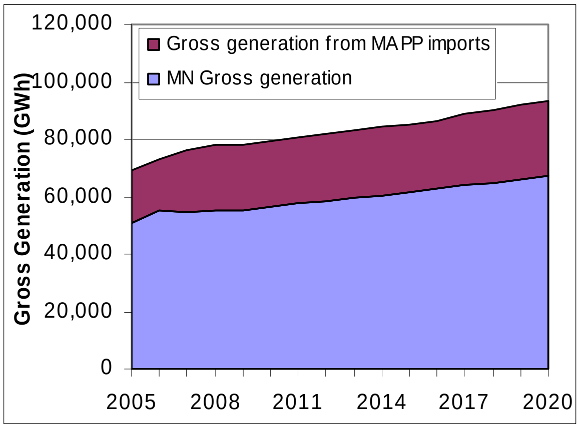
a. RPS Excluded **b. RPS Included**



Imported Electricity

To meet annual demand for electricity in MN, total gross generation by MN power plants needs to be augmented by electricity imports. As indicated earlier, it was assumed that this power is imported from the MAPP region. Figure A4 summarizes the gross generation within and beyond Minnesota border needed to satisfy electricity demand in Minnesota.

Figure A4. Composition of Gross Generation to Meet Demand for Electricity in MN

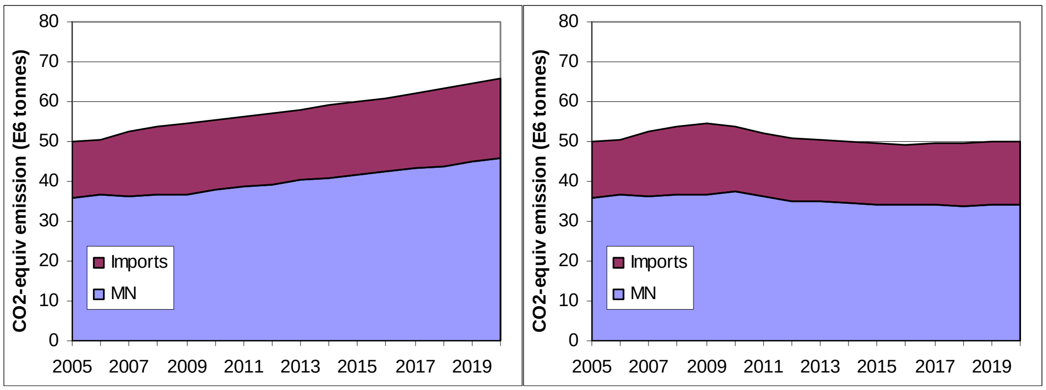


Total Emissions

Total emissions associated with generation by MN power plants as well as generation by power plants located outside MN to meet electricity demand within MN are summarized in Figure A5 for both Reference Cases. In the Reference Case without the RPS, emissions reach 66.4 MMtCO2e in 2020. In the Reference Case with the RPS, renewable energy accounts for a substantially decrease in emissions, resulting in a total of 50.5 MMtCO2e in 2020. This represents is roughly equal to 2005 levels.

Figure A5. Total Emissions Associated with Electric Demand in MN (MMtCO$_2$e)

a. RPS Excluded **b. RPS Included**



Appendix B. Residential, Commercial, and Industrial (RCI) Fuel Combustion

Overview

Activities in the RCI[18] sectors produce carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions when fuels are combusted to provide space heating, water heating, process heating, cooking, and other energy end-uses. Carbon dioxide accounts for about 99% of RCI emissions in Minnesota on a million metric tons (MMt) of CO_2 equivalent (CO_2e) basis. In addition, since these sectors consume electricity, one can also attribute emissions associated with electricity generation to these sectors in proportion to their electricity use.[19] Direct use of oil, natural gas, coal, and wood in the RCI sectors accounted for an estimated 32 $MMtCO_2e$ of gross greenhouse gas (GHG) emissions in 2005.[20]

Emissions and Reference Case Projections

The Minnesota Pollution Control Agency (MPCA) has prepared a detailed inventory of GHG emissions from 1970 through 2004 for CH_4 and N_2O, and through 2005 for CO_2. The MPCA inventory follows the United States Environmental Protection Agency's (US EPA) methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for RCI fossil fuel combustion.[21] The MPCA emission estimates for 1990 through 2004 were used for the historical inventory presented in this appendix. Emissions were projected starting from 2004 through 2020 since 2004 is the last year for which MPCA estimated emissions for all three pollutants. Table B1 provides the references that MPCA used to compile information on fuel use activity data that informed the historical inventory.

Note that the EIIP methods for the industrial sector exclude from CO_2 emission estimates the amount of carbon that is stored in products produced from fossil fuels for non-energy uses. For example, the methods account for carbon stored in petrochemical feedstocks, and in liquefied petroleum gases (LPG) and natural gas used as feedstocks by chemical manufacturing plants (i.e., not used as fuel), as well as carbon stored in asphalt and road oil produced from petroleum.

[18] The industrial sector includes emissions associated with agricultural energy use. Emissions associated with the direct use of fuel by the natural gas transmission and distribution (T&D) industry are included in Appendix E.

[19] Emissions associated with the electricity supply sector (presented in Appendix A) have been allocated to each of the RCI sectors for comparison of those emissions to the fuel-consumption-based emissions presented in Appendix B. Note that this comparison is provided for information purposes and that emissions estimated for the electricity supply sector are not double-counted in the total emissions for the state. One could similarly allocate GHG emissions from natural gas T&D, other fuels production, and transport-related GHG sources to the RCI sectors based on their direct use of gas and other fuels, but we have not done so here due to the difficulty of ascribing these emissions to particular end-users. Estimates of emissions associated with the transportation sector are provided in Appendix C, and estimates of emissions associated with natural gas T&D are provided in Appendix E.

[20] Emissions estimates from wood combustion include only N_2O and CH_4. Carbon dioxide emissions from biomass combustion are assumed to be "net zero", consistent with US EPA and Intergovernmental Panel on Climate Change (IPCC) methodologies, and any net loss of carbon stocks due to biomass fuel use should be accounted for in the land use and forestry analysis.

[21] Emission Inventory Improvement Program (EIIP), *Volume VIII*: Chapter 1 "Methods for Estimating Carbon Dioxide Emissions from Combustion of Fossil Fuels", August 2004, and Chapter 2 "Methods for Estimating Methane and Nitrous Oxide Emissions from Stationary Combustion", August 2004.

The carbon storage assumptions for these products are explained in Volume III, Chapter 1 of the EIIP guidance document.

Table B1. References for RCI Activity Data for 1990 - 2004

Residential Sector:

Natural gas and propane-air - United States Department of Energy (US DOE), Energy Information Administration (EIA), *Natural Gas Annual*, http://tonto.eia.doe.gov/dnav/ng/ng_sum_snd_dcu_SMN_a.htm

LPG and coal - EIA, *State Energy Data* (SED), http://www.eia.doe.gov/emeu/states/state.html?q_state_a=mn&q_state=MINNESOTA

Distillate fuel oil and kerosene - EIA, *Fuel Oil Kerosene Sales*, http://www.eia.doe.gov/oil_gas/petroleum/data_publications/fuel_oil_and_kerosene_sales/foks.html

Wood - Minnesota Department of Natural Resources (DNR) Fuelwood Surveys

Commercial Sector:

Natural gas and propane-air - EIA, *Natural Gas Annual* and Minnesota Pollution Control Agency (MPCA) Emission Inventory System (EIS) data

Distillate fuel oil and kerosene - EIA, *Fuel Oil Kerosene Sales* and MPCA-EIS data

Coal - MPCA-EIS data

Residual fuel oil and waste oil - MPCA-EIS data

Wood - EIA, SED

Industrial and Agricultural Sectors:

Bituminous, subbituminous, anthracite, and lignite coal - MPCA-EIS data

Refinery petroleum coke, residual fuel oil, heavy oil; solid resins; waste solvent; and other industrial - MPCA-EIS data

Refinery gas - 1990-1995, MPCA-EIS data; 1996-2004, calculated from refinery capacity, utilization rates, assumed energy input to refinery production, and assumed percentage of refinery gas contribution to total refinery fuel inputs

Coking coal and LPG - EIA, SED

Natural gas and propane-air - EIA, *Natural Gas Annual*

Distillate fuel oil and kerosene - EIA, *Fuel Oil Kerosene Sales*

Wood and wood waste, sawdust, bark, mixed wood, bark and sawdust, wet wood, wood sludge, black liquor - MPCA-EIS data

Waste oil - MPCA-EIS data and EIA, SED

Motor gasoline for agricultural sector - Federal Highway Administration's *Highway Statistics*

Reference case emissions from direct fuel combustion were estimated based on fuel consumption forecasts from EIA's *Annual Energy Outlook 2006* (AEO2006),[22] with adjustments for Minnesota's projected population[23] and employment growth. Minnesota employment data for the manufacturing (goods-producing) and non-manufacturing (commercial or services-providing) sectors were obtained from the Minnesota Department of Employment and Economic Development.[24] Regional employment data for the same sectors were obtained from EIA for the EIA's West North Central region.[25]

Table B2 shows historic and projected growth rates for electricity sales by sector. Table B3 shows historic and projected growth rates for non-electric energy use by sector and fuel type. For the residential sector, the rate of population growth is expected to average about 0.8% annually between 2005 and 2020; this demographic trend is reflected in the growth rates for residential fuel consumption. Based on the Minnesota Department of Employment and Economic Development's industry projections (2004 to 2014), commercial and industrial employment are projected to increase at compound annual rates averaging about 1.5% and 0.4%, respectively, and these growth rates are reflected in the growth rates in energy use shown in Table B3 for the two sectors. The 2004-to-2014 commercial and industrial employment growth rates were carried forward to 2020 for the purpose of estimating emissions for the reference case projections. These estimates of growth relative to population and employment reflect expected responses of the economy — as simulated by the EIA's National Energy Modeling System — to changing fuel and electricity prices and changing technologies, as well as to structural changes within each sector (such as shifts in subsectoral shares and in energy use patterns).

Table B2. Electricity Sales Annual Growth Rates, Historical and Projected

Sector	1990-2000[a]	1990-2005[a]	2005-2020[b]
Residential	2.3%	2.6%	1.8%
Commercial	3.4%	6.3%	2.3%
Industrial	2.1%	-0.4%	1.2%
Total	**2.4%**	**2.3%**	**1.7%**

[a] 1990-2000 and 2000-2005 compound annual growth rates calculated from Minnesota electricity sales by year from EIA state electricity profiles (Table 8), http://www.eia.doe.gov/cneaf/electricity/st_profiles/e_profiles_sum.html. According to the EIA, starting in 2001 some facilities that previously reported their retail electricity purchases as industrial began reporting their retail purchases as commercial. Thus, between 2000 and 2001, there was a significant decline in retail sales reported for the industrial sector and a significant increase in retail sales reported for the commercial sector. The EIA was unable to identify the facilities that changed the sector for which they reported retail sales.
[b] 2005-2020 compound annual growth rates based on average annual Mid-Continent Area Power Pool (MAPP) region annual growth rates by sector.

[22] EIA AEO2006 with Projections to 2030, (http://www.eia.doe.gov/oiaf/aeo/index.html).
[23] Minnesota Department of Administration, Office of Geographic and Demographic Analysis, http://www.mnplan.state.mn.us/resource.html?Id=3124.
[24] Minnesota Department of Employment and Economic Development, Industry Projections 2004-2014, http://www.deed.state.mn.us/lmi/tools/projections/default.aspx.
[25] AEO2006 employment projections for EIA's West North Central region obtained through special request from EIA (dated September 27, 2006).

As shown in Table B2, the growth rates for electricity sales for the commercial and industrial sectors changed significantly from 2000 through 2005 as a result of an accounting change--facilities changing the sector under which they reported their electricity sales.[26] From 1990 through 2000, the commercial and industrial sectors accounted for about 30% and 70%, respectively, of total retail electricity sales for these two sectors combined. Thus, these proportions were used to attribute emissions associated with the electricity supply sector presented in Appendix A to the commercial and industrial sectors for 2000 through 2020.

Table B3. Historical and Projected Average Annual Growth in Non-Electric Energy Use in Minnesota, by Sector and Fuel, 1990-2020

	1990-2005[a]	2005-2010[b]	2010-2015[b]	2015-2020[b]
Residential				
natural gas	1.2%	1.4%	0.8%	0.5%
petroleum	1.3%	0.3%	0.6%	0.3%
wood	-2.6%	1.8%	0.3%	0.6%
coal[c]	-7.1%	1.9%	-0.3%	-0.3%
Commercial				
natural gas	1.4%	1.3%	2.5%	1.7%
petroleum	2.4%	0.0%	1.3%	0.7%
wood	1.3%	0.4%	0.9%	0.6%
coal[d]	-7.5%	0.3%	0.9%	0.6%
Industrial				
natural gas	0.5%	5.8%	2.7%	0.6%
petroleum	3.6%	0.9%	0.4%	0.5%
wood	0.5%	2.0%	1.5%	1.3%
coal	3.4%	1.6%	0.6%	0.4%

[a] Compound annual growth rates calculated from historical fuel consumption by sector and fuel type for Minnesota. Petroleum includes distillate fuel, kerosene, and liquefied petroleum gases (LPG) for all sectors plus residual oil and motor gasoline for the commercial and industrial sectors.
[b] Figures for growth periods starting after 2005 are calculated from AEO2006 projections for EIA's US West North Central region, adjusted for Minnesota's projected population for the residential sector, projections for non-manufacturing employment for the commercial sector, and projections for manufacturing employment for the industrial sector.
[c] In 1990, on a Btu basis, residential coal consumption accounted for only 0.04% of total residential energy consumption (based on the use of all fossil fuels and wood combined) and declined to about 0.01% of total energy consumption by 2005.
[d] In 1990, on a Btu basis, commercial coal consumption accounted for only 1.5% of total commercial energy consumption (based on the use of all fossil fuels and wood combined) and declined to about 0.3% of total energy consumption by 2005.

Results

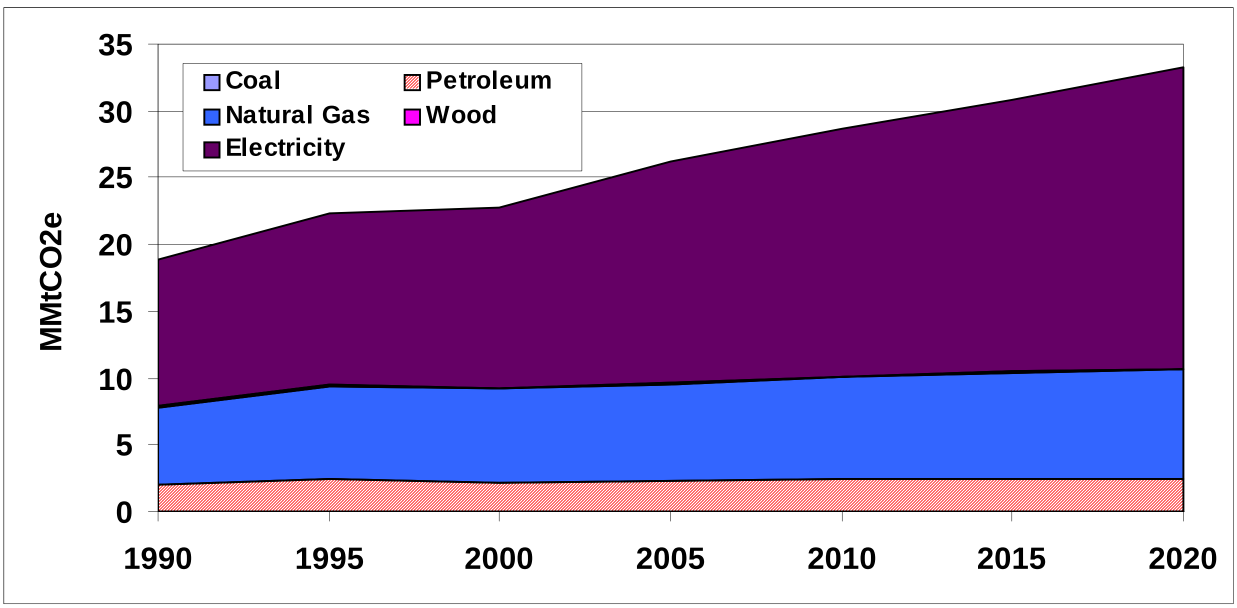
Figures B1, B2, and B3 show historical and projected emissions for the RCI sectors in Minnesota from 1990 through 2020. These figures show the emissions associated with the direct consumption of fossil fuels and, for comparison purposes, show the share of emissions associated with the generation of electricity consumed by each sector. During the period from 1990 through 2020, the residential sector's share of total RCI emissions from direct fuel use and electricity ranged from 31% in 1990 to 32% in 2020. The commercial sector's share of total RCI emissions from direct fuel use and electricity use ranged from 19% in 1990 to 21% in 2020. The

[26] Personal communication between Randy Strait, CCS, and Thomas Lecky, DOE, EIA ((202) 586-3548), July 19, 2007.

industrial sector's share of total RCI emissions from direct fuel use and electricity use ranged from 50% in 1990 to 47% in 2020. Emissions associated with the generation of electricity to meet RCI demand accounts for about 62% of the emissions for the residential sector, 61% of the emissions for the commercial sector, and 58% of the emissions for the industrial sector, on average, over the 1990 to 2020 time period. From 1990 to 2020, natural gas consumption is the next highest source of emissions for the residential and commercial sectors, accounting, on average, for about 28% and 33% of total emissions, respectively. For the industrial sector, emissions associated with the combustion of petroleum, natural gas, and coal account for about 20%, 15%, and 6% respectively, on average, of total industrial emissions from 1990 to 2020.

Residential Sector
Figure B1 presents the emission inventory and reference case projections for the residential sector. Figure B1 was developed from the emissions data in Table B4a. Table B4b shows the relative contributions of emissions associated with each fuel type to total residential sector emissions.

Figure B1. Residential Sector GHG Emissions from Fuel Consumption



Source: CCS calculations based on approach described in text.
Note: Emissions associated with coal and wood combustion are too small to be seen on this graph.

For the residential sector, emissions from electricity and direct fossil fuel use in 1990 were about 19 $MMtCO_2e$, and are estimated to increase to about 33 $MMtCO_2e$ by 2020. Emissions associated with the generation of electricity to meet residential energy consumption demand accounted for about 58% of total residential emissions in 1990, and are estimated to increase to 68% of total residential emissions by 2020. In 1990, natural gas consumption accounted for about 30% of total residential emissions, and is estimated to account for about 24% of total residential emissions by 2020. Residential-sector emissions associated with the use of coal, petroleum, and wood in 1990 were about 2.2 $MMtCO_2e$ combined, and accounted for about 12% of total residential emissions. By 2020, emissions associated with the consumption of these three fuels are estimated to be about 2.6 $MMtCO_2e$, accounting for 8% of total residential sector emissions by that year.

For the 15-year period 2005 to 2020, residential-sector GHG emissions associated with the use of electricity and natural gas are projected to increase at average annual rates of about 2% and 0.8% respectively. Emissions associated with the use of wood, petroleum, and coal are projected to increase annually by about 0.8%, 0.4%, and 0.3%, respectively. Total GHG emissions for the residential sector are projected to increase by an average of about 1.6% annually over the 15-year period.

Table B4a. Residential Sector Emissions Inventory and Reference Case Projections ($MMtCO_2e$)

Fuel Type	1990	1995	2000	2005	2010	2015	2020
Coal	0.007	0.005	0.002	0.002	0.003	0.003	0.002
Petroleum	2.06	2.47	2.21	2.36	2.40	2.47	2.51
Natural Gas	5.66	6.87	6.94	7.15	7.63	7.91	8.09
Wood	0.16	0.12	0.11	0.11	0.11	0.12	0.12
Electricity Consumption	11.0	12.9	13.5	16.6	18.5	20.3	22.5
Total	18.9	22.3	22.8	26.3	28.7	30.8	33.2

Source: CCS calculations based on approach described in text.

Table B4b. Residential Sector Proportions of Total Emissions by Fuel Type (%)

Fuel Type	1990	1995	2000	2005	2010	2015	2020
Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Petroleum	11	11	10	9	8	8	8
Natural Gas	30	31	30	27	27	26	24
Wood	0.8	0.5	0.5	0.4	0.4	0.4	0.4
Electricity Consumption	58	58	59	63	65	66	68

Source: CCS calculations based on approach described in text.
Note: The percentages shown in this table reflect the emissions for each fuel type as a percentage of total emissions shown in Table B4a.

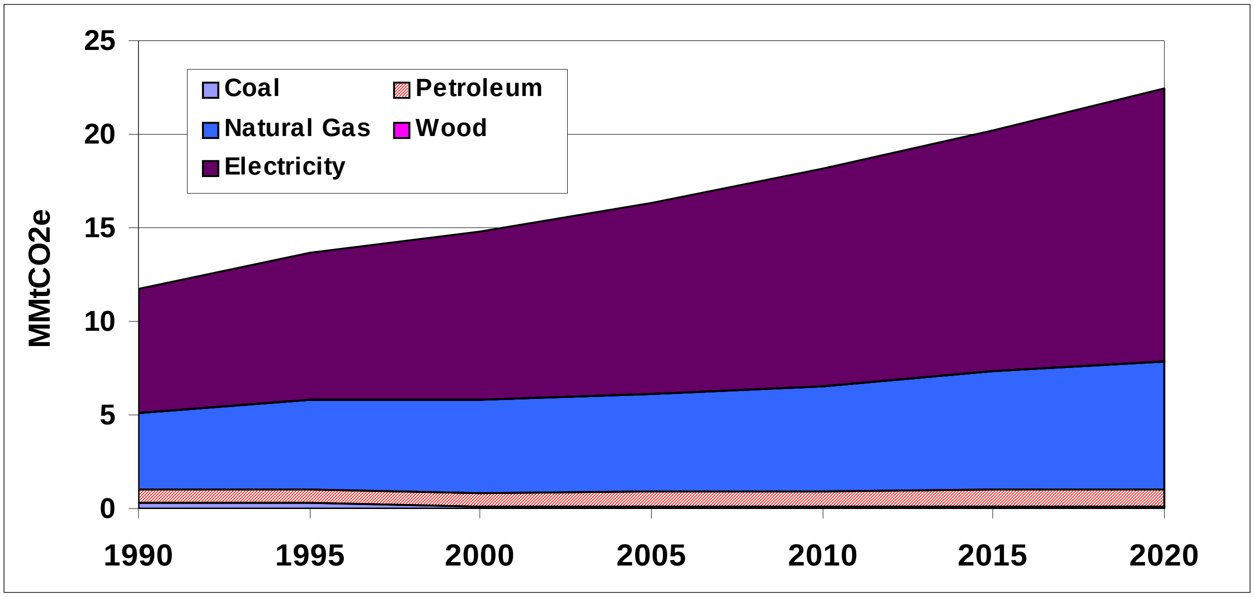
Commercial Sector

Figure B2 presents the emission inventory and reference case projections for the commercial sector. Figure B2 was developed from the emissions data in Table B5a. Table B5b shows the relative contributions of emissions associated with each fuel type to total commercial sector emissions.

For the commercial sector, emissions from electricity and direct fossil fuel use in 1990 were about 12 $MMtCO_2e$, and are estimated to increase to about 22 $MMtCO_2e$ by 2020. Emissions associated with the generation of electricity to meet commercial energy consumption demand accounted for about 56% of total commercial emissions in 1990, and are estimated to increase to 65% of total commercial emissions by 2020. In 1990, natural gas consumption accounted for about 35% of total commercial emissions and is estimated to account for about 30% of total commercial emissions by 2020. Commercial-sector emissions associated with the use of coal, petroleum, and wood in 1990 were about 1.0 $MMtCO_2e$ combined, and accounted for about 9% of total commercial emissions. By 2020, emissions associated with the consumption of these three fuels are estimated to be 1.1 $MMtCO_2e$ and to account for about 5% of total commercial sector emissions.

For the 15-year period 2005 to 2020, commercial-sector GHG emissions associated with the use of electricity and natural gas are projected to increase at average annual rates of about 2.4% and 1.8% respectively. Emissions associated with the use of wood, petroleum, and coal are projected to increase annually by about 0.6%, 0.7%, and 0.6%, respectively. Total GHG emissions for the commercial sector are projected to increase by an average of about 2.1% annually over the 15-year period.

Figure B2. Commercial Sector GHG Emissions from Fuel Consumption



Source: CCS calculations based on approach described in text.
Note: Emissions associated with coal combustion are too small to be seen on this graph.

Table B5a. Commercial Sector Emissions Inventory and Reference Case Projections ($MMtCO_2e$)

Fuel Type	1990	1995	2000	2005	2010	2015	2020
Coal	0.35	0.29	0.09	0.12	0.12	0.12	0.13
Petroleum	0.68	0.69	0.69	0.83	0.84	0.89	0.92
Natural Gas	4.11	4.80	5.08	5.19	5.60	6.28	6.83
Wood	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Electricity Consumption	6.54	7.88	8.94	10.2	11.5	12.9	14.5
Total	11.7	13.7	14.8	16.3	18.1	20.2	22.4

Source: CCS calculations based on approach described in text.

Table B5b. Commercial Sector Proportions of Total Emissions by Fuel Type (%)

Fuel Type	1990	1995	2000	2005	2010	2015	2020
Coal	3.0	2.1	0.6	0.7	0.7	0.6	0.6
Petroleum	5.8	5.0	4.6	5.1	4.6	4.4	4.1
Natural Gas	35	35	34	32	31	31	30
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Electricity Consumption	56	58	60	62	64	64	65

Source: CCS calculations based on approach described in text.
Note: The percentages shown in this table reflect the emissions for each fuel type as a percentage of total emissions shown in Table B5a.

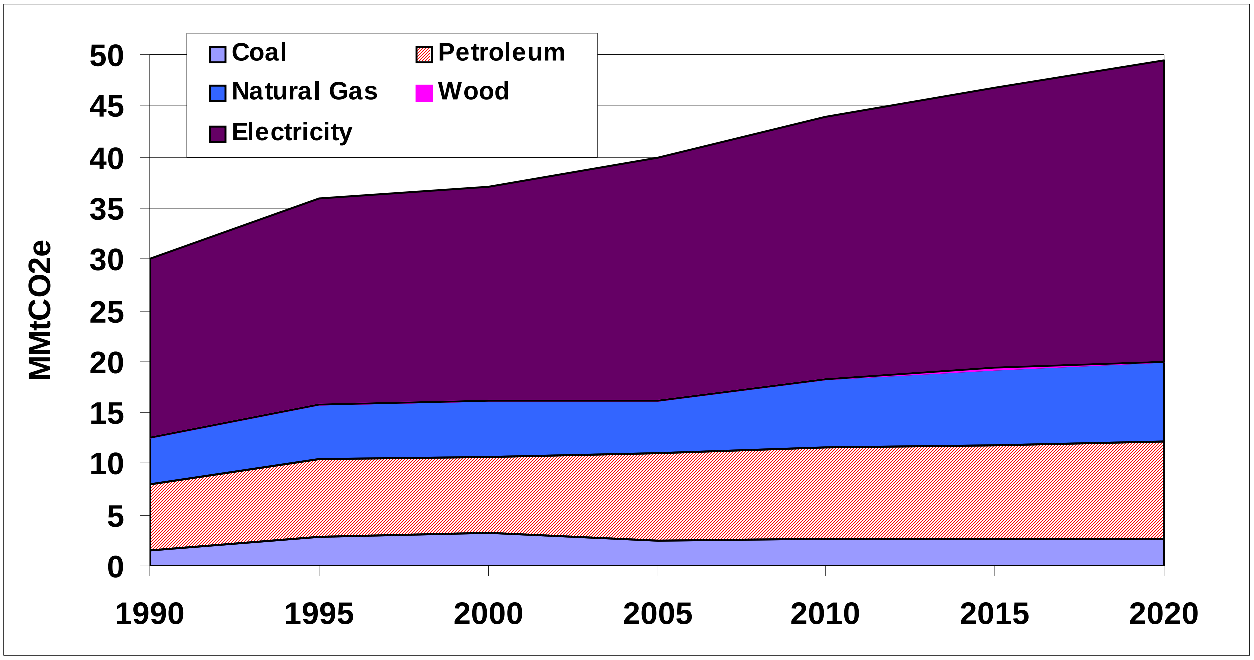
Industrial Sector

Figure B3 presents the emission inventory and reference case projections for the industrial sector. Figure B3 was developed from the emissions data in Table B6a. Table B6b shows the relative contributions of emissions associated with each fuel type to total industrial sector emissions.

For the industrial sector, emissions from electricity and direct fuel use in 1990 were about 30 MMtCO_2e and are estimated to increase to about 49 MMtCO_2e by 2020. Emissions associated with the generation of electricity to meet industrial energy consumption demand accounted for about 58% of total industrial emissions in 1990, and are estimated increase to about 59% of total industrial emissions by 2020. In 1990, petroleum consumption accounted for about 21% of total industrial emissions, and is estimated to account for about 19% of total industrial emissions by 2020. In 1990, natural gas consumption accounted for about 15% of total industrial emissions, and is estimated to account for about 16% of total industrial emissions by 2020. Industrial-sector emissions associated with the use of coal and wood in 1990 were about 1.6 MMtCO_2e combined, and accounted for about 6% of total industrial emissions. For 2020, emissions associated with the consumption of these two fuels are estimated to be 2.8 MMtCO_2e, and to continue to account for about 6% of total industrial sector emissions.

For the 15-year period 2005 to 2020, industrial-sector GHG emissions associated with the use of electricity, petroleum, and natural gas are projected to increase at average annual rates of about 1.4%, 0.6%, and 2.7% respectively. Emissions associated with the use of wood and coal are projected to increase annually by about 1.6% and 0.8%, respectively. Total GHG emissions for the industrial sector are projected to increase by an average of about 1.4% annually over the 15-year period.

Figure B3. Industrial Sector GHG Emissions from Fuel Consumption



Source: CCS calculations based on approach described in text.
Note: Emissions associated with wood combustion are too small to be seen on this graph.

Table B6a. Industrial Sector Emissions Inventory and Reference Case Projections (MMtCO$_2$e)

Fuel Type	1990	1995	2000	2005	2010	2015	2020
Coal	1.61	2.80	3.25	2.42	2.59	2.67	2.74
Petroleum	6.43	7.60	7.33	8.56	8.92	9.12	9.42
Natural Gas	4.49	5.38	5.55	5.18	6.67	7.47	7.77
Wood	0.04	0.06	0.06	0.08	0.09	0.09	0.10
Electricity Consumption	17.4	20.1	20.9	23.7	25.7	27.3	29.4
Total	30.0	36.0	37.1	39.9	44.0	46.7	49.4

Source: CCS calculations based on approach described in text.

Table B6b. Industrial Sector Proportions of Total Emissions by Fuel Type (%)

Fuel Type	1990	1995	2000	2005	2010	2015	2020
Coal	5.4	7.8	8.8	6.1	5.9	5.7	5.5
Petroleum	21	21	20	21	20	20	19
Natural Gas	15	15	15	13	15	16	16
Wood	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Electricity Consumption	58	56	56	59	58	59	59

Source: CCS calculations based on approach described in text.
Note: The percentages shown in this table reflect the emissions for each fuel type as a percentage of total emissions shown in Table B6a.

Key Uncertainties

Key sources of uncertainty underlying the estimates above are as follows:

- Population and economic growth are the principal drivers for electricity and fuel use. The reference case projections are based on regional fuel consumption projections for EIA's West North Central modeling region, scaled for Minnesota population and employment growth projections. Consequently, there are significant uncertainties associated with the projections. Future work should attempt to base projections of GHG emissions on fuel consumption estimates specific to Minnesota, to the extent that such data become available.
- The AEO2006 projections assume no large long-term changes in relative fuel and electricity prices, relative to current price levels and to US DOE projections for fuel prices. Price changes would influence consumption levels and, to the extent that price trends for competing fuels differ, may encourage switching among fuels, thereby affecting emissions estimates.

Appendix C. Transportation Energy Use

Overview

Transportation is one the largest greenhouse gas (GHG) source sectors in Minnesota. The transportation sector includes light and heavy-duty (onroad) vehicles, aircraft, rail engines, and marine engines. Emissions from this sector include carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) from combustion of fuels.

Emissions Inventory and Reference Case Projection Methods

Historical Emissions
GHG emissions for 1990 through 2004 were estimated by Minnesota Pollution Control Agency (MPCA) using United States Environmental Protection Agency (US EPA) methods and emission factors as provided in the Emission Inventory Improvement Program (EIIP) guidance document for the sector and the national greenhouse gas inventory.[27,28,29] For CO_2, emission factors are in units of lb/MMBtu, and the activity data are fuel consumption. Key sources of fuel consumption data are listed in Table C1.

Table C1. Sources for Historical Minnesota Fuel Consumption Estimates

Fuel Type	Fuel Consumption Data Source
Gasoline (highway, marine[a])	*Highway Statistics*, Federal Highway Administration (FHWA)
Diesel (highway, rail, military)	Fuel Oil and Kerosene Sales, Energy Information Administration (EIA)
Ethanol	*Highway Statistics*, Federal Highway Administration (FHWA)
Jet Fuel	Petroleum Tax Division, Minnesota Department of Revenue
Aviation Gasoline	*Highway Statistics*, Federal Highway Administration (FHWA)
Liquified Petroleum Gas (LPG)	Calculated from Vehicle Inventory and Use Survey (VIUS) vehicles, VMT/vehicle, and approximate fuel economy
Natural Gas	*Natural Gas Annual*, Energy Information Administration (EIA)
Waste Oil	Calculated at a rate of 1 quart of motor oil/2000 miles traveled

[a] Estimation of marine diesel and residual fuel consumption discussed under commercial marine section.

For CH_4 and N_2O, nonroad engine emissions are estimated using fuel consumption data, shown in Table C1. CH_4 and N_2O emissions from onroad vehicles are estimated from vehicle miles traveled (VMT), which were obtained from Minnesota Department of Transportation (MNDOT) by MPCA.[30] Onroad emissions are also dependent on the distribution of model years that are

[27] Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2004, US Environmental Protection Agency, April 2006, http://epa.gov/climatechange/emissions/usinventoryreport.html.
[28] CO_2 emissions were calculated using EPA's State Greenhouse Gas Inventory Tool (SGIT) software, with reference to the EIIP guidance provided in Volume VIII: Chapter. 1. "Methods for Estimating Carbon Dioxide Emissions from Combustion of Fossil Fuels", August 2004.
[29] CH_4 and N_2O emissions were calculated using SGIT, with reference to the EIIP guidance provided in Volume VIII: Chapter. 3. "Methods for Estimating Methane and Nitrous Oxide Emissions from Mobile Combustion", August 2004.
[30] Minnesota Department of Transportation

operating in each year. Vehicle vintage data were obtained from the Vehicle Inventory and Use Survey (VIUS) and the National Household Travel Survey.[31,32]

State-total VMT were allocated to specific vehicle types using data from MNDOT (i.e. VMT for passenger cars and heavy duty trucks).[33] Vehicle-type specific VMT and estimated fuel economy obtained by MPCA were used to estimate vehicle-specific fuel consumption. Vehicle-type specific fuel consumption was then allocated to gasoline and diesel categories based on the following:

- Light-duty vehicles – MPCA data;
- Heavy-duty vehicles – MPCA data;
- Recreational vehicles – assumed national value of 85% gasoline for 1990-1993, 67% for 1999-2004, interpolated for 1994-1998;[34]
- School buses – 90% diesel;[35]
- Transit buses – fuel consumption data from National Transit Database;[36]
- Other buses – assumed 100% diesel.

Commercial Marine Vessels
For the commercial marine sector (marine diesel and residual fuel), 1990-2004 emission estimates are based on EPA emission factors applied to estimates of Minnesota marine vessel diesel and residual fuel consumption. The MPCA inventory estimated marine diesel and residual fuel emissions based on fuel consumption data from EIA. Because EIA estimates of marine vessel fuel consumption represent the State in which fuel is sold rather than consumed, an alternative method was used to estimate Minnesota marine vessel fuel consumption.

Minnesota fuel consumption estimates were developed by allocating 1990-2004 national diesel and residual oil vessel bunkering fuel consumption estimates obtained from EIA.[37] Marine vessel fuel consumption was allocated to Minnesota using the marine vessel activity allocation methods/data compiled to support the development of EPA's National Emissions Inventory (NEI).[38] In keeping with the NEI, 75 percent of each year's distillate fuel and 25 percent of each year's residual fuel were assumed to be consumed within the port area (remaining consumption assumed to occur while ships are underway). National port area fuel consumption was allocated to Minnesota based on year-specific freight tonnage data as reported in "Waterborne Commerce

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[31] Vehicle Inventory and Use Survey, US Census Bureau, http://www.census.gov/svsd/www/vius/products.html.
[32] National Household Travel Survey, Federal Highway Administration, http://nhts.ornl.gov/.
[33] MPCA
[34] MOVES2004 Highway Vehicle Population and Activity Data, US Environmental Protection Agency, EPA420-P-04-020, Dec 2004.
[35] MPCA
[36] National Transit Database, US Federal Transit Administration, http://www.ntdprogram.com/ntdprogram/.
[37] US Department of Energy, Energy Information Administration, "Petroleum Navigator" (diesel data obtained from http://tonto.eia.doe.gov/dnav/pet/hist/kd0vabnus1a.htm; residual data obtained from http://tonto.eia.doe.gov/dnav/pet/hist/kprvatnus1a.htm).
[38] See methods described in ftp://ftp.epa.gov/EmisInventory/2002finalnei/documentation/mobile/2002nei_mobile_nonroad_methods.pdf

of the United States, Part 5 – Waterways and Harbors National Summaries."[39] Offshore CO_2 and hydrocarbon (HC) emissions for Minnesota's Exclusive Economic Zone (EEZ) were taken from a study by Corbett et al for the Commission for Environmental Cooperation in North America (CEC).[40] Offshore CH_4 emissions were estimated by speciating the HC emissions using the California Air Resources Board (CARB) total organic gases (TOG) profile #818.[41] Offshore N_2O emissions were estimated by applying the ratio of N_2O to CH_4 emission factors for residual fuel to the CH_4 emission estimate. The 2002 offshore emissions from the CEC inventory were scaled to other historic years based on the estimated port fuel consumption.

2005 Emission Estimates

Fuel consumption for 2005 was available from the sources listed in Table C1. Therefore, 2005 CO_2 emissions (except for marine diesel and residual fuel) were estimated based on historical fuel consumption estimates. Emissions of CH_4 and N_2O for all sources, except marine diesel and residual and onroad vehicles, was also estimated based on 2005 fuel consumption data. 2005 CH_4 and N_2O emissions from onroad vehicles were based on 2005 VMT projections (described in the Onroad Vehicle Projections section). Marine diesel and residual fuel consumption was projected from 2004 to 2005 using methods described in the Commercial Marine Projections section below. Table C2 provides a summary of key inventory projection issues.

Table C2. Key Assumptions and Methods for the Transportation Projections

Vehicle Type and Pollutants	Methods
Onroad gasoline, diesel, natural gas, and LPG vehicles – CO_2	Gasoline and diesel fuel projected using VMT projections provided by MNDOT adjusted by fuel efficiency improvement projections from AEO2006. Other onroad fuels projected using West North Central Region fuel consumption projections from EIA AEO2006.
Onroad gasoline and diesel vehicles – CH_4 and N_2O	VMT projections from MNDOT allocated to vehicle types using vehicle specific growth rates from AEO2006.
Non-highway fuel consumption (jet aircraft, aviation gasoline, boats, locomotives) – CO_2, CH_4 and N_2O	Aircraft projected using aircraft operations projections from the Federal Aviation Administration (FAA). Rail and marine gasoline projected based on historical fuel consumption. Commercial marine projected based on historical trend in freight tonnage at Minnesota ports.

[39] Waterborne Commerce Statistics Center, US Army Corps of Engineers, http://www.iwr.usace.army.mil/ndc/wcsc/wcsc.htm.

[40] Estimate, Validation, and Forecasts of Regional Commercial Marine Vessel Inventories, submitted by J. Corbett, prepared for the California Air Resources Board, California Environmental Protection Agency, and Commission for Environmental Cooperation in North America, http://coast.cms.udel.edu/NorthAmericanSTEEM/.

[41] California Air Resources Board, Speciation Profiles, http://www.arb.ca.gov/ei/speciate/speciate.htm.

Onroad Vehicle Projections

Onroad vehicle gasoline and diesel emissions were projected from 2005-2030 based on VMT forecasts from MNDOT[4] and growth rates developed from national vehicle type VMT forecasts reported in EIA's *Annual Energy Outlook* 2006 (AEO2006). The AEO2006 data were incorporated because they indicate significantly different VMT growth rates for certain vehicle types (e.g., 34 percent growth between 2002 and 2020 in heavy-duty gasoline vehicle VMT versus 284 percent growth in light-duty diesel truck VMT over this period). The procedure first applied the AEO2006 vehicle type-based national growth rates to 2004 Minnesota estimates of VMT by vehicle type. LPG vehicle VMT were assumed to grow at the regional transportation LPG fuel consumption growth rate from AEO2006. These data were then used to calculate the estimated proportion of total VMT by vehicle type in each year. Next, these proportions were applied to the MNDOT estimates for total VMT in the State for each year to yield the vehicle type annual average growth rates displayed in Table C3.

Table C3. Minnesota Vehicle Miles Traveled Annual Growth Rates

Vehicle Type	2004-2005	2005-2010	2010-2015	2015-2020	2020-2025	2025-2030
Light-duty gas	-0.4%	2.2%	1.6%	1.4%	1.1%	0.9%
Heavy-duty gas	-0.7%	-0.3%	1.1%	1.7%	2.1%	2.3%
Light-duty diesel	3.1%	6.5%	6.6%	6.6%	7.2%	6.8%
Heavy-duty diesel	2.6%	3.1%	2.8%	2.6%	2.3%	2.3%
LPG	0%	4.9%	2.1%	1.7%	1.9%	1.6%
Total VMT	**0%**	**2.4%**	**1.9%**	**1.7%**	**1.6%**	**1.5%**

For forecasting GHG emissions, growth in fuel consumption is also needed along with VMT. Onroad gasoline and diesel fuel consumption were forecasted by developing a set of growth factors that adjusted the VMT projections to account for improvements in fuel efficiency. Fuel efficiency projections were taken from AEO2006.

The 2005-2006 growth factors for onroad diesel were also adjusted to account for increased consumption of biodiesel. The recent biodiesel mandate, which requires that 2% of diesel fuel sold at filling stations is blended with biodiesel, took effect in late September of 2005. Since the 2% mandate was in effect for approximately one quarter of the year, 2005 consumption of biodiesel was assumed to be 0.5% of diesel consumption. Biodiesel consumption was assumed to increase to 2% in 2006 and to remain at this level through 2030.

The Minnesota Legislature also recently passed an ethanol mandate that would require the state's gasoline supplies to contain 20% ethanol (E-20). This standard, which is to take effect in 2013, would double the current ethanol consumption. Since Minnesota must obtain federal approval to use E-20 blends, and this approval has not yet been granted, increased ethanol consumption was not included in the business as usual projection. If, following further review of these draft emission estimates, the standards are determined to be likely to take effect, the resulting emission reductions should be incorporated into the BAU projection.

The effects of increased fuel efficiency and increased consumption of biodiesel yield the fuel consumption annual growth rates shown in Table C4.

Table C4. Minnesota Onroad Fuel Consumption Annual Growth Rates

Vehicle Type	2005-2010	2010-2015	2015-2020	2020-2025	2025-2030
Passenger car gas	0.9%	1.2%	1.1%	0.7%	0.8%
Light-duty truck gas	1.2%	1.0%	0.8%	0.5%	0.6%
Heavy-duty gas	-0.6%	0.9%	1.5%	2.1%	2.2%
Passenger car diesel	6.4%	6.4%	6.6%	7.0%	6.8%
Light-duty truck diesel	5.7%	6.2%	6.3%	6.7%	6.6%
Heavy-duty diesel	2.7%	2.2%	1.6%	1.6%	1.7%

Emissions from transportation LPG, natural gas, and lubricants were projected using West North Central Regional fuel consumption projections from AEO2006.

Aviation Projections

Emissions from jet fuel and aviation gasoline consumption were projected from 2005 to 2006 using prime supplier sales volume of these fuels in Minnesota from EIA.[42] Emissions were projected from 2006-2030 using general aviation and commercial aircraft operations from the Federal Aviation Administration's Terminal Area Forecast System[43,44] and national aircraft fuel efficiency forecasts. To estimate changes in jet fuel consumption, itinerant aircraft operations from air carrier, air taxi/commuter, and military aircraft were first summed for each year of interest. The post-2006 estimates were adjusted to reflect the projected increase in national aircraft fuel efficiency (indicated by increased number of seat miles per gallon), as reported in AEO2006. Because AEO2006 does not estimate fuel efficiency changes for general aviation aircraft, forecast changes in aviation gasoline consumption were based solely on the projected number of itinerant general aviation aircraft operations in Minnesota, which was obtained from the Federal Aviation Administration (FAA) source noted above. The resulting compound annual growth rates are displayed in Table C5.

Table C5. Minnesota Aviation Fuels Annual Growth Rates

Fuel	2005-2010	2010-2015	2015-2020	2020-2025	2025-2030
Aviation Gasoline	-1.06%	1.04%	0.90%	0.95%	0.95%
Jet Fuel	-1.41%	1.23%	1.16%	1.12%	1.12%

Rail and Marine Vehicles Projections

Marine gasoline consumption was projected to 2020 using historical data, which shows an average annual growth rate of 3.2%. The historic data for rail shows no significant positive or negative trend; therefore, no growth was assumed for this sector. Port and offshore commercial marine emissions were projected based on linear projection of the 1990-2004 freight tonnage data, resulting in an annual average growth rate of -0.8% for 2005-2030.

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42 US Department of Energy, Energy Information Administration, "Petroleum Navigator", http://tonto.eia.doe.gov/dnav/pet/hist/c400013451a.htm.

43 Terminal Area Forecast, Federal Aviation Administration, http://www.apo.data.faa.gov/main/taf.asp.

44 2005 aircraft operations in the FAA projections were estimated using a different modeling scenario and were not consistent with the 2006-2030 projections; therefore, 2005 to 2006 growth was estimated using the historical prime supplier data from EIA.

Nonroad Engines
It should be noted that fuel consumption data from EIA includes nonroad gasoline and diesel fuel consumption in the commercial and industrial sectors. Emissions from these nonroad engines are included in the inventory and forecast for the residential, commercial, and industrial (RCI) sectors. Table C6 shows how EIA divides gasoline and diesel fuel consumption between the transportation, commercial, and industrial sectors.

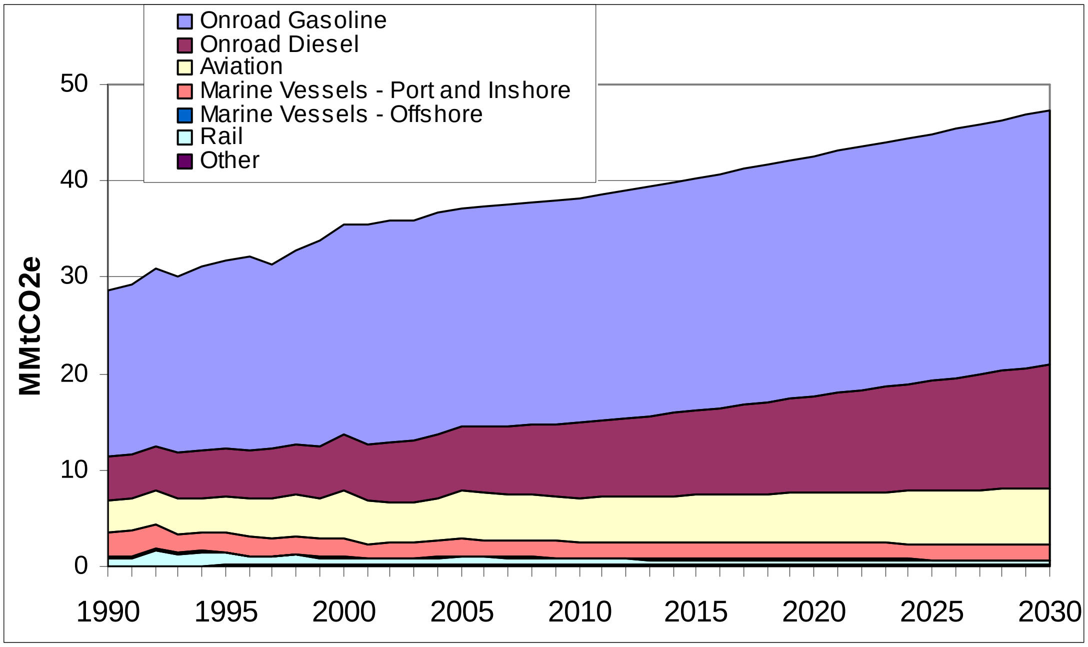
Table C6. EIA Classification of Gasoline and Diesel Consumption

Sector	Gasoline Consumption	Diesel Consumption
Transportation	Highway vehicles, marine	Vessel bunkering, military use, railroad, highway vehicles
Commercial	Public non-highway, miscellaneous use	Commercial use for space heating, water heating, and cooking
Industrial	Agricultural use, construction, industrial and commercial use	Industrial use, agricultural use, oil company use, off-highway vehicles

Results

As shown in Figure C1, onroad gasoline consumption accounts for the largest share of transportation GHG emissions. Emissions from onroad gasoline vehicles increased by about 31% from 1990-2005 and contributed 61% of total transportation emissions in 2005. GHG emissions from onroad diesel fuel consumption increased by 49% from 1990 to 2005, and by 2005 accounted for 18% of GHG emissions from the transportation sector. Emissions from aviation grew by 44% between 1990 and 2005 to cover 13% of transportation emissions in 2005, and emissions from boats and ships decreased by 31% from 1990-2005 to cover 5% of transportation emissions in 2005. Emissions from all other categories combined (locomotives, natural gas and LPG, and oxidation of lubricants) contributed less than 3% of total transportation emissions in 2005.

Figure C1. Transportation GHG Emissions by Fuel, 1990-2030



GHG emissions from all onroad vehicles combined are projected to increase by 32% between 2005 and 2030, due to a 56% increase in VMT during this period and projected fuel efficiency improvements. Historical growth for diesel fuel was stronger than for gasoline. This trend is expected to continue for the 2005-2030 period, with gasoline and diesel fuel consumption projected to increase by 15% and 93%, respectively. Jet fuel and aviation gasoline consumption is projected to increase by 17% between 2005 and 2030. The historical negative growth for marine vessels is projected to continue with a decline of 7% from 2005 to 2030.

Key Uncertainties

Projections of VMT
One source of uncertainty is the future year vehicle mix, which was calculated based on national growth rates for specific vehicle types. These growth rates may not reflect vehicle-type specific VMT growth rates for the state.

Uncertainties in Aviation Fuel Consumption and Projection
The jet fuel and aviation gasoline fuel consumption from EIA is actually fuel *purchased* in the state, and therefore includes fuel consumed during state-to-state flights and international flights. There is a question as to whether fuel consumption associated with state-to-state and international air flights should be included in Minnesota's inventory; however, data were not available to subtract fuel consumption occurring outside of Minnesota air space from total jet fuel estimates (also IPCC guidance directs countries to include all emissions associated with fuel sales in the totals for each country). Another uncertainty associated with aviation emissions is the use of general aviation forecasts to project aviation gasoline consumption. General aviation aircraft consume both jet fuel and aviation gasoline, but fuel specific data were not available.

Uncertainties in Marine Fuel Consumption
There are several assumptions that introduce uncertainty into the estimates of commercial marine fuel consumption. These assumptions include:

- 75% of marine diesel and 25% of residual fuel is consumed in port (based on EPA NEI assumptions);
- The state's fraction of national fuel consumption is proportional to the fraction of national freight tonnage moving through Minnesota ports; and
- Future emissions from marine vessels will follow the same trend as historical freight tonnage.

Our handling of commercial marine emissions differs from commercial aircraft in that we have attempted to account only for fuel consumption that occurs within the State's waters. Reviewers might decide to base the estimates on total fuel sales instead to maintain consistency with the methods used in the aircraft subsector.

Appendix D. Industrial Processes

Overview

Emissions in the industrial processes category span a wide range of activities, and reflect non-combustion sources of greenhouse gas (GHG) emissions from several industries. The industrial processes that exist in Minnesota, and for which emissions are estimated in this inventory, include the following:

- Carbon Dioxide (CO_2) from:
  - Production of lime and taconite;
  - Consumption of limestone;
  - Peat mining and use;
- Sulfur hexafluoride (SF_6) from transformers used in electric power transmission and distribution (T&D) systems;
- Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) from consumption of substitutes for ozone-depleting substances (ODS) used in cooling and refrigeration equipment;
- HFCs, PFCs, and SF_6 from semiconductor manufacture;
- CO_2 from ammonia (NH_3) manufacturing; and
- Nitrous oxide (N_2O) from medical uses.

Other industrial processes that are sources of GHG emissions but are not found in Minnesota include the following:

- Nitrous oxide (N_2O) from nitric and adipic acid production;
- PFCs from aluminum production;
- SF_6 from magnesium production and processing;
- CO_2 from cement and soda ash production; and
- HFCs from HCFC-22 production.

Emissions and Reference Case Projections

The Minnesota Pollution Control Agency (MPCA) has prepared an inventory of GHG emissions from 1970 through 2004 for industrial non-fuel use processes. The MPCA inventory follows the United States Environmental Protection Agency's (US EPA) methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for this sector.[45] Annual activity data for each industry was compiled by MPCA using information it has collected from industrial sources or compiled from US government information sources. Table D1 lists the data sources used to support projection of industrial process emissions from 2005 through 2020.

[45] EIIP, Volume VIII: Chapter. 6. "Methods for Estimating Non-Energy Greenhouse Gas Emissions from Industrial Processes", August 2004.

Table D1. Approach to Estimating Projections for 2005 through 2020

			Annual Growth Rates (%)		
Source Category	**Projection Assumptions**	**Data Source**	**2005 to 2010**	**2010 to 2015**	**2015 to 2020**
Lime Production	Based on Minnesota employment forecast for 2004-2014 for the Sugar/Confectionery Product Manufacture sector (Standard Industrial Classification (SIC) 28)	Minnesota Department of Employment and Economic Development, Industry Projections 2004-2014, http://www.deed.state.mn.us/lmi/tools/projections/default.aspx.	-0.4	-0.4	-0.4
Limestone Consumption	Based on Minnesota employment forecast for 2004-2014 for Primary Metal Manufacturing (SIC 331) and Glass and Glass Product Manufacturing (SIC 3272). Assumed no growth for limestone use in flue gas desulfurization scrubbers.	Ditto	Steel -0.2 Glass 1.0	Steel -0.2 Glass 1.0	Steel -0.2 Glass 1.0
Taconite Production	Based on annual growth rate in historic production of flux pellets from 1999-2004.	Production data reported to state.	1%	1%	1%
Peat Mining and Use	Assumed no growth. From 1990 to 2004, average annual growth rate in tons of peat mined was about 2%, but fluxuated significantly over this time period.	Assumed no growth for this industry until better data are available to estimate growth.	0	0	0
Ammonia (NH_3) Manufacture	This industry discontinued operation in Minnesota after 1996.		0	0	0
ODS Substitutes	Based on national growth rate for use of ODS substitutes.	EPA, 2004 ODS substitutes cost study report (http://www.epa.gov/ozone/snap/emissions/TMP6si9htnvca.htm).	7.9	5.8	5.3
Electric Power T&D Systems	National growth rate (based on aggregate for all stewardship program categories provided in referenced data source).	US Department of State, US Climate Action Report, May 2002, Washington, D.C., May 2002 (Table 5-7). http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BNQ76/$File/ch5.pdf	-6.2	-9.0	-2.8
Semiconductor Manufacturing	Ditto	Ditto	-6.2	-9.0	-2.8
Medical Uses of N_2O	Minnesota population growth for 2005 through 2020.	Minnesota Department of Administration, Office of Geographic and Demographic Analysis, http://www.mnplan.state.mn.us/resource.html?Id=3124.	1.0	0.9	0.7

Results

Figures D1 and D2 show historic and projected emissions for the industrial processes sector from 1990 to 2020. Table D2 shows the historic and projected emission values upon which Figures D1 and D2 are based. Total gross Minnesota GHG emissions were about 2.5 $MMtCO_2e$ in 1990, 4.3 $MMtCO_2e$ in 2005, and are projected to increase to about 6.6 $MMtCO_2e$ in 2020. Emissions from the overall industrial processes category are expected to grow by about 3.1% annually from 2005 through 2020, as shown in Figures D1 and D2, with emissions growth after 2000 essentially entirely associated with increasing use of HFCs and PFCs in refrigeration and air conditioning equipment.

Figure D1. GHG Emissions from Industrial Processes, 1990-2020

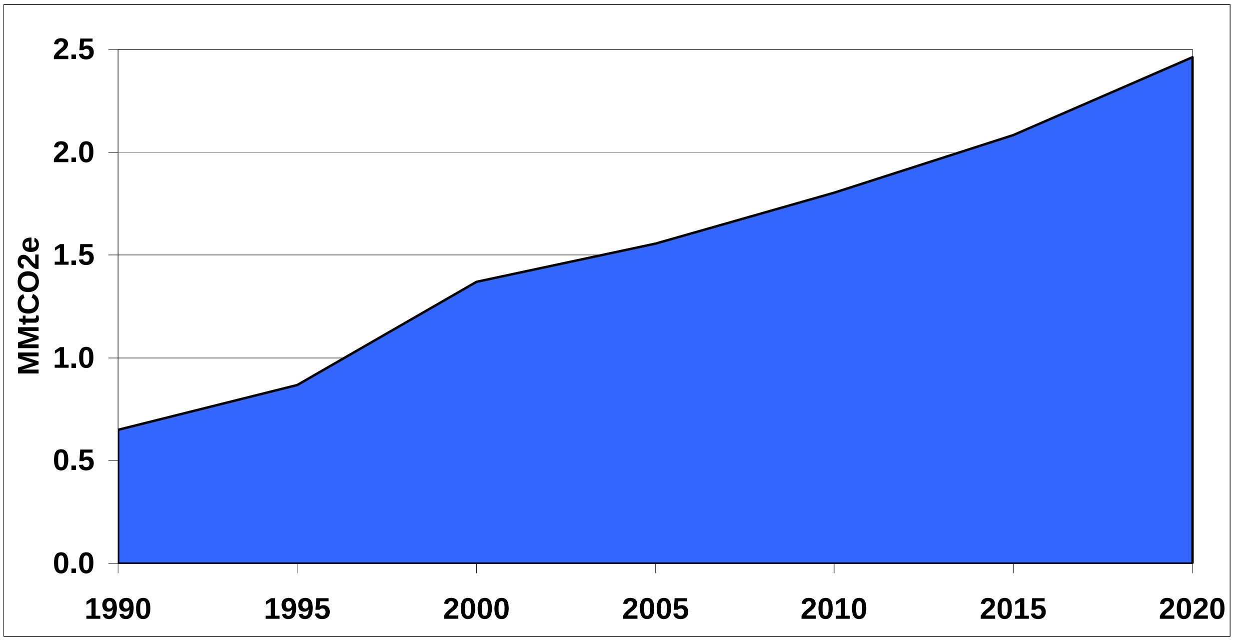


Figure D2. GHG Emissions from Industrial Processes, 1990-2020, by Source

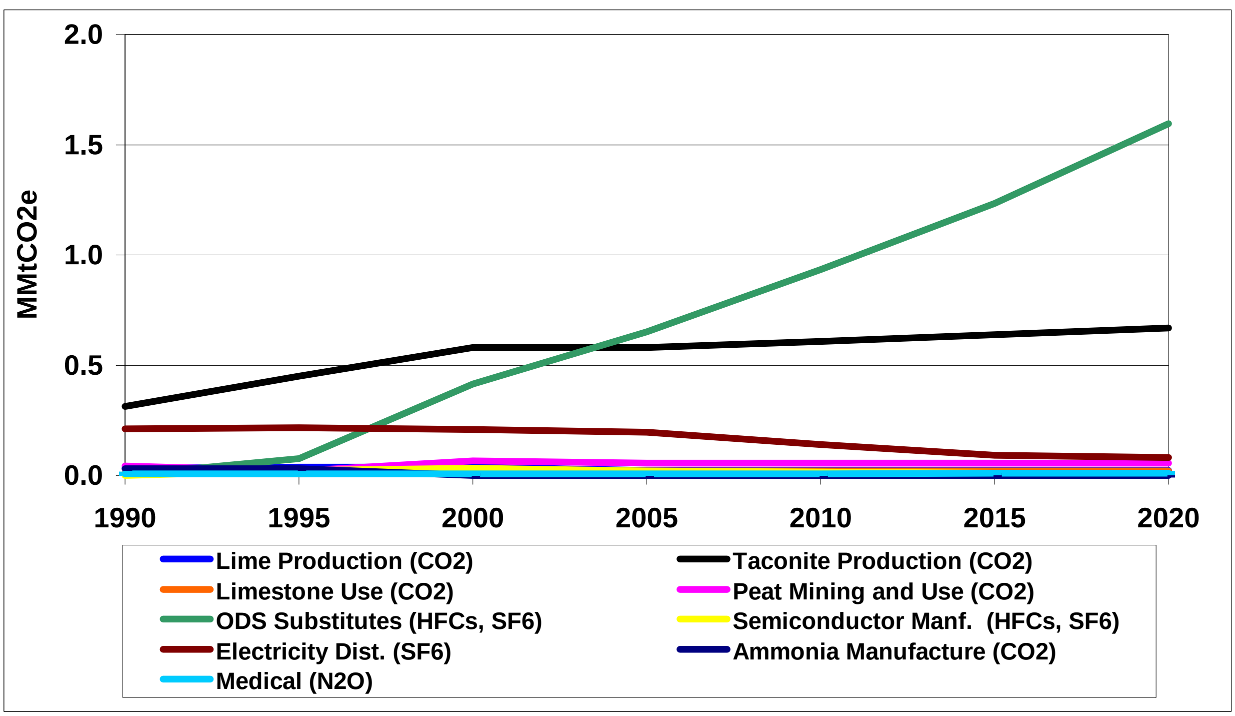


Table D2. Historic and Projected Emissions for the Industrial Processes Sector ($MMtCO_2e$)

Industry	1990	1995	2000	2005	2010	2015	2020
Lime Production (CO_2)	0.03	0.04	0.04	0.02	0.02	0.02	0.02
Limestone Use (CO_2)	0.01	0.01	0.02	0.02	0.02	0.02	0.02
Taconite Production (CO_2)	0.31	0.45	0.58	0.58	0.61	0.64	0.67
Peat Mining and Use (CO_2)	0.04	0.02	0.07	0.06	0.06	0.06	0.06
Ammonia Manufacture (CO_2)	0.03	0.03	0.00	0.00	0.00	0.00	0.00
ODS Substitutes (HFC, PFC, and SF_6)	0.002	0.08	0.41	0.65	0.93	1.23	1.60
Semiconductor Manufacturing (HFC, PFC, and SF_6)	-	0.02	0.03	0.02	0.01	0.01	0.01
Electricity Dist. (SF_6)	0.21	0.22	0.21	0.20	0.14	0.09	0.08
Medical (N_2O)	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total	**0.65**	**0.87**	**1.37**	**1.56**	**1.80**	**2.08**	**2.46**

Substitutes for Ozone-Depleting Substances (ODS)

HFCs and PFCs are used as substitutes for ODS, most notably CFCs (CFCs are also potent warming gases, with global warming potentials on the order of thousands of times that of CO_2 per unit of emissions) in compliance with the *Montreal Protocol* and the *Clean Air Act Amendments of 1990*.[46] Even low amounts of HFC and PFC emissions, for example, from leaks and other releases associated with normal use of the products, can lead to high GHG emissions on a CO_2e basis. Estimated emissions of HFCs and PFCs have increased from 0.002 $MMtCO_2e$ in 1990 to about 1.6 $MMtCO_2e$ in 2000, and are projected to increase at an average rate of 7% per year from 2000 to 2020 due to increased substitutions of these gases for ODS (see dark green line in Figure D2). The projected rate of increase for these emissions is based on projections for national emissions from the US EPA report referenced in Table D1.

Taconite Production

The majority of taconite iron ore processing in the US occurs in Minnesota. This industry produces usable concentrations of iron-bearing material by removing nonferrous rock (gangue) from low-grade ore. Processing of taconite consists of crushing and grinding the ore to free iron-bearing particles, concentrating the ore by separating the particles from the waste material (gangue), and pelletizing the iron ore concentrate. The pellets are hardened by a procedure called induration, which involves the use of a furnace or kiln to harden the pellets, followed by processing in a separate "cooler" unit. These pelletizing processes release CO_2 emissions. Acid pellets are produced from iron ore and a binder only, and flux pellets are produced by adding between 1% and 10% limestone to the ore and binder before pelletization. The MPCA estimated

[46] As noted in EIIP Chapter 6, ODS substitutes are primarily associated with refrigeration and air conditioning, but also many other uses including as fire control agents, cleaning solvents, aerosols, foam blowing agents, and in sterilization applications. The applications, stocks, and emissions of ODS substitutes depend on technology characteristics in a range of equipment types. For the US national inventory, a detailed stock vintaging model was used to track ODS substitutes uses and emissions, but this modeling approach has not been completed at the state level.

CO_2 emissions for 1990 through 2004 using production data obtained from plants and US EPA emission factors.[47]

As shown in Figure D2, CO_2 emissions associated with pellet production from 1990 to 2000 increased by about 85% (from 0.31 to 0.58 $MMtCO_2e$) and have leveled off since 2000. In the past five years (1999 through 2004), the majority of pellets have been produced using the flux pellet process. Flux pellet production from 1999 through 2004 increased at an average annual rate of about 1%. For the purpose of this preliminary forecast, this annual growth rate (1%) was used to project emissions from 2005 through 2020. In 2020, emissions are projected to be about 0.67 $MMtCO_2e$.

Electricity Distribution
Emissions of SF_6 from electrical equipment have experienced declines since the mid-nineties (see brown line in Figure D2), mostly due to voluntary action by industry. SF_6 is used as an electrical insulator and interrupter in the electricity T&D system. Emissions for Minnesota from 1990 to 2004 were estimated based on the miles of transmission lines and an emission factor of 1.93 pounds of SF_6 per mile of transmission line. The *US Climate Action Report* shows expected decreases in these emissions at the national level, and the same rate of decline is assumed for emissions in Minnesota. The decline in SF_6 emissions in the future reflects expectations of future actions by the electric industry to reduce these emissions. Sulfur hexafluoride emissions from electrical equipment were about 0.21 $MMtCO_2e$ in 1990 and are projected to be 0.08 $MMtCO_2e$ in 2020.

Peat Mining and Use
According to the United States Geological Survey (USGS), peat is a renewable, natural, organic material that occurs predominately in shallow wetland areas where large deposits develop from the gradual decomposition of plant matter under anaerobic (low oxygen) conditions. Peat is used in a variety of horticultural and agricultural applications because its fibrous structure and porosity promote a combination of water-retention and drainage. Commercial applications include potting soils, lawn and garden soil amendments, and turf maintenance on golf courses. In industry, peat is used primarily as a filtration medium to remove toxic materials from process waste streams, pathogens from sewage effluents, and deleterious materials suspended in municipal storm-drain water. In its dehydrated form, peat is a highly effective absorbent for fuel and oil spills on land and water.[48]

The mining and usage of peat releases CO_2 emissions. The MPCA estimated emissions for this sector for 1990 through 2004 using mining production data from the US Geological Survey (USGS), *Minerals Yearbook*. The amount of peat mined in Minnesota varied considerably from 1990 through 2004, but had an average annual overall growth rate of 2% over this 14-year period. Information was not available to determine if this historical growth rate will continue into the future, therefore, emissions for this category were assumed not to change after 2004. Relative to total industrial non-combustion process emissions, the estimated emissions associated with

[47] US EPA, AP-42, Supplement C, Section 11.23 (Taconite Ore Processing), February 1997, http://www.epa.gov/ttn/chief/ap42/ch11/related/c11s23.html.
[48] USGS, http://minerals.usgs.gov/minerals/pubs/commodity/peat/index.html#myb.

peat mining and use are low (about 0.04 $MMtCO_2e$ in 1995, 0.07 $MMtCO_2e$ in 2000, and 0.06 $MMtCO_2e$ in 2004), and therefore cannot be seen in Figure D2 due to scaling effects.

Lime Production
Lime is a manufactured product that is used in many chemical, industrial, and environmental applications including steel making, construction, pulp and paper manufacturing, and water and sewage treatment. Lime is manufactured by heating limestone (mostly $CaCO_3$) in a kiln, creating calcium oxide and CO_2. The CO_2 is driven off as a gas and is normally emitted to the atmosphere, leaving behind a product known as quicklime. Some of this quicklime undergoes slaking (combining with water), which produces hydrated lime. The consumption of lime for certain uses, specifically the production of precipitated $CaCO_3$ and refined sugar, results in the reabsorption of some airborne CO_2 (see footnote 1 for reference to EIIP guidance document.). Emissions are estimated by multiplying the amount of high-calcium and dolomitic lime produced by emission factors for each product.

Emissions were estimated for 1991 through 2004 using the amount of lime produced and an emission factor of 0.79 ton CO_2 per ton lime produced. Lime production data for 1990 were not available for Minnesota, therefore, production data for 1991 were used as a surrogate to estimate emissions for 1990. The annual employment growth rate for Minnesota's Sugar/Confectionery Product Manufacture subsector (i.e., -0.4% annual) for 2004 through 2014 was used to project emissions to 2020, assuming no substantial change in productivity in the subsector. Relative to total industrial non-combustion process emissions, CO_2 emissions from lime production are low (about 0.03 $MMtCO_2e$ in 1990, 0.04 $MMtCO_2e$ from 1994 through 2003, and 0.02 $MMtCO_2e$ from 2004 through 2020), and therefore appear at the bottom of the graph because of scaling effects in Figure D2.

Limestone Consumption
Limestone is a basic raw material used by a wide variety of industries, including the construction, agriculture, chemical, glass manufacturing, and environmental pollution control industries, as well as in metallurgical industries such as magnesium production. Emissions associated with the use of limestone to manufacture steel and glass and for use in flue-gas desulfurization scrubbers to control sulfur dioxide emissions from the combustion of coal in boilers are included in the industrial processes sector.[49] The MPCA compiled activity data for 1990 through 2004 on the amount of limestone used by steel and glass manufacturing plants and by flue-gas desulfurization scrubbers and applied the US EPA emission factor (0.44 ton CO_2 per ton limestone processed) to estimate emissions for these sources. Minnesota annual employment forecasts for 2004-2014 for the Primary Metal Manufacturing (-0.2%) and Glass and Glass Product Manufacturing (1.0%) subsectors were used to project emissions from 2005 through 2020 for the steel and glass manufacturing CO_2 emissions sources, respectively. Information was not readily available to determine how to project emissions associated with the use of limestone

[49] In accordance with EIIP Chapter 6 methods, emissions associated with the following uses of limestone and dolomite are not included in this category: (1) crushed limestone consumed for road construction or similar uses (because these uses do not result in CO_2 emissions), (2) limestone used for agricultural purposes (which is counted under the methods for the agricultural sector), and (3) limestone used in cement production (which is counted in the methods for cement production).

in flue-gas desulfurization scrubbers, therefore, emissions for this sector were assumed not to change over time. Relative to total industrial non-combustion process emissions, estimated emissions associated with limestone and dolomite consumption are low (about 0.01 $MMtCO_2e$ in 1990 and 0.02 $MMtCO_2e$ in 2020), and therefore cannot be seen in Figure D2 due to scaling effects.

Semiconductor Manufacture
Emissions of SF_6 and HFCs from the manufacture of semiconductors have experienced declines since 2000. The MPCA used the dollar value of shipments for semiconductor sales in Minnesota and the US EPA emission factor to estimate emissions for each year from 1992 through 2004. Data for 1990 and 1991 were not available, therefore, emissions were not estimated for those two years. The US Climate Action Report shows expected decreases in these emissions at the national level, and the same rate of decline is assumed for emissions in Minnesota. The decline in emissions in the future reflects expectations of future actions by the semiconductor industry to reduce these emissions. Relative to total industrial non-combustion process emissions, estimated emissions associated with semiconductor manufacturing are low (about 0.02 $MMtCO_2e$ in 1995 and 0.01 $MMtCO_2e$ in 2020), and therefore cannot be seen in Figure D2 due to scaling effects.

Ammonia (NH_3) Production
The MPCA estimated emissions for 1990 through 1996 associated with the production of NH_3, using plant-specific NH_3 production data and the US EPA emission factor (1.2 $MMtCO_2/MtNH_3$ produced). Ammonia manufacturing in Minnesota was discontinued after 1996. From 1990 through 1996, emissions were estimated to be about 0.03 $MMtCO_2e$ annually.

Medical Uses of N_2O
The MPCA estimated emissions for 1990 through 2004 associated with medical uses (e.g., as an anesthetic) of N_2O, based on a per-capita emission factor it has developed. Minnesota's average annual population growth rate for 2005 through 2020 was used to project emissions for this category. Relative to total industrial non-combustion process emissions, estimated emissions associated with medical uses of N_2O are low (about 0.01 $MMtCO_2e$ from 1990 through 2020), and therefore, cannot be seen in Figure D2 due to scaling effects.

Key Uncertainties

Key sources of uncertainty underlying the estimates above are as follows:

- Since emissions from industrial processes are determined by the level of production and the production processes of a few key industries—and in some cases, a few key plants—there is relatively high uncertainty regarding future emissions from the industrial processes category as a whole. Future emissions depend on the competitiveness of Minnesota manufacturers in these industries, and the specific nature of the production processes used in Minnesota.
- The projected largest source of future industrial emissions, HFCs and PFCs used in cooling applications, is subject to several uncertainties as well. Emissions through 2020 and beyond will be driven by future choices regarding mobile and stationary air

conditioning technologies and the use of refrigerants in commercial applications, for which several options currently exist.

- The annual employment growth rates for Minnesota's manufacturing sectors for 2004 through 2014 were used to project emissions from 2005 to 2020 for the lime production and limestone consumption sectors. There is significant uncertainty associated with assuming that the 10-year growth rates will remain the same for 2015 through 2020. If these industries implement significant production improvements to increase the efficiency for producing their goods, it is possible that these industries would show a decline in employment.

Appendix E. Fossil Fuel Production Industry

Overview

The inventory for this subsector of the Energy Supply sector includes methane (CH_4) emissions associated with the transmission and distribution (T&D) of natural gas in Minnesota, as well as carbon dioxide (CO_2) emissions associated with the combustion of natural gas in compressor engines (referred to as pipeline fuel). There is no oil or natural gas production or processing, and no coal mining in Minnesota. In 2005, emissions from natural gas T&D accounted for an estimated 2.25 million metric tons (MMt) of CO_2 equivalent (CO_2e) of greenhouse gas (GHG) emissions in Minnesota, and are estimated to increase to about 3.5 MMtCO_2e by 2020.

Natural Gas T&D Emissions and Reference Case Projections

The Minnesota Pollution Control Agency (MPCA) has prepared a detailed inventory of GHG emissions for this subsector covering the years 1970 through 2004. The MPCA inventory follows the United States Environmental Protection Agency's (US EPA) methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for natural gas T&D systems and the combustion of fossil fuels.[50,51]

For the natural gas distribution system, annual CH_4 emissions were estimated for each year using US EPA emission factors and (1) the miles of distribution pipeline constructed of cast iron, unprotected steel, protected steel, and plastic; (2) the number of protected and unprotected steel, copper, and plastic service connections; (3) the number of metering and pressure regulating stations; and (4) the number of residential and commercial customer meters. For the transmission system, CH_4 emissions were estimated for each year using US EPA emission factors and the (1) the total miles of pipeline; (2) the total number of pipeline interconnects, direct industrial customers, transmission pipeline and storage compressor stations, and storage wells; and (3) the amount of gas withdrawn from storage. The MPCA obtained the annual amount of natural gas pipeline fuel combusted in compressor engines from the United States Department of Energy (US DOE), Energy Information Administration (EIA), *Natural Gas Annual*.[52]

For the natural gas distribution system, a compound annual average growth rate of 1.6% was applied to forecast emissions from 2006 through 2020. This annual growth assumption is based on the historical annual average growth rate in CH_4 emissions associated with the natural gas distribution system in Minnesota. This historical growth rate is slightly higher than the 1.5% annual growth rate calculated from the EIA's AEO2007 forecast for natural gas consumption for all sectors for the West North Central region of the US for 2005 through 2020.

For the natural gas transmission system and for pipeline fuel use, a compound annual average growth rate of 3.3% was applied to forecast emissions from 2006 through 2020. This annual

[50] Emission Inventory Improvement Program (EIIP), *Volume VIII*: Chapter. 5. "Methods for Estimating Methane Emissions from Natural Gas and Oil Systems", March 2005.
[51] EIIP, *Volume VIII*: Chapter 1 "Methods for Estimating Carbon Dioxide Emissions from Combustion of Fossil Fuels", August 2004.
[52] http://tonto.eia.doe.gov/dnav/ng/ng_sum_snd_dcu_SMN_a.htm.

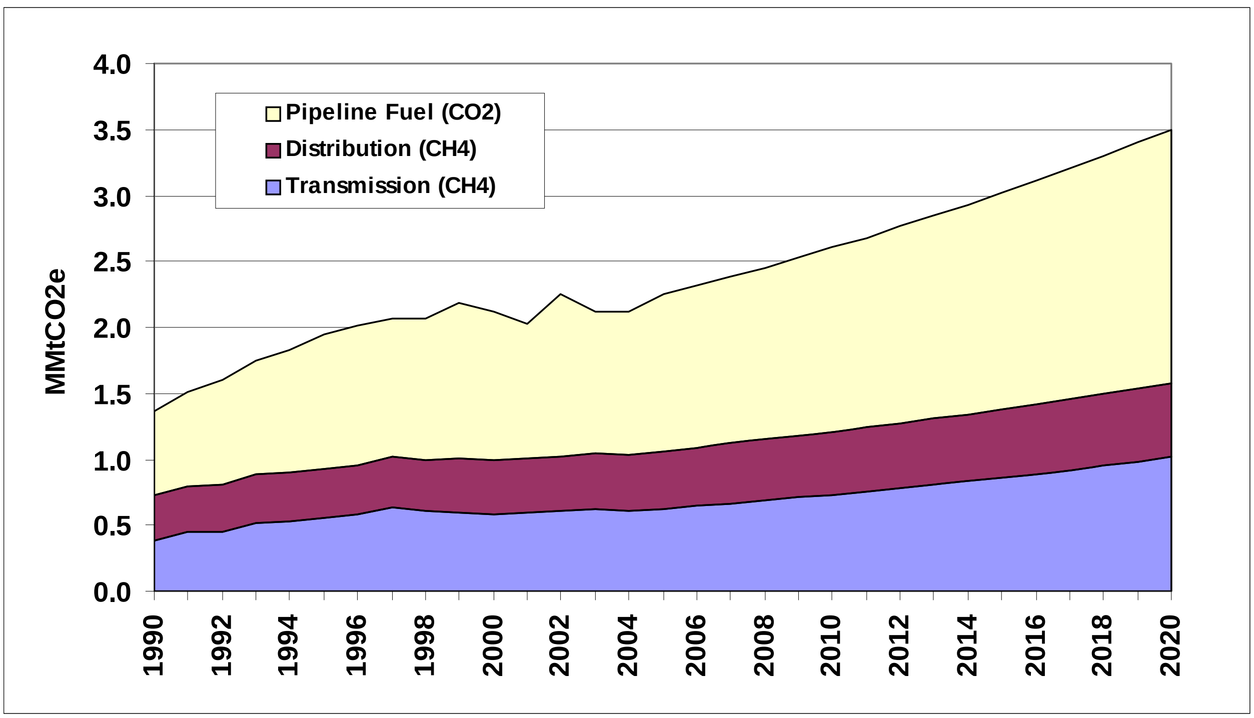
growth assumption is based on the historical annual average growth rate in CH_4 emissions associated with the gas transmission system in Minnesota.

Results

Figure E1 displays the estimated GHG emissions associated with natural gas T&D system and pipeline fuel use in Minnesota from 1990 to 2004, with projections to 2020. Figure E1 was developed from the emissions data in Table E1. Table E2 shows the relative contributions of emissions associated with the distribution and transmission systems and pipeline fuel use to total subsector emissions.

Emissions associated with this subsector were estimated to be about 1.37 $MMtCO_2e$ in 1990 and 2.25 $MMtCO_2e$ in 2005, and are projected to total 3.5 $MMtCO_2e$ in 2020. From 1990 through 2004, natural gas companies in Minnesota reduced the rate of CH_4 emissions from the distribution system by replacing cast iron and unprotected steel distribution pipe with protected steel and plastic pipe. Gas companies also replaced unprotected steel service connections with protected steel and plastic service connections that helped reduce emissions during this 14-year period.

Figure E1. Methane Emissions and Projections from the Fossil Fuel Industry



Source: Calculations based on approach described in text.

Table E1. Emissions Inventory and Reference Case Projections (MMtCO$_2$e)

Fuel Type	1990	1995	2000	2005	2010	2015	2020
Transmission (CH_4)	0.39	0.55	0.59	0.62	0.73	0.86	1.01
Distribution (CH_4)	0.35	0.37	0.41	0.44	0.48	0.52	0.56
Pipeline Fuel (CO_2)	0.63	1.02	1.12	1.18	1.39	1.64	1.93
Total	1.37	1.95	2.12	2.25	2.60	3.02	3.50

Table E2. Proportions of Total Subsector Emissions by Type and Source (%)

Fuel Type	1990	1995	2000	2005	2010	2015	2020
Transmission (CH_4)	28	28	28	28	28	29	29
Distribution (CH_4)	25	19	19	20	18	17	16
Pipeline Fuel (CO_2)	46	52	53	53	54	54	55

Key Uncertainties

The main uncertainties in estimating emissions for the natural gas T&D subsector are associated with the reference case projection assumptions. For this preliminary forecast, it was assumed that emissions would increase at the historical rate of emissions growth for the T&D system and pipeline fuel use. Market factors (e.g., price of natural gas relative to other available energy sources) could have a significant impact on the growth for this sector. In addition, neither potential future application of improvements to pipeline technologies that can yield emission reductions nor the potential effect of demand-side management programs in reducing gas consumption have been accounted for in the emissions projections shown here.

Appendix F. Agriculture

Overview

The emissions discussed in this appendix refer to non-energy methane (CH_4) and nitrous oxide (N_2O) emissions from enteric fermentation, manure management, and agricultural soils. Emissions and sinks of carbon in agricultural soils are also covered. Energy emissions (combustion of fossil fuels in agricultural equipment) are included in the residential, commercial, and industrial (RCI) sector estimates.

There are two livestock sources of greenhouse gas (GHG) emissions: enteric fermentation and manure management. Methane emissions from enteric fermentation are the result of normal digestive processes in ruminant and non-ruminant livestock. Microbes in the animal digestive system break down food and emit CH_4 as a by-product. More CH_4 is produced in ruminant livestock because of digestive activity in the large fore-stomach. Methane and N_2O emissions from the storage and treatment of livestock manure (e.g., in compost piles or anaerobic treatment lagoons) occur as a result of manure decomposition. The environmental conditions of decomposition drive the relative magnitude of emissions. In general, the more anaerobic the conditions are, the more CH_4 is produced because decomposition is aided by CH_4-producing bacteria that thrive in oxygen-limited aerobic conditions. Under aerobic conditions, N_2O emissions are dominant. Emissions estimates from manure management are based on manure that is stored and treated at livestock operations. Emissions from manure that is applied to agricultural soils as an amendment or deposited directly to pasture and grazing land by grazing animals are accounted for in the agricultural soils emissions.

The management of agricultural soils can result in N_2O emissions and net fluxes of carbon dioxide (CO_2) causing emissions or sinks. In general, soil amendments that add nitrogen to soils can also result in N_2O emissions. Nitrogen additions drive underlying soil nitrification and de-nitrification cycles, which produce N_2O as a by-product. The emissions estimation methodologies used in this inventory account for several sources of N_2O emissions from agricultural soils, including decomposition of crop residues, synthetic and organic fertilizer application, manure application, sewage sludge, nitrogen fixation, and histosols (high organic soils, such as wetlands or peatlands) cultivation. Both direct and indirect emissions of N_2O occur from the application of manure, fertilizer, and sewage sludge to agricultural soils. Direct emissions occur at the site of application and indirect emissions occur when nitrogen leaches to groundwater or in surface runoff or volatilizes and is transported off-site before entering the nitrification/denitrification cycle.

The net flux of CO_2 in agricultural soils depends on the balance of carbon losses from management practices and gains from organic matter inputs to the soil. Carbon dioxide is absorbed by plants through photosynthesis and ultimately becomes the carbon source for organic matter inputs to agricultural soils. When inputs are greater than losses, the soil accumulates carbon and there is a net sink of CO_2 into agricultural soils. In addition, soil disturbance from the cultivation of histosols releases large stores of carbon from the soil to the atmosphere.

Other agricultural soils emissions include CH_4 and N_2O from crop residue burning. Also, CH_4 emissions occur during rice cultivation. Finally, the practice of adding limestone and dolomite to agricultural soils results in CO_2 emissions.

Emissions Inventory and Reference Case Projection Methods

Methane and Nitrous Oxide
GHG emissions for 1990 through 2005 were estimated by MPCA using EPA methods and emission factors as provided in the Emission Inventory Improvement Program (EIIP) guidance document for the sector and the national GHG inventory.[53,54] These methods apply emission factors developed for the US to activity data for the agriculture sector. Activity data include livestock population statistics, crop production statistics, amounts of fertilizer applied to crops, and trends in manure management practices. This methodology is based on international guidelines developed by sector experts for preparing GHG emissions inventories.[55]

Data on crop production in Minnesota from 1990 to 2005 and the number of animals in the state from 1990 to 2002 were obtained by MPCA.[56] The distribution of manure management systems for each livestock category, fertilizer usage data and data on acres of cultivated histosols (high organic content soils) were obtained by MPCA.[57]

Agricultural residue burning was not estimated in the MPCA inventory; therefore, emissions were estimated using the United States Environmental Protection Agency's (US EPA) State Greenhouse Gas Inventory Tool (SGIT) software. The SGIT methodology calculates emissions by multiplying the amount (e.g., bushels or tons) of each crop produced by a series of factors to calculate the amount of crop residue produced, the resultant dry matter, the carbon/nitrogen content of the dry matter, and the fraction of residue burned.

Emissions from enteric fermentation and manure management were projected based on forecasted animal populations. Dairy cattle forecasts were based on state-level projections of dairy cows from the Food and Agricultural Policy Research Institute (FAPRI).[58] Projections for all other livestock categories, except sheep, were estimated based on linear forecasts of the historical 1990-2004 populations. The sheep population dropped by almost 50% between 2003 and 2004, and forecasting the 1990-2004 historical sheep populations resulted in negative

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[53] GHG emissions were calculated using SGIT, with reference to EIIP, Volume VIII: Chapter 8. "Methods for Estimating Greenhouse Gas Emissions from Livestock Manure Management", August 2004; Chapter 10. "Methods for Estimating Greenhouse Gas Emissions from Agricultural Soil Management", August 2004; and Chapter 11. "Methods for Estimating Greenhouse Gas Emissions from Field Burning of Agricultural Residues", August 2004.
[54] Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004, U.S. Environmental Protection Agency, April 2006, http://epa.gov/climatechange/emissions/usinventoryreport.html.
[55] Revised 1996 1ntergovermental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, published by the National Greenhouse Gas Inventory Program of the IPCC, available at (http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm; and Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, published in 2000 by the National Greenhouse Gas Inventory Program of the IPCC, available at: (http://www.ipcc-nggip.iges.or.jp/public/gp/english/).
[56] MPCA
[57] MPCA
[58] FAPRI Agricultural Outlook 2006, Food and Agricultural Policy Research Institute, http://www.fapri.iastate.edu/outlook2006.

populations before 2030. Therefore, no growth from the 2004 population was assumed for this category. Livestock population growth rates are shown in Table F1.

Table F1. Growth Rates Applied for the Enteric Fermentation and Manure Management Categories

Livestock Category	2005-2030 Annual Growth
Dairy Cattle	-2.4%
Beef Cattle on Feed	-1.4%
Beef Cattle not on Feed	-0.4%
Swine	1.6%
Sheep	0.0%
Goats	3.0%
Horses and Mules	2.8%
Turkeys	1.9%
Broilers	-2.5%

Projections for agricultural burning and agricultural soils were based on linear extrapolation of the 1990-2004 historical data. Table F2 shows the 2005-2030 annual growth rates estimated for each category.

Table F2. Growth Rates Applied for Agricultural Soils and Burning

Agricultural Category	2005-2030 Annual Growth
Mineral Fertilizer	1.7%
Manure Soil Applications	-0.2%
Legumes	1.6%
Crop Residues	2.1%
Atmospheric Deposition	0.6%
Cultivated Histosols	0.7%
Leaching and Runoff	1.4%
Rice Cultivation	3.7%
Residential Fertilizer	1.6%
Agricultural Burning	1.9%

Soil Carbon

Net carbon fluxes from agricultural soils have been estimated by researchers at the Natural Resources Ecology Laboratory at Colorado State University and are reported in the US Inventory of Greenhouse Gas Emissions and Sinks[59] and the US Agriculture and Forestry Greenhouse Gas Inventory. The estimates are based on the Intergovernmental Panel on Climate Change (IPCC)

[59] US Inventory of Greenhouse Gas Emissions and Sinks: 1990-2004 (and earlier editions), US Environmental Protection Agency, Report # 430-R-06-002, April 2006. Available at: http://www.epa.gov/climatechange/emissions/usinventoryreport.html.

methodology for soil carbon adapted to conditions in the US. Preliminary state-level estimates of CO_2 fluxes from mineral soils and emissions from the cultivation of organic soils were reported in the US Agriculture and Forestry Greenhouse Gas Inventory.[60] Currently, these are the best available data at the state-level for this category. The inventory did not report state-level estimates of CO_2 emissions from limestone and dolomite applications; hence, this source is not included in this inventory.

Carbon dioxide fluxes resulting from specific management practices were reported. These practices include: conversions of cropland resulting in either higher or lower soil carbon levels; additions of manure; participation in the Federal Conservation Reserve Program (CRP); and cultivation of organic soils (with high organic carbon levels). For Minnesota, Table F3 shows a summary of the latest estimates available from the United States Department of Agriculture (USDA), which are for 1997.[61] These data show that changes in agricultural practices are estimated to result in emissions of 4.1 million metric tons of CO_2 equivalent per year ($MMtCO_2e$/yr) in Minnesota. This flux is driven largely by the amount of cultivated organic (i.e., histosol) soils and plowout of grassland to annual cropland. Since data are not yet available from USDA to make a determination of whether the emissions are increasing or decreasing, emissions of 4.1 $MMtCO_2e$/yr are assumed to remain constant in the emissions forecast.

Table F3. GHG Emissions from Soil Carbon Changes Due to Cultivation Practices ($MMtCO_2e$)

Changes in Cropland			Changes in Hayland				Other			Total[4]
Plowout of grassland to annual cropland[1]	Cropland manage-ment	Other cropland[2]	Cropland converted to hayland[3]	Hayland manage-ment	Cropland converted to grazing land[3]	Grazing land manage-ment	CRP	Manure application	Cultivation of organic soils	Net soil carbon emissions
4.62	0	-0.04	-3.01	-0.11	-0.55	0.04	-0.95	-1.18	5.24	4.06

Based on USDA 1997 estimates. Negative values indicate net sequestration.
[1] Losses from annual cropping systems due to plow-out of pastures, rangeland, hayland, set-aside lands, and perennial/horticultural cropland (annual cropping systems on mineral soils, e.g., corn, soybean, cotton, and wheat).
[2] Perennial/horticultural cropland and rice cultivation.
[3] Gains in soil carbon sequestration due to land conversions from annual cropland into hay or grazing land.
[4] Total does not include change in soil organic carbon storage on federal lands, including those that were previously under private ownership, and does not include carbon storage due to sewage sludge applications.

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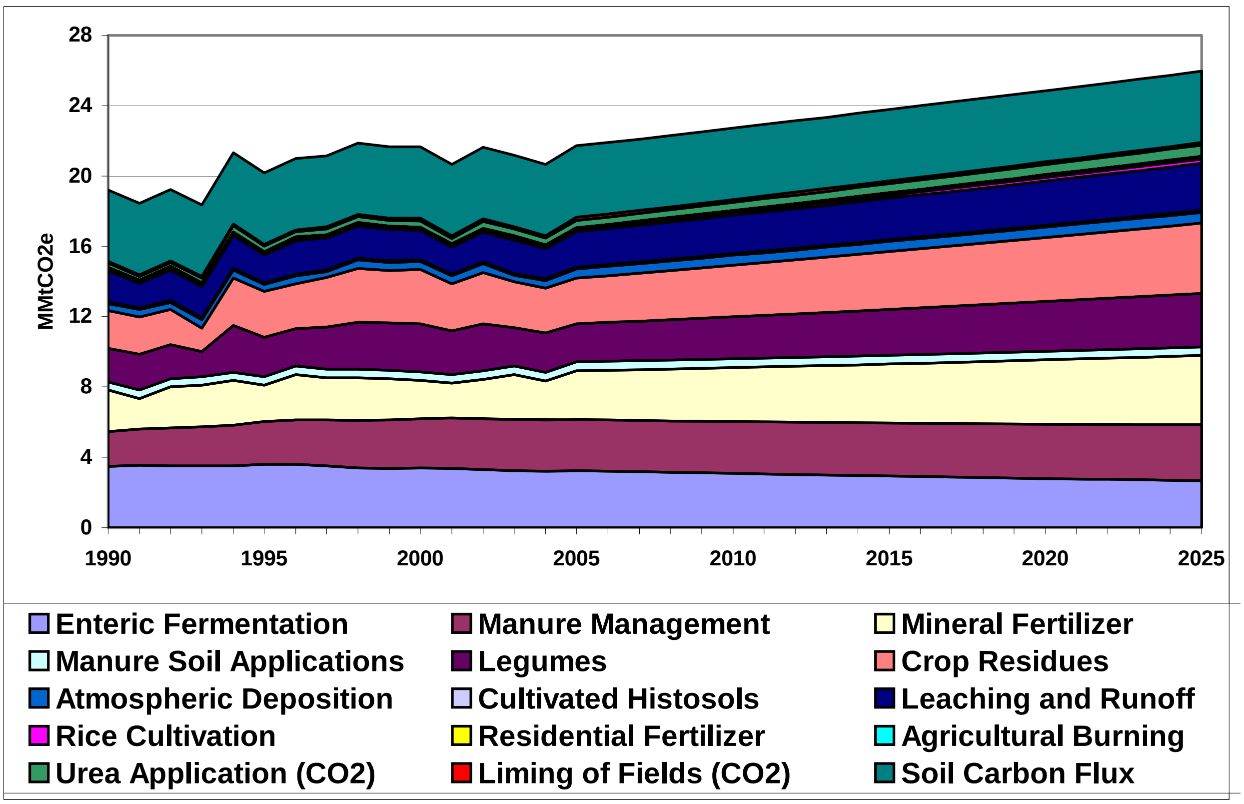
[60] US Agriculture and Forestry Greenhouse Gas Inventory: 1990-2001. Global Change Program Office, Office of the Chief Economist, US Department of Agriculture. Technical Bulletin No. 1907, 164 pp. March 2004. http://www.usda.gov/oce/global_change/gg_inventory.htm; the data are in appendix B table B-11. The table contains two separate IPCC categories: "carbon stock fluxes in mineral soils" and "cultivation of organic soils." The latter is shown in the second to last column of Table F2. The sum of the first nine columns is equivalent to the mineral soils category.
[61] US Agriculture and Forestry Greenhouse Gas Inventory: 1990-2001. Global Change Program Office, Office of the Chief Economist, US Department of Agriculture. Technical Bulletin No. 1907, 164 pp. March 2004. http://www.usda.gov/oce/global_change/gg_inventory.htm; the data are in Appendix B, Table B-11. The table contains two separate IPCC categories: "carbon stock fluxes in mineral soils" and "cultivation of organic soils." The latter is shown in the second to last column of Table F1. The sum of the first nine columns is equivalent to the mineral soils category.

The MPCA inventory included estimates of CO_2 emissions from pastured and cultivated peat, which range from 0.59 MMtCO_2e in 1990 to 0.66 MMtCO_2e in 2004.[62] However, CO_2 emissions for other types of cultivated high organic soils were not estimated.

Results

Figure F1 shows gross GHG emissions associated with the agricultural sector from 1990 through 2025. The GHG emissions forecast is also presented in tabular form in Table F4. In 1990, enteric fermentation accounted for about 18% (3.49 MMtCO_2e) of total agricultural emissions. Enteric fermentation emissions decreased to 3.21 MMtCO_2e (16% of total agricultural emissions) in 2004 due to the decline in beef and dairy cattle populations. Enteric fermentation emissions are projected to continue declining to 2.68 MMtCO_2e by 2025.

Figure F1. Gross GHG Emissions from Agriculture (MMtCO_2e)



[62] MPCA

Table F4: Gross Annual GHG Emissions from Agriculture ($MMtCO_2e$)

Year	1990	1995	2000	2005	2010	2015	2020	2025
Enteric Fermentation	3.49	3.61	3.39	3.25	3.08	2.93	2.80	2.68
Manure Management	1.96	2.43	2.80	2.91	2.96	3.02	3.09	3.16
Mineral Fertilizer	2.37	2.07	2.17	2.77	3.07	3.36	3.66	3.95
Manure Soil Application	0.46	0.48	0.49	0.50	0.49	0.49	0.49	0.48
Legumes	1.91	2.24	2.73	2.18	2.40	2.61	2.83	3.05
Crop Residues	2.17	2.60	3.11	2.59	2.94	3.29	3.64	3.99
Atmospheric Deposition	0.38	0.39	0.45	0.53	0.55	0.57	0.59	0.61
Cultivated Histosols	0.10	0.09	0.10	0.10	0.10	0.10	0.11	0.11
Leaching and Runoff	1.76	1.59	1.66	2.02	2.18	2.35	2.52	2.68
Rice Cultivation	0.10	0.09	0.09	0.11	0.14	0.17	0.20	0.24
Residential Fertilizer	0.09	0.09	0.10	0.12	0.13	0.14	0.15	0.16
Agricultural Burning	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Urea Application (CO_2)	0.20	0.32	0.36	0.41	0.47	0.52	0.58	0.64
Liming of Fields (CO_2)	0.09	0.10	0.14	0.18	0.17	0.16	0.15	0.14
Soil Carbon Flux	4.06	4.06	4.06	4.06	4.06	4.06	4.06	4.06
Total	**19.2**	**20.17**	**21.7**	**21.7**	**22.7**	**23.8**	**25.1**	**26.0**

The manure management category accounted for 10% (1.96 $MMtCO_2e$) of total agricultural emissions in 1990 and increased to 14% (2.90 $MMtCO_2e$) in 2004. Manure management is projected to increase to 3.16 $MMtCO_2e$ by 2025. This emissions growth is mainly due to historical and projected increases in the swine population.

The largest source of emissions in the agricultural sector is the agricultural soils category, which includes crops (legumes and crop residues), cultivated histosols, fertilizer, manure application, and indirect sources (leaching, runoff, and atmospheric deposition). Agricultural soils account for 48% (5.55 $MMtCO_2e$) of total agricultural emissions in 1990 and decrease to 47% (8.41 $MMtCO_2e$) in 2004. Emissions from this category, however, are projected to increase to 14.88 $MMtCO_2e$ in 2025. Agricultural soils do not include emissions due to soil carbon flux. Soil carbon flux is a net source in MN, accounting for 4.06 $MMtCO_2e$ annually.

Agricultural burning emissions were estimated to be relatively small based on the SGIT activity data (0.10 $MMtCO_2e$ in 2004). Emissions from rice cultivation and residential fertilizer are also estimated to be relatively small, 0.10 $MMtCO_2e$ and 0.08 $MMtCO_2e$, respectively in 2004.

The only standard IPCC source category missing from this report is CO_2 emissions from limestone and dolomite application. Estimates for limestone and dolomite application in Minnesota were not available; however, the USDA's national estimate for soil liming is about 9 $MMtCO_2e$/yr.[63]

[63] US Agriculture and Forestry Greenhouse Gas Inventory: 1990-2001. Global Change Program Office, Office of the Chief Economist, US Department of Agriculture. Technical Bulletin No. 1907. 164 pp. March 2004.

Key Uncertainties

Emissions from enteric fermentation and manure management are dependent on the estimates of animal populations and the various factors used to estimate emissions for each animal type and manure management system (i.e., emission factors which are derived from several variables including manure production levels, volatile solids content, and CH_4 formation potential). Each of these factors has some level of uncertainty. Also, application of these emission factors to the actual types of manure management systems employed in Minnesota produces uncertainty, since the distribution of manure management systems is based on survey data. Finally, animal populations fluctuate throughout the year, and thus using point estimates introduces uncertainty into the average annual estimates of these populations. In addition, there is uncertainty associated with the original population survey methods employed by USDA. CCS believes that the largest contributors to uncertainty in emissions from manure management are the emission factors, which are derived from limited data sets.

As mentioned above, for emissions associated with changes in agricultural soil carbon levels, the only data currently available are for 1997. When newer data are released by the USDA, these should be reviewed for incorporation to represent current conditions as well as to assess trends. In particular, given the potential for some CRP acreage to retire and possibly return to active cultivation prior to 2030 (given growing interest in biofuels production), the forecasted emissions could be appreciably affected. As mentioned above, emission estimates for soil liming have not been developed for Minnesota.

Another contributor to the uncertainty in the emission estimates is the forecast assumptions. The growth rates for most categories are assumed to continue growing at historical 1990-2004 growth rates.

Appendix G. Waste Management

Overview

Greenhouse gas (GHG) emissions from waste management include:

- Solid waste management – methane (CH_4) emissions from waste decomposition at municipal and industrial solid waste landfills, accounting for CH_4 that is flared or captured for energy production (this includes both open and closed landfills);
- Solid waste combustion – CH_4, carbon dioxide (CO_2), and nitrous oxide (N_2O) emissions from the controlled combustion of solid waste in incinerators or waste to energy plants or open burning of waste (e.g. at city dumps or in residential burn barrels); and
- Wastewater (WW) management – CH_4 and N_2O from municipal wastewater and CH_4 from industrial WW treatment facilities.

Inventory and Reference Case Projections

Solid Waste Management

Solid Waste Landfills**.** GHG emissions from municipal solid waste (MSW) landfills were estimated by Minnesota Pollution Control Agency (MPCA) from 1990 through 2004 using the United States Environmental Protection Agency's (US EPA) Landfill Gas Emissions Model (LandGEM) Version 3.02, with landfill input data (year opened, year closed, waste acceptance rate).[64] Emissions were modeled for the following landfill sites: Anoka; Burnsville; Flying Cloud; Pine Bend; Louisville; Woodlake; Elk River; and Spruce Ridge. For closed city dumps, emissions were estimated for three model scenarios: a low scenario (high rate of waste burning during the 1970's and 1980's); a high scenario (low burn rate during the 1970's and 1980's), and a medium scenario (average of the low and high scenarios).[65] For this inventory, in consultation with MPCA, estimates were taken from the medium scenario for the closed city dumps. Finally, emissions were also estimated for an "other" landfill category.

These estimates include CH_4 emissions from all MSW landfills, as well as CH_4 and N_2O estimates at sites where landfill gas was collected and combusted in either a flare or engine/turbine. In developing the landfill emission estimates, MPCA adjusted uncontrolled emissions estimated with LandGEM by subtracting CH_4 flared or used for energy production and by adding CH_4 produced by flares or engines.[66] Emissions from the open burning of waste are described in the next section below.

Emissions from industrial paper pulp landfills were also estimated using LandGEM. Modeling of emissions from the Moonlight landfill was performed, and the results were extrapolated to the State level.[67] Data on the annual amount of decomposable material landfilled was estimated by

[64] MPCA
[65] MPCA
[66] MPCA
[67] MPCA

MPCA.[68] Emissions from other industrial landfilled waste were assumed to be captured within the municipal landfill modeling described above.

Growth rates were estimated by using the overall historic emissions for MSW landfills from 1995-2004. Throughout the U.S., many of the smaller and older unlined landfills were closed during the mid-1980's to mid-1990s as a result of new requirements for solid waste management. Hence, CCS believes that the period from 1995 onward better reflects recent landfilling practices and growth in waste emplacement. The annual growth rate for MSW landfills is -0.45%. For industrial landfills, the forecasted emissions are also declining. The growth rate (-1.6%/yr) was estimated based on emissions estimated from 1990 to 2004.

Solid Waste Combustion**.** GHG emissions from municipal and industrial solid waste combustion were estimated by MPCA from 1990 through 2004. Sources include solid waste burning in municipal and medical waste incinerators, rural open burning, and hazardous waste incineration. Emissions were estimated for CO_2 from the fraction of non-biogenic carbon in the waste. Emissions were also estimated for CH_4 and N_2O. Data on the amount of waste combusted by waste category and emission factors were obtained by MPCA.[69] For the waste management sector, the emissions associated with waste combustion for the purposes of electricity generation and commercial steam/heat production are excluded. Emissions associated with residential burning of solid waste are not included in this inventory and are assumed to be negligible.

The growth rate for solid waste combustion was estimated based on emissions estimated from 1990 to 2004. The emissions trend during this period was declining at the rate of -2.5%/yr.

Wastewater (WW) Management

Municipal WW Treatment**.** GHG emissions from municipal WW and septic systems were also estimated by MPCA. Emissions from municipal WW and septic systems were calculated based on state population, biochemical oxygen demand (BOD), protein consumption per capita, and emission factors for N_2O and CH_4.[70]

Municipal WW management projections are based on the growth in emissions from 1990 to 2004. The growth rate is 1.5%/yr.

Industrial WW Treatment. No sources of data were identified to estimate emissions from industrial WW management. The US EPA's State Greenhouse Gas Inventory Tool (SGIT) software allows for the calculation of emissions from the following industry sectors, if data on production levels are available: pulp & paper; fruit & vegetable processing; and meat & poultry processing. Data on WW flow rates and chemical oxygen demand could also be used to develop emission estimates.

[68] MPCA
[69] MPCA
[70] MPCA

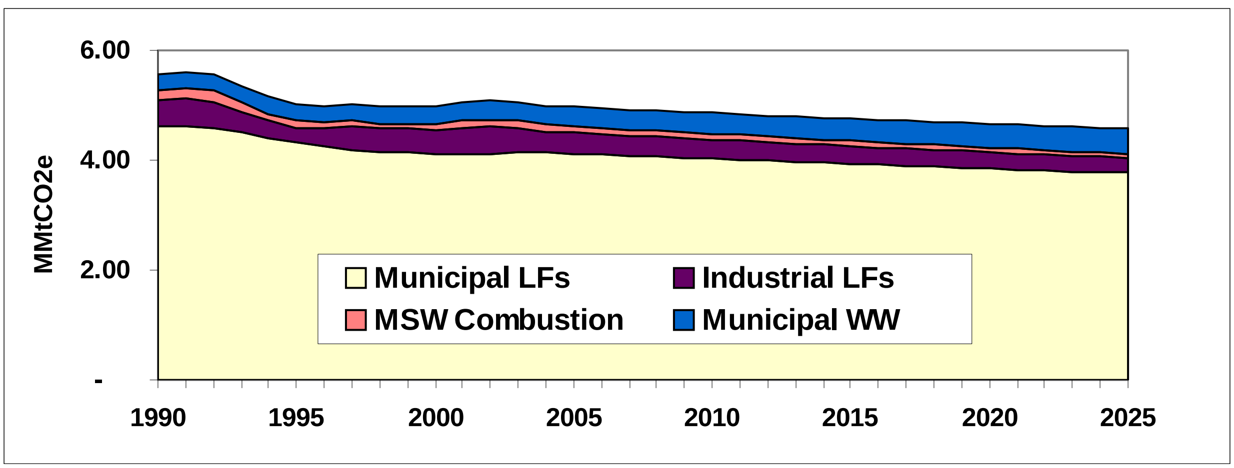
Results

Figure G1 shows the emission estimates for the waste management sector and Table G1 displays these results in tabular form. Overall, the sector accounts for 5.0 $MMtCO_2e$ in 2005. By 2025, emissions are expected to decrease to 4.6 $MMtCO_2e$/yr. This decrease in emissions is driven by declining emissions in the solid waste management sector, in particular MSW landfills. While data were not available to verify this, CCS believes that the declining trend in MSW landfill emissions is due to more waste being emplaced into landfills that are collecting and controlling CH_4 emissions over time. From 2005 through 2025, the contribution of emissions from the MSW landfills sector is expected to remain about the same (about 82%).

In 2005, about 7% of the waste management sector emissions were contributed by municipal WW treatment systems. By 2025, municipal WW treatment is expected to contribute about 10% of the waste management sector emissions.

There were no readily-available sources of data identified to estimate emissions from the industrial WW treatment sector. If sources of data can be identified during the advisory group process for production levels or WW flow rates at pulp and paper mills, fruit and vegetable processors, and meat and poultry plants, then emissions for this subsector can be estimated and incorporated. CCS believes that this subsector would likely contribute only small amounts to the sector emissions.

Figure G1. Minnesota GHG Emissions from Waste Management ($MMtCO_2e$)



Notes: LF – landfill; WW – wastewater; MSW – municipal solid waste.

Table G1: Annual GHG Emissions from Waste Management (MMtCO2e)

Year	1990	1995	2000	2005	2010	2015	2020	2025
Municipal LFs	4.62	4.32	4.10	4.12	4.03	3.94	3.85	3.76
Industrial LFs	0.47	0.28	0.44	0.37	0.34	0.31	0.29	0.27
MSW Combustion	0.18	0.13	0.11	0.12	0.11	0.10	0.09	0.08
Municipal WW	0.28	0.30	0.33	0.35	0.37	0.40	0.43	0.47
Industrial WW	0	0	0	0	0	0	0	0
Total	**5.55**	**5.03**	**4.97**	**4.96**	**4.85**	**4.75**	**4.66**	**4.58**

Key Uncertainties

The key uncertainties for the waste management sector are primarily associated with the MSW landfill emission estimates. Uncertainty stems from: the initial LandGEM modeling results at individual landfill sites, data from each site collecting and combusting landfill gas, and the associated emission factors. For industrial (pulp and paper) landfills, the emission estimates are extrapolated from measurements at the Moonlight landfill. Hence, depending on how representative this site is to the overall population of pulp and paper landfills, emissions could be under- or over-estimated.

As mentioned above, the current inventory does not include estimates for the industrial WW treatment sector. These estimates will be added, if data can be identified during the advisory group process.

Appendix H. Forestry

Overview

Forestland emissions refer to the net carbon dioxide (CO_2) flux[71] from forested lands in Minnesota, which account for about 32% of the state's land area.[72] The dominant forest type in Minnesota is Aspen-Birch which makes up about 41% of forested lands. Another common forest type is Spruce-Fir at 27% of forested land. All other forest types make up less than 10% each of the State's forests.

Through photosynthesis, CO_2 is taken up by trees and plants and converted to carbon in biomass within the forests. Carbon dioxide emissions occur from respiration in live trees, decay of dead biomass, and fires. In addition, carbon is stored for long time periods when forest biomass is harvested for use in durable wood products. Carbon dioxide flux is the net balance of CO_2 removals from and emissions to the atmosphere from the processes described above.

Inventory and Reference Case Projections

For over a decade, the United States Forest Service (USFS) has been developing and refining a forest carbon modeling system for the purposes of estimating forest carbon inventories. The methodology is used to develop national forest CO_2 fluxes for the official *US Inventory of Greenhouse Gas Emissions and Sinks*. The national estimates are compiled from state-level data. The Minnesota forest CO_2 flux data in this report come from the national analysis and are provided by the USFS. See the footnotes below for the most current documentation for the forest carbon modeling.[73] Additional forest carbon information is in the form of specific carbon conversion factors.[74]

The forest CO_2 flux methodology relies on input data in the form of plot level forest volume statistics from the Forest Inventory Analysis (FIA). FIA data on forest volumes are converted to values for ecosystem carbon stocks (i.e., the amount of carbon stored in forest carbon pools) using the FORCARB2 modeling system. Coefficients from FORCARB2 are applied to the plot level survey data to give estimates of C density [megagrams (Mg) per hectare] for a number of

[71] "Flux" refers to both emissions of CO_2 to the atmosphere and removal (sinks) of CO_2 from the atmosphere.
[72] Total forested acreage is 16.2 million acres in 2003; J. Smith, USFS, personal communication with S. Roe, CCS, April 2007. Acreage by forest type available from the USFS at: http://www.fs.fed.us/ne/global/pubs/books/epa/states/MN.htm. The total land area in Minnesota is 51 million acres (http://www.50states.com/minnesot.htm).
[73] The most current citation for an overview of how USFS calculates the inventory based forest carbon estimates as well as carbon in harvested wood products is the current EPA publication on the national GHG http://epa.gov/climatechange/emissions/usinventoryreport.html. Both Annex 3.12 and Chapter 7 LULUCF are useful sources of reference. See also Smith, J.E., L.S. Heath, and M.C. Nichols (in press), *U.S. Forest Carbon Calculation Tool User's Guide: Forestland Carbon Stocks and Net Annual Stock Change*, Gen Tech Report, Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.
[74] Smith, J.E., and L.S. Heath (2002). "A model of forest floor carbon mass for United States forest types," Res. Pap. NE-722. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 37 p., or Jenkins, J.C., D.C. Chojnacky, L.S. Heath, R.A. Birdsey (2003), "National-scale biomass estimators for United States tree species", *Forest Science*, 49:12-35.

separate C pools. Additional background on the FORCARB system is provided in a number of publications.[75]

Carbon dioxide flux is estimated as the change in carbon mass for each carbon pool over a specified time frame. Forest volume data from at least two points in time are required. The change in carbon stocks between time intervals is estimated at the plot level for specific carbon pools (Live Tree, Standing Dead Wood, Understory, Down & Dead Wood, Forest Floor, and Soil Organic Carbon) and divided by the number of years between inventory samples. Annual increases in carbon density reflect carbon sequestration in a specific pool; decreases in carbon density reveal CO_2 emissions or carbon transfers out of that pool (e.g., death of a standing tree transfers carbon from the live tree to standing dead wood pool). The amount of carbon in each pool is also influenced by changes in forest area (e.g., an increase in area could lead to an increase in the associated forest carbon pools and the estimated flux). The sum of carbon stock changes for all forest carbon pools yields a total net CO_2 flux for forest ecosystems.

In preparing these estimates, USFS estimates the amount of forest carbon in different forest types as well as different carbon pools. The different forests include those in the national forest (NF) system and those that are not federally-owned (private and other public forests). Additional details on the forest carbon inventory methods can be found in Annex 3 to the US EPA's 2006 GHG inventory for the US.[76]

Carbon pool data for two FIA cycles were available for the USFS to estimate flux for the 1990-2003 period. These are shown in Table H1 below. These are the most recent USFS estimates available and will be included in EPA's latest national greenhouse gas (GHG) inventory. The underlying FIA data show a net decrease in forested area of 452,000 acres in the 1990-2003 period. There was also a loss of 90 million metric tons of carbon from forested areas during this period.

In addition to the forest carbon pools, additional carbon is stored in biomass removed from the forest for the production of harvested wood products (HWP). Carbon remains stored in the durable wood products pool or is transferred to landfills where much of the carbon remains stored over a long period of time. The USFS uses a model referred to as WOODCARB2 for the purposes of modeling national HWP carbon storage.[77]

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[75] Smith, J.E., L.S. Heath, and P.B. Woodbury (2004). "How to estimate forest carbon for large areas from inventory data", *Journal of Forestry*, 102: 25-31; Heath, L.S., J.E. Smith, and R.A. Birdsey (2003), "Carbon trends in U.S. forest lands: A context for the role of soils in forest carbon sequestration", In J. M. Kimble, L. S. Heath, R. A. Birdsey, and R. Lal, editors. *The Potential of US Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect.* CRC Press, New York; and Woodbury, Peter B.; Smith, James E.; Heath, Linda S. 2007, "Carbon sequestration in the U.S. forest sector from 1990 to 2010", *Forest Ecology and Management*, 241:14-27.
[76] Annex 3 to EPA's 2006 report, which contains estimates for calendar year 2004, can be downloaded at: http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR6MBLNQ/$File/06_annex_Chapter3.pdf.
[77] Skog, K.E., and G.A. Nicholson (1998), "Carbon cycling through wood products: the role of wood and paper products in carbon sequestration", *Forest Products Journal*, 48(7/8):75-83; or Skog, K.E., K. Pingoud, and J.E. Smith (2004), "A method countries can use to estimate changes in carbon stored in harvested wood products and the uncertainty of such estimates", *Environmental Management*, 33(Suppl. 1): S65-S73.

As shown in the Table H2, 2.2 million metric tons (MMt) of CO_2 per year (yr) is estimated by the USFS to be sequestered annually in wood products.[78] Also, as shown in this table, the total flux estimate including all forest pools is 24.9 $MMtCO_2e$/yr. This total includes a large net source estimate for soil carbon (21.6 $MMtCO_2$/yr). Given the changes noted above in forested area, it appears that much of the positive carbon flux is from the loss of forested lands between 1990 and 2003.

Table H1. USFS Forest Carbon Pool Data for Minnesota

Forest Pool	**1990 (MMtC)**	**2003 (MMtC)**
Live Tree – Above Ground	292	282
Live Tree – Below Ground	58.1	56.2
Understory	12.8	12.5
Standing Dead	29.3	27.4
Down Dead	27.5	26.4
Forest Floor	120	117
Soil Carbon	1,180	1,110
Totals	**1,719**	**1,629**
Forest Area	**1990 (10^3 acres)**	**2003 (10^3 acres)**
All Forests	16,682	16,230
Timberland	14,722	14,759

Positive numbers indicate net emission. Totals may not sum exactly due to independent rounding.
Data source: Jim Smith, USFS, personal communications with S. Roe, CCS, October 2006 and May 2007.

Table H2. USFS Forest Carbon Fluxes for Minnesota

Forest Pool	**1990-2003 Flux (MMtC/yr)**	**1990-2003 Flux ($MMtCO_2$/yr)**
Forest Carbon Pools (non-soil)	1.5	5.5
Soil Organic Carbon	5.9	21.6
Harvested Wood Products	-0.6	-2.2
Totals	**6.8**	**24.9**
Totals (excluding soil carbon)	**0.9**	**3.3**

Positive numbers indicate net emission. Totals may not sum exactly due to independent rounding.
Data source: Jim Smith, USFS, personal communications with S. Roe, CCS, October 2006 and May 2007.

Based on discussions with the USFS, CCS recommends excluding the soil carbon pool from the overall forest flux estimates due to high level of uncertainty associated with these estimates. The forest carbon flux estimates provided in the summary tables at the front of this report are those without the soil carbon pool.

For historic emission estimates, the Center for Climate Strategies (CCS) used the flux to represent forest carbon flux from 1990 to 2005. For the reference case projections, the forest area and carbon densities of forestlands were assumed to remain at the same levels as in 2003.

[78] Jim Smith, USFS, personal communication with S. Roe, CCS, July 2007.

Information is not available on the near term effects of climate change and their impacts on forest productivity. Nor were data readily-available on projected losses in forested area.

Comparison to Minnesota Pollution Control Agency (MPCA) Estimates
The MPCA provided data to CCS on forest carbon pools in Minnesota. These included estimates of forest carbon based on the same 1990-2003 FIA data (these appear to cover all forest pools except soil carbon and possibly forest floor and understory); carbon pool estimates in Minnesota's landfills; and carbon pool estimates in Minnesota's housing. Based on the pools calculated for 1990 and 2003 a net flux rate of 1.3 MMtC/yr (4.7 $MMtCO_2$/yr) was calculated. The MPCA estimate of 4.7 $MMtCO_2$/yr is fairly close to the USFS estimate of 3.3 $MMtCO_2$/yr, excluding soil carbon. Information was not available on the specific forest carbon pools included in the Minnesota forest carbon analysis, making direct comparison of the estimates difficult. Differences may stem from the inclusion of different forest carbon pools in each analysis, and/or different modeling methods and data sources used by the USFS and MPCA. In addition, the Minnesota analysis accounts for carbon stored in HWP in terms of carbon in landfills and in housing. The USFS categorizes carbon stored in HWP in terms of carbon in landfills and in wood products in use, the latter category being broader than carbon in housing alone.

Key Uncertainties

It should be noted that methane (CH_4) and nitrous oxide (N_2O) emissions from wildfires and prescribed burns have not been included in the estimates presented in Table H1. In work that CCS has completed for a number of western states, where wildfire activity is significant, emission estimates have tended to range from <1 to 3 $MMtCO_2e$/yr. We expect that the emissions from wildfires in Minnesota would be much lower than these levels and to not impact the estimated flux significantly.

It is important to note that there were methodological differences in the two FIA cycles (used to calculate carbon pools and flux) that can produce different estimates of forested area and carbon density. For example, the FIA program modified the definition of forest cover for the woodlands class of forestland (considered to be non-productive forests). Earlier FIA cycles defined woodlands as having a tree cover of at least 10%, while the newer sampling methods used a woodlands definition of tree cover of at least 5% (leading to more area being defined as woodland). In woodland areas, the earlier FIA surveys might not have inventoried trees of certain species or with certain tree form characteristics (leading to differences in both carbon density and forested acreage). It is not clear whether these definitional issues have had a substantial effect on the flux estimates in Minnesota; however CCS' understanding is that these issues have tended to be most important in some western states with significant woodland forested area.

Also, FIA surveys since 1999 include all dead trees on the plots, but data prior to that are variable in terms of these data. The modifications to FIA surveys are a result of an expanded focus in the FIA program, which historically was only concerned with timber resources, while more recent surveys have aimed at a more comprehensive gathering of forest biomass data. In addition, the FIA program has moved from periodic to annual inventory methods. The effect of these changes in survey methods has not been estimated by the USFS.

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

Original Reference: Material for this Appendix is 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. Michael Gillenwater directed the preparation of this appendix.

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[79] 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

[79] See FCCC/CP/1999/7 at www.unfccc.de

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 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 10.

Table 10. 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 is 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:

$$\text{Tg CO}_2\text{ Eq} = (\text{Gg of gas}) \times (\text{GWP}) \times \left(\frac{\text{Tg}}{1{,}000\text{ Gg}}\right) \text{where,}$$

Tg CO_2 Eq. = Teragrams of Carbon Dioxide Equivalents
GWP = Global Warming Potential
Gg = Gigagrams (equivalent to a thousand metric tons)
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 11).

> *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 11. 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 12 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 12. 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.

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