Wyoming Greenhouse Gas Inventory and Reference Case Projections 1990-2020

Center for Climate Strategies
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Disclaimer

The Center for Climate Strategies (CCS) prepared this report for the Wyoming Department of Environmental Quality (WYDEQ) through an effort of the Western Regional Air Partnership (WRAP). This report presents a preliminary draft greenhouse gas (GHG) emissions inventory and forecast from 1990 to 2020 for Wyoming. This report provides an initial comprehensive understanding of Wyoming's current and possible future GHG emissions. The information presented provides the State with a starting point for revising the initial estimates as improvements to data sources and assumptions are identified. Please contact Mr. Brian Bohlman of the WYDEQ to determine if Wyoming has developed any updates to the information presented in this report.

Executive Summary

The Center for Climate Strategies (CCS) prepared this report for the Wyoming Department of Environmental Quality (WYDEQ) through an effort of the Western Regional Air Partnership (WRAP). The report contains an inventory and forecast of the State's greenhouse gas (GHG) emissions from 1990 to 2020 to provide an initial comprehensive understanding of Wyoming's current and possible future GHG emissions. The information presented provides the State with a starting point for revising the initial estimates as improvements to data sources and assumptions are identified.

Wyoming's anthropogenic GHG emissions and anthropogenic/natural sinks (carbon storage) were estimated for the period from 1990 to 2020. Historical GHG emission estimates (1990 through 2005) 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 Wyoming-specific data and inputs when it was possible to do so. 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 Wyoming. Activities in Wyoming accounted for approximately 56 million metric tons (MMt) of *gross*[1] carbon dioxide equivalent (CO_2e) emissions in 2005, an amount equal to 0.8% of total US gross GHG emissions. These emission estimates focus on activities in Wyoming and are *consumption-based;* they exclude emissions associated with electricity that is exported from the State.[2] Wyoming's gross GHG emissions increased 25% from 1990 to 2005, while national emissions rose by only 16% from 1990 to 2004. Annual sequestration (removal) of GHG emissions due to forestry and other land-uses in Wyoming are estimated at 36 $MMtCO_2e$ in 2005.

Figure ES-1 illustrates the State's gross GHG emissions per capita and per unit of economic output. Wyoming's per capita emission rate is more than four times greater than the national average of 25 $MtCO_2e$/yr. This large difference between national and State per capita emissions occurs in most of the sectors – Wyoming's emission per capita significantly exceed national emissions per capita for the following sectors: electricity, industrial, fossil fuel production, transportation, industrial process and agriculture. The reasons for the higher per capita intensity in Wyoming are varied but include the State's strong fossil fuel production industry and other industries with high fossil fuel consumption intensity, large agriculture industry, large distances, and low population base. Between 1990 and 2005, per capita emissions in Wyoming have increased, mostly due to increased activity in the fossil fuel industry, while national per capita emissions have changed relatively little. Economic growth exceeded emissions growth both nationally and in Wyoming throughout the

[1] Excluding GHG emissions removed due to forestry and other land uses and excluding GHG emissions associated with exported electricity.
[2] See Appendix A for *production-based* GHG emission estimates, which include emissions associated with electricity exports.

1990-2005 period, as seen by the decreasing GHG emissions per Gross Domestic Product or Gross State Product.[3]

The principle sources of Wyoming's consumption-based gross GHG emissions are electricity use (excluding electricity exports to other states), fossil fuel consumption in the residential, commercial and industrial sectors, and fugitive (non-energy) emissions from the fossil fuel production industries. The next largest contributor to emissions is the transportation fuel use sector.

As illustrated in Figure ES-2 and shown numerically in Table ES-1, under the reference case projections, Wyoming's gross GHG emissions are expected to continue to grow to 69 MMtCO_2e by 2020, 56% above 1990 levels. As shown in Figure ES-3, demand for electricity is projected to be the largest contributor to future emissions growth, followed by emissions associated with transportation. Although GHG emissions from fossil fuel production had the greatest increase by sector in the period 1990 to 2005, the growth from this sector is projected to decline due to assumption of decreased carbon dioxide emissions from venting at processing plants.

Some data gaps exist in this analysis, particularly for the reference case projections. Next steps for further refinement include the review and revision of key emissions drivers (such as electricity consumption and production, fossil fuel production, and transportation fuel use growth rates) that will be major determinants of Wyoming's future GHG emissions. Appendices A through H provide the detailed methods, data sources, and assumptions used in estimating GHG emissions for each major sector. Key sources of uncertainty and recommendations for next steps in the refinement of these estimates are also provided.

Emissions of aerosols, particularly "black carbon" (BC) from fossil fuel combustion, could have significant climate impacts through their effects on radiative forcing. Estimates of these aerosol emissions on a CO_2e basis were developed for Wyoming based on 2002 and 2018 data from the WRAP. The results were a total of 4.1 MMtCO_2e, which is the mid-point of a range of estimated emissions (2.6 – 5.5 MMtCO_2e) in 2002. Based on an assessment of the primary contributors, it is estimated that BC emissions will decrease substantially by 2018 after new engine and fuel standards take effect in the onroad and nonroad diesel engine sectors. Details of this analysis are presented in Appendix I to this report. These estimates are not incorporated into the totals shown in Table ES-1 because a global warming potential for BC has not yet been assigned by the Intergovernmental Panel on Climate Change (IPCC).

[3] Based on gross domestic product by state (millions of current 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.

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

(Million Metric Tons CO2e)	1990	2000	2005	2010	2020	Explanatory Notes for Projections
Energy	**38.0**	**43.6**	**47.5**	**51.6**	**59.6**	
Electricity Production Based	39.8	43.3	44.2	47.8	54.2	
Coal	39.8	43.2	44.1	47.7	53.9	See electric sector assumptions in appendix A
Natural Gas	0.0	0.1	0.1	0.1	0.2	
Petroleum	0.0	0.0	0.0	0.0	0.0	
Geothermal, Biomass and Waste (CO_2, CH_4 and N_2O)	0.0	0.0	0.0	0.0	0.0	
Net Imported/Exported Electricity	-26.6	-30.3	-28.7	-30.4	-31.5	Negative values represent exports
Electricity Consumption Based	**13.2**	**13.0**	**15.4**	**17.4**	**22.6**	
Residential/Commercial/Industrial (RCI) Fuel Use	**11.9**	**11.4**	**10.2**	**10.5**	**10.5**	
Coal	4.2	4.0	3.3	3.3	3.0	Based on USDOE regional projections
Natural Gas	5.0	4.6	3.5	3.6	3.7	Based on USDOE regional projections
Oil	2.7	2.8	3.4	3.6	3.8	Based on USDOE regional projections
Wood (CH_4 and N_2O)	0.0	0.0	0.0	0.0	0.0	Based on USDOE regional projections
Transportation	**6.2**	**7.7**	**8.3**	**9.2**	**11.4**	
Motor Gasoline	3.2	3.7	3.6	3.8	4.3	Based on WYDOT VMT projections
Diesel	2.8	3.7	4.4	5.2	6.9	Based on WYDOT VMT projections
Natural Gas, LPG, other	0.1	0.1	0.1	0.1	0.1	Based on USDOE regional projections
Jet Fuel and Aviation Gasoline	0.1	0.2	0.21	0.2	0.2	Based on FAA projections
Fossil Fuel Industry (fugitive)	**6.7**	**11.4**	**13.5**	**14.4**	**14.9**	
Natural Gas Industry	5.0	9.2	11.0	11.6	12.0	
Oil Industry	0.8	0.5	0.4	0.5	0.5	See assumptions in Appendix E
Refineries (CH_4)	0.0	0.0	0.0	0.0	0.0	
Coal Mining (CH_4)	1.0	1.8	2.1	2.3	2.4	
Industrial Processes	**2.0**	**2.4**	**2.6**	**2.7**	**3.0**	
Cement Manufacture	0.3	0.6	0.5	0.5	0.6	Based on WY manufacturing employment growth
Lime Manufacture	0.1	0.1	0.2	0.2	0.2	
Limestone and Dolomite Use	0.0	0.0	0.0	0.0	0.0	
Soda Ash Manufacture	1.4	1.5	1.5	1.5	1.6	Based on 2004 and 2009 projections for US production
Soda Ash Use	0.0	0.0	0.0	0.0	0.0	
ODS Substitutes	0.0	0.1	0.2	0.3	0.6	EPA 2004 ODS cost study report
Electric Power T & D	0.1	0.1	0.1	0.0	0.0	Based on national projections(USEPA)
Waste Management	**0.3**	**0.4**	**0.5**	**0.7**	**0.9**	
Solid Waste Management	0.3	0.4	0.5	0.6	0.9	Projections based on population.
Wastewater Management	0.0	0.0	0.0	0.0	0.0	Projections based on population.
Agriculture	**4.1**	**5.5**	**5.1**	**5.4**	**6.0**	
Enteric Fermentation	1.6	2.0	2.0	2.2	2.5	USDA Livestock Projections
Manure Management	0.1	0.1	0.1	0.1	0.1	USDA Livestock Projections
Agricultural Soils	2.4	3.4	3.0	3.1	3.3	
Total Gross Emissions	**44.4**	**51.9**	**55.6**	**60.3**	**69.4**	
increase relative to 1990		*17%*	*25%*	*36%*	*57%*	
Forestry and Land Use	**-35.5**	**-35.5**	**-35.5**	**-35.5**	**-35.5**	
Agricultural Soils	**-0.9**	**-0.9**	**-0.9**	**-0.9**	**-0.9**	
Net Emissions (including sinks)	**8.0**	**15.5**	**19.2**	**23.9**	**33.0**	

[a] Totals may not equal exact sum of subtotals shown in this table due to independent rounding.

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

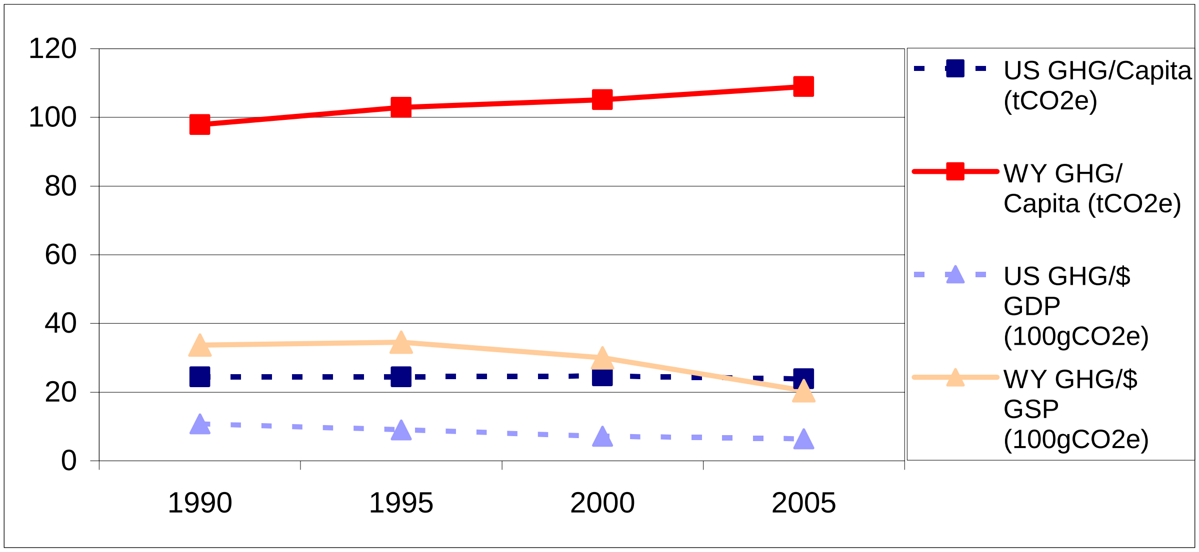
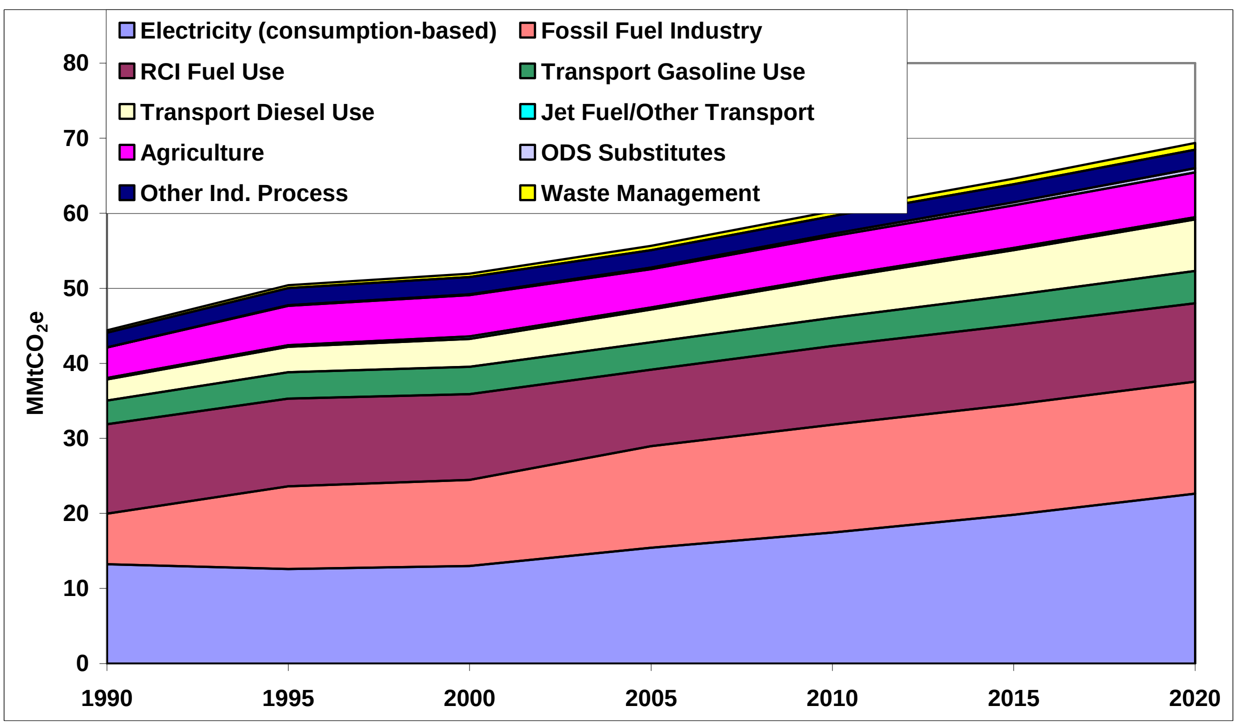
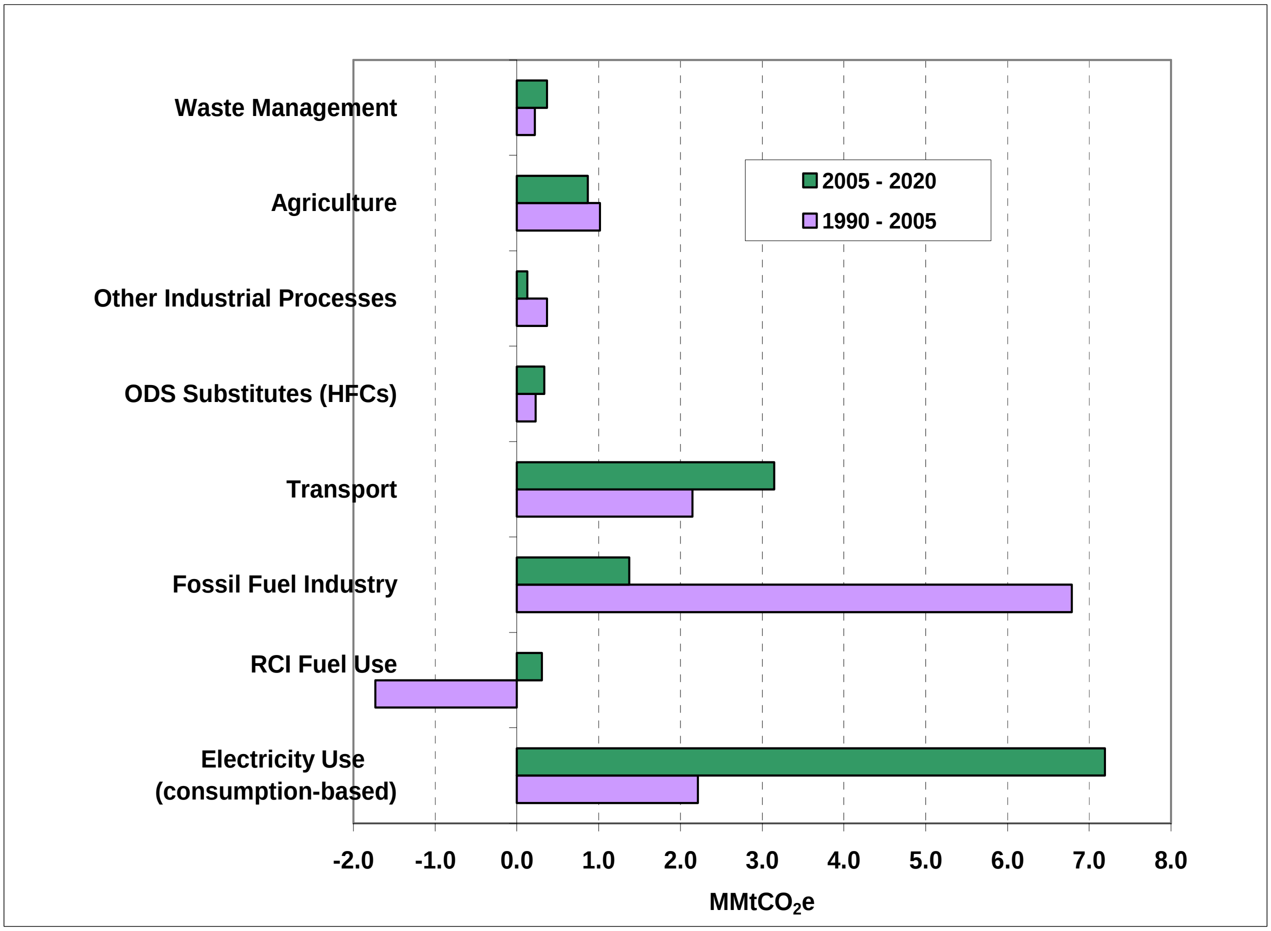


Figure ES-2. Wyoming Gross GHG Emissions by Sector, 1990-2020: Historical and Projected



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

Figure ES-3. Sector Contributions to Gross Emissions Growth in Wyoming, 1990-2020: Reference Case Projections ($MMtCO_2e$ 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

AEO – Annual Energy Outlook, EIA

Ag – Agriculture

bbls – Barrels

BC – Black Carbon*

Bcf – Billion cubic feet

BLM – United States Bureau of Land Management

BOD – Biochemical Oxygen Demand

BTU – British Thermal Unit

C – Carbon*

$CaCO_3$ – Calcium Carbonate

CBM – Coal Bed Methane

CCS – Center for Climate Strategies

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*

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

EGU – Electricity Generating Unit

EIA – US DOE Energy Information Administration

EIIP – Emissions Inventory Improvement Program

Eq. – Equivalent

FAA – Federal Aviation Administration

FIA – Forest Inventory and Analysis

Gg – Gigagram

GHG – Greenhouse Gases*

GSP – Gross State Product

GWh – Gigawatt-hour

GWP – Global Warming Potential*

HFCs – Hydrofluorocarbons*

IPCC – Intergovernmental Panel on Climate Change*

kWh – Kilowatt-hour

LF – Landfill

LFGTE – Landfill-Gas-to-Energy

LMOP – Landfill Methane Outreach Program

LNG – Liquefied Natural Gas

LPG – Liquefied Petroleum Gas

Mt – Metric ton (equivalent to 1.102 short tons)

MMt – Million Metric tons

MPO – Metropolitan Planning Organization

MSW – Municipal Solid Waste

MW – Megawatt

MWh – Megawatt-hour

N – Nitrogen

N_2O – Nitrous Oxide*

NO_2 – Nitrogen Dioxide*

NO_x – Nitrogen Oxides*

NASS – National Agricultural Statistics Service

NMVOCs – Non-methane Volatile Organic Compounds*

O_3 – Ozone*

ODS – Ozone-Depleting Substances*

OM – Organic Matter*

PADD – Petroleum Administration for Defense Districts

PFCs – Perfluorocarbons*

PM – Particulate Matter*

ppb – parts per billion

ppm – parts per million

ppt – parts per trillion

PV – Photovoltaic

RCI – Residential, Commercial, and Industrial

RES – Renewable Energy 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

Tg – Teragram

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

VMT – Vehicle-Miles Traveled

WAPA – Western Area Power Administration

WECC – Western Electricity Coordinating Council

W/m^2 – Watts per Square Meter

WMO – World Meteorological Organization*

WRAP – Western Regional Air Partnership

WW – Wastewater

WYDEQ – Wyoming Department of Environmental Quality

* - See Appendix J for more information.

Acknowledgements

We appreciate all of the time and assistance provided by numerous contacts throughout Wyoming, as well as in neighboring States, and at federal agencies. Thanks go to in particular the many staff at several Wyoming State Agencies for their inputs, and in particular to Dan Herman and Lee Gribovicz, and the peer review staff of the Wyoming Department of Environmental Quality (WYDEQ) who provided key guidance for this analytical effort.

The authors would also like to express their appreciation to Katie Bickel, Michael Lazarus, Lewison Lem, Katie Pasko, June Taylor, and David Von Hippel of the Center for Climate Strategies (CCS) who provided valuable review comments during development of this report. Thanks also to Michael Gillenwater for directing preparation of Appendix J.

Summary of Preliminary Findings

Introduction

The Center for Climate Strategies prepared this report for the Wyoming Department of Environmental Quality (WYDEQ) through an effort of the Western Regional Air Partnership (WRAP). This report presents initial estimates of base year and projected Wyoming anthropogenic greenhouse gas (GHG) emissions and anthropogenic/natural 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 Wyoming.

Historical GHG emission estimates (1990 through 2005)[4] were developed using a set of generally accepted principles and guidelines for State GHG emissions inventories, as described the "Approach" section below, relying to the extent possible on Wyoming-specific data and inputs. 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.[5] The final appendix to this report provides a more complete discussion of GHGs and GWPs. Emissions of black carbon (BC) were also estimated. Black carbon is an aerosol species with a positive climate forcing potential (that is, the potential to warm the atmosphere, as GHGs do); however, black carbon currently does not have a GWP defined by the IPCC due to uncertainties in both the direct and indirect effects of BC on atmospheric processes (see Appendices I and J for more details).

It is important to note that the preliminary emissions estimates for the electricity sector reflect the *GHG emissions associated with the electricity sources used to meet Wyoming'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 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.*

[4] The last year of available historical data varies by sector; ranging from 2000 to 2005.
[5] These gases and the concepts of radiative forcing and GWP are described in Appendix J.

Wyoming Greenhouse Gas Emissions: Sources and Trends

Table 1 provides a summary of GHG emissions estimated for Wyoming by sector for the years 1990, 2000, 2005, 2010, and 2020. Details on the methods and data sources used to construct these 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 forecasted 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 information on 2002 and 2018 black carbon (BC) estimates for Wyoming. CCS estimated that BC emissions in 2002 ranged from 2.6 – 5.5 million metric tons (MMt) of carbon dioxide equivalent (CO_2e) with a mid-point of 4.1 MmtCO_2e. A range is estimated based on the uncertainty in the global modeling analyses that serve as the basis for converting BC mass emissions into their CO_2e. Emissions are expected to drop by about 1.3 MmtCO_2e/yr by 2018 as a result of new engine and fuel standards affecting onroad and nonroad diesel engines. Appendix I contains a detailed breakdown of 2002 emissions contribution by source sector. Since the IPCC has not yet assigned a global warming potential for BC, CCS has excluded these estimates from the GHG summary shown in Table 1.

As noted above, Appendix J provides background information on GHGs and climate-forcing aerosols.

Table 1. Wyoming Historical and Reference Case GHG Emissions, by Sector[a]

(Million Metric Tons CO2e)	1990	2000	2005	2010	2020	Explanatory Notes for Projections
Energy	**38.0**	**43.6**	**47.5**	**51.6**	**59.6**	
Electricity Production Based	39.8	43.3	44.2	47.8	54.2	
Coal	39.8	43.2	44.1	47.7	53.9	See electric sector assumptions in appendix A
Natural Gas	0.0	0.1	0.1	0.1	0.2	
Petroleum	0.0	0.0	0.0	0.0	0.0	
Geothermal, Biomass and Waste (CO_2, CH_4 and N_2O)	0.0	0.0	0.0	0.0	0.0	
Net Imported/Exported Electricity	-26.6	-30.3	-28.7	-30.4	-31.5	Negative values represent exports
Electricity Consumption Based	**13.2**	**13.0**	**15.4**	**17.4**	**22.6**	
Residential/Commercial/Industrial (RCI) Fuel Use	**11.9**	**11.4**	**10.2**	**10.5**	**10.5**	
Coal	4.2	4.0	3.3	3.3	3.0	Based on USDOE regional projections
Natural Gas	5.0	4.6	3.5	3.6	3.7	Based on USDOE regional projections
Oil	2.7	2.8	3.4	3.6	3.8	Based on USDOE regional projections
Wood (CH_4 and N_2O)	0.0	0.0	0.0	0.0	0.0	Based on USDOE regional projections
Transportation	**6.2**	**7.7**	**8.3**	**9.2**	**11.4**	
Motor Gasoline	3.2	3.7	3.6	3.8	4.3	Based on WYDOT VMT projections
Diesel	2.8	3.7	4.4	5.2	6.9	Based on WYDOT VMT projections
Natural Gas, LPG, other	0.1	0.1	0.1	0.1	0.1	Based on USDOE regional projections
Jet Fuel and Aviation Gasoline	0.1	0.2	0.21	0.2	0.2	Based on FAA projections
Fossil Fuel Industry (fugitive)	**6.7**	**11.4**	**13.5**	**14.4**	**14.9**	
Natural Gas Industry	5.0	9.2	11.0	11.6	12.0	
Oil Industry	0.8	0.5	0.4	0.5	0.5	See assumptions in Appendix E
Refineries (CH_4)	0.0	0.0	0.0	0.0	0.0	
Coal Mining (CH_4)	1.0	1.8	2.1	2.3	2.4	
Industrial Processes	**2.0**	**2.4**	**2.6**	**2.7**	**3.0**	
Cement Manufacture	0.3	0.6	0.5	0.5	0.6	Based on WY manufacturing employment growth
Lime Manufacture	0.1	0.1	0.2	0.2	0.2	
Limestone and Dolomite Use	0.0	0.0	0.0	0.0	0.0	
Soda Ash Manufacture	1.4	1.5	1.5	1.5	1.6	Based on 2004 and 2009 projections for US production
Soda Ash Use	0.0	0.0	0.0	0.0	0.0	
ODS Substitutes	0.0	0.1	0.2	0.3	0.6	EPA 2004 ODS cost study report
Electric Power T & D	0.1	0.1	0.1	0.0	0.0	Based on national projections(USEPA)
Waste Management	**0.3**	**0.4**	**0.5**	**0.7**	**0.9**	
Solid Waste Management	0.3	0.4	0.5	0.6	0.9	Projections based on population.
Wastewater Management	0.0	0.0	0.0	0.0	0.0	Projections based on population.
Agriculture	**4.1**	**5.5**	**5.1**	**5.4**	**6.0**	
Enteric Fermentation	1.6	2.0	2.0	2.2	2.5	USDA Livestock Projections
Manure Management	0.1	0.1	0.1	0.1	0.1	USDA Livestock Projections
Agricultural Soils	2.4	3.4	3.0	3.1	3.3	
Total Gross Emissions	**44.4**	**51.9**	**55.6**	**60.3**	**69.4**	
increase relative to 1990		*17%*	*25%*	*36%*	*57%*	
Forestry and Land Use	**-35.5**	**-35.5**	**-35.5**	**-35.5**	**-35.5**	
Agricultural Soils	**-0.9**	**-0.9**	**-0.9**	**-0.9**	**-0.9**	
Net Emissions (including sinks)	**8.0**	**15.5**	**19.2**	**23.9**	**33.0**	

[a] Totals may not equal sum of subtotals shown due to independent rounding.

Historical Emissions

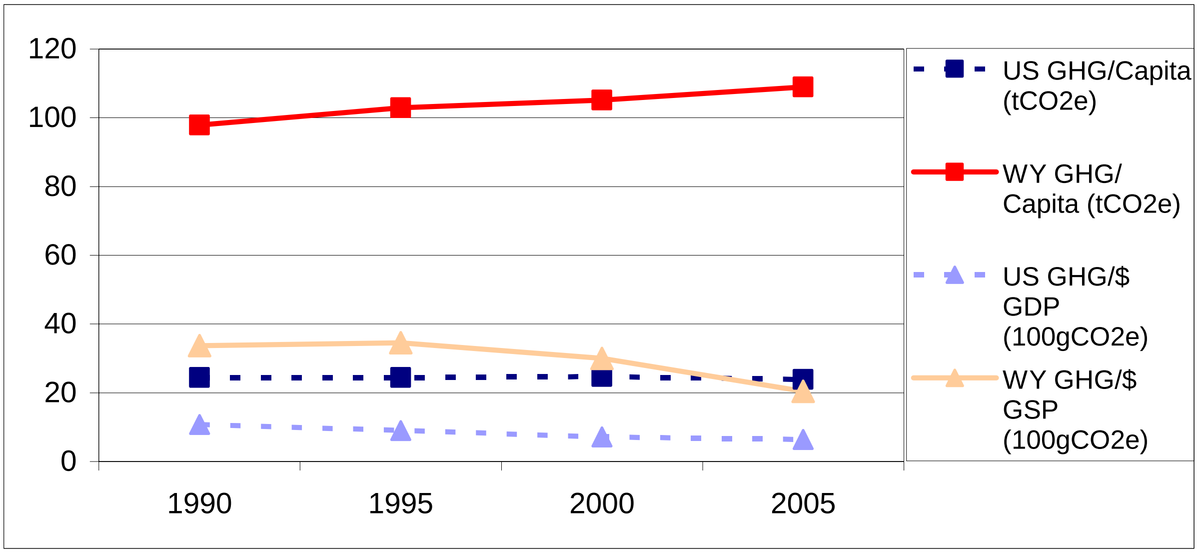
Overview

Preliminary analyses suggest that in 2005, activities in Wyoming accounted for approximately 56 million metric tons (MMt) of CO_2e emissions, an amount equal to 0.8% of total US GHG emissions.[6] Wyoming's gross GHG emissions are rising faster than those of the nation as a whole. Wyoming's gross GHG emissions increased by 25% from 1990 to 2005, while national emissions rose only 18% during the same period.

Figure 1 illustrates the State's emissions per capita and per unit of economic output. Wyoming's per capita emission rate is more than four times greater than the national average of 25 MtCO_2e/yr. This large difference between national and State per capita emissions occurs in most of the sectors – Wyoming's emission per capita significantly exceed national emissions per capita for the following sectors: electricity, industrial, fossil fuel production, transportation, industrial process and agriculture. The reasons for the higher per capita intensity in Wyoming are varied but include the State's strong fossil fuel production industry and other industries with high fossil fuel consumption intensity, large agriculture industry, large distances, and low population base. Between 1990 and 2005, per capita emissions in Wyoming have increased, mostly due to increased activity in the fossil fuel industry, while national per capita emissions have changed relatively little. Economic growth exceeded emissions growth both nationally and in Wyoming throughout the 1990-2005 period, as seen by the decreasing GHG emissions per dollar of Gross Domestic Product or Gross State Product.[7]

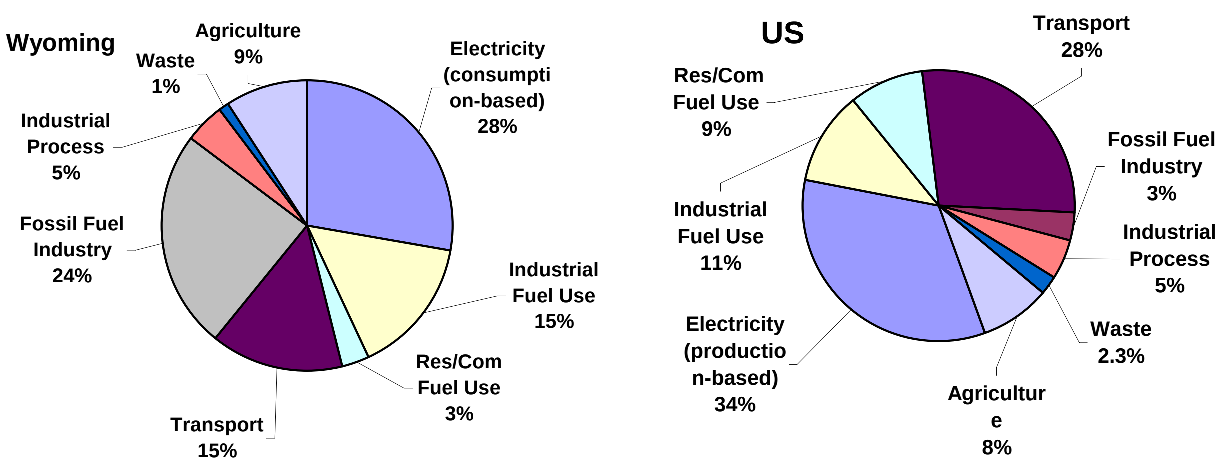
[6] United States emissions estimates are drawn from US EPA 2006, *Inventory of US Greenhouse gas Emissions and Sinks: 1990-2004*.
[7] Based on gross domestic product by state (millions of current dollars), available from the US Bureau of Economic Analysis (http://www.bea.gov/regional/gsp/). The national emissions used for these comparisons are based on 2004 emissions.

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



As shown in Figure 2, the three largest sources of Wyoming's consumption-based gross GHG emissions in 2005 are electricity consumption, fugitive (non-energy) emissions from the fossil fuel production industries, and fossil fuel consumption in the residential, commercial and industrial sectors, and. The next largest contributor to emissions is the transportation fuel use sector.

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



Industrial process emissions comprised almost 5% of State GHG emissions in 2005. CO_2 emitted during the production of soda ash in the State is the largest source of GHG emissions from industrial processes. Although industrial process emissions are rising rapidly due to the increasing use of HFC as substitutes for ozone-depleting chlorofluorocarbons[8] (CFCs), their overall contribution is estimated to be only 1% of Wyoming's gross GHG emissions in 2020 due to significant growth estimated for the other major contributors to GHG emissions. CO_2 emitted during the production of soda ash in the State are the largest source of GHG emissions from industrial process. Other industrial process emissions result from CO_2 released during soda ash, limestone, and dolomite use. Agriculture (CH_4 and N_2O emissions from manure management, fertilizer use, and livestock), landfills, and wastewater management facilities produced CH_4 and N_2O emissions that together accounted for the remaining 10% of the State's emissions in 2005.

Forestry activities in Wyoming are estimated to be net sinks for GHG emissions, and forested lands account for a sink of 36 $MMtCO_2e$ per year.

A Closer Look at the Two Major Sources: Electricity and Fossil Fuel Production

As shown in Figure 2, electricity consumption accounted for about 28% of Wyoming's gross GHG emissions in 2005 (about 15 $MMtCO_2e$), which was lower than the national average share of emissions from electricity consumption (34%).[9] The GHG emissions associated with Wyoming's electricity sector increased by just over 2 $MMtCO_2e$ between 1990 and 2005, accounting for about 20% of the State's net growth in gross GHG emissions in this time period.

It is important to note that the GHG emissions estimates for the electric sector reflect the *GHG emissions associated with the electricity sources used to meet Wyoming 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. In 2005, emissions associated with Wyoming's electricity consumption (15 $MMtCO_2e$, see Table 1) were much lower than those associated with electricity production (44 $MMtCO_2e$, see Table 1). The lower level for consumption-based emissions reflects GHG emissions associated with net exports of electricity to meet the other State's electricity demands.[10] The consumption-based approach is particularly useful for policy-making as it can better reflect the emissions (and emissions reductions) associated with activities occurring in the State, particularly with respect to electricity use (and efficiency improvements). Under this approach, emissions associated with electricity exported to other States would need to be covered in those States' accounts in order to avoid double-counting or exclusions. (Indeed, Arizona, California, Oregon, New Mexico, and Washington are currently considering such an approach.)

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[8] CFCs are also potent GHGs; they are not, however, included in GHG estimates because of concerns related to implementation of the Montreal Protocol (See Appendix I for additional information). HFCs are used as refrigerants in the residential, commercial and transport sectors as well as in the industrial sector. They are included here, however, within the industrial processes emissions.

[9] 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. Wyoming's situation is different, since it is a large electricity exporter.

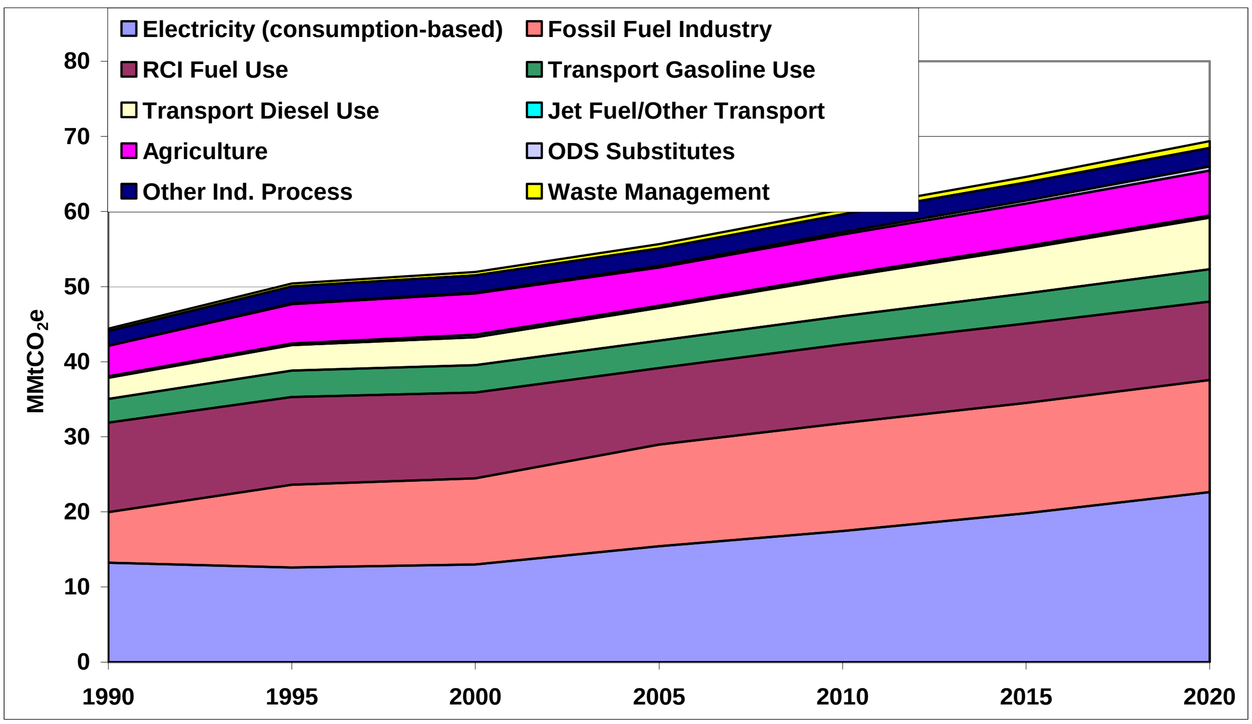
[10] Estimating the emissions associated with electricity use requires an understanding of the electricity sources (both in-state and out-of-state) used by utilities to meet consumer demand. The current estimate reflects some very simple assumptions, as described in Appendix A.

Estimated methane and vented carbon dioxide emissions from the fossil fuel industry in Wyoming accounted for about 24% of the State's gross GHG emissions in 2005. Emissions from this sector doubled from 1990 to 2005 and are projected to increase by a further 10% between 2005 and 2020. The natural gas industry is the major contributor to both GHG emissions and emissions growth. More than half of the emissions attributed to the natural gas industry are due to vented gas from a few processing plants, which process gas largely used for injection in enhanced oil recovery operations.

Reference Case Projections

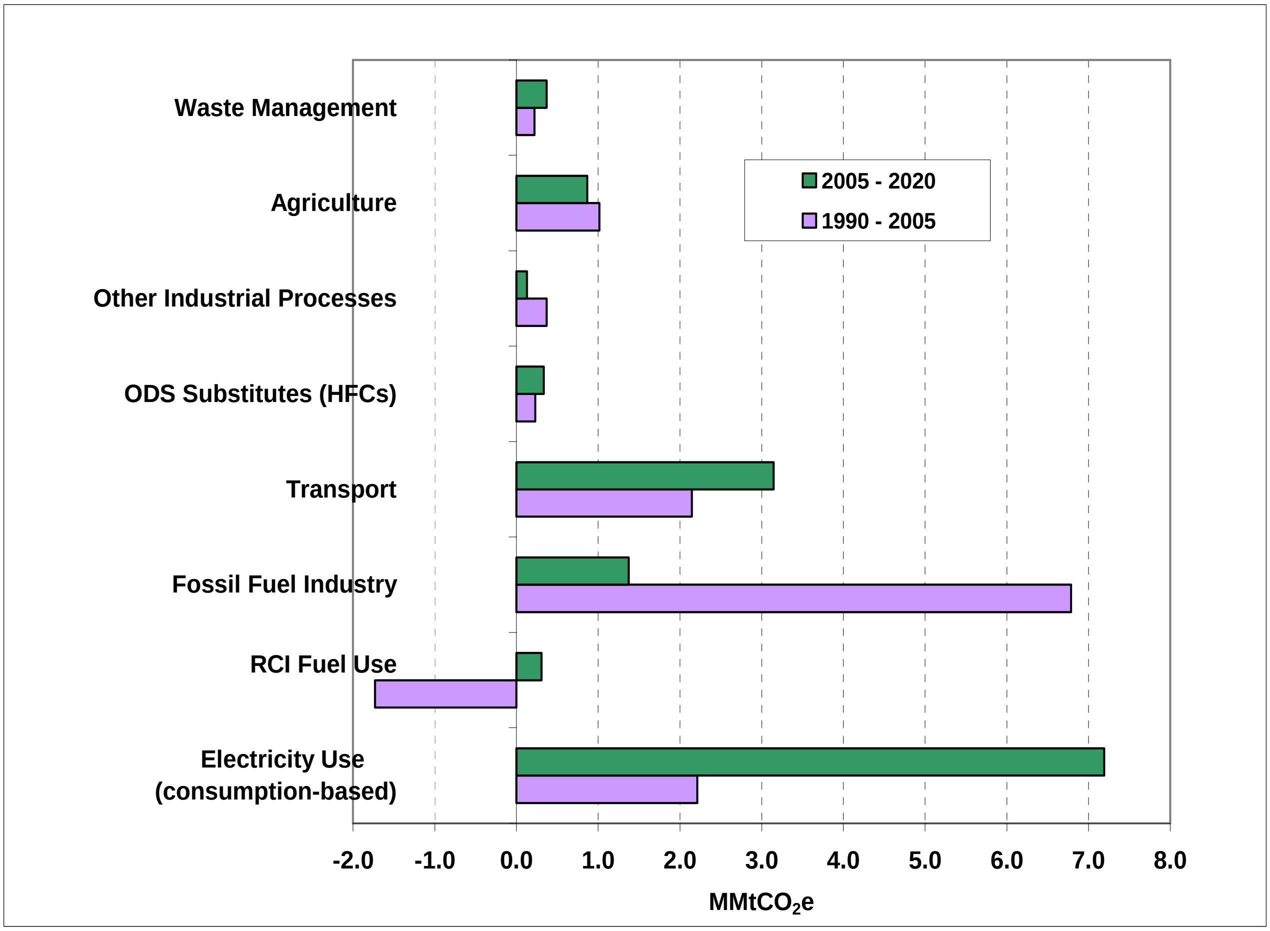
Relying on a variety of sources for projections of electricity and fuel use, as noted below and in the Appendices, we developed a simple reference case projection of GHG emissions through 2020. As illustrated in Figure 3 and shown numerically in Table 1, under the reference case projections, Wyoming gross GHG emissions continue to grow steadily, climbing to 69 $MMtCO_2e$ by 2020, 56% above 1990 levels. Demand for electricity is projected to be the largest contributor to future emissions growth, followed by emissions associated with transportation and fossil fuel production, as shown in Figure 4. Much of the projected increase in electricity consumption in Wyoming is due to expected growth in the fossil fuel production industry.

Figure 3. Wyoming 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 Wyoming, 1990-2020: Historic and Reference Case Projections ($MMtCO_2e$ Basis)



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

Key Uncertainties and Next Steps

Some data gaps exist in this inventory, and particularly in the reference case projections. Key tasks for future refinement of this inventory and forecast include review and revision of key drivers, such as the electricity and transportation fuel use growth rates that will be major determinants of Wyoming's future GHG emissions (See Table 2). These growth rates are driven by uncertain economic, demographic and land use trends (including growth patterns and transportation system impacts), all of which deserve closer review and discussion.

Perhaps the variables with the most important implications for GHG emissions are (i) the type and number of power plants built in Wyoming between now and 2020 and (ii) the amount of fossil fuel production. The assumptions on VMT and air travel growth also have large impacts on projected GHG emissions growth in the State. Finally, uncertainty remains on estimates for historic and projected GHG sinks from forestry, which can greatly affect the net GHG emissions attributed to Wyoming.

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

	1990-2005	2005-2020	Sources
Population*	0.8%	0.6%	Wyoming Department of Information and Administration
Employment*			Wyoming Department of Information and Administration
Goods	2.1%	0.4%	
Services	1.8%	1.5%	
Electricity Sales	1.2%	3.0%	US DOE Energy Information Administration (EIA) data for 1990-2005. The growth rate for 2005-2020 is based on electricity sales forecasts developed for the energy supply sector (see Appendix A).
Vehicle Miles Traveled	2.9%	2.0%	Wyoming Department of Transportation.

* For the RCI fuel consumption sectors, population and employment projections for Wyoming were used together with US DOE EIA's Annual Energy Outlook 2006 (AEO2006) projections of changes in fuel use for the EIA's Mountain 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 Wyoming's residential natural gas use is calculated as the Wyoming population growth times the change in per capita natural gas use for the Mountain region.

Emissions of aerosols, particularly black carbon (BC) — essentially soot — from fossil fuel combustion, could have significant impacts in terms of radiative forcing (i.e., climate impacts). Methodologies for conversion of BC mass estimates and projections to global warming potential involve significant uncertainty at present, but CCS has developed and used a recommended approach for estimating BC emissions based on methods used in other States. Current estimates suggest a relatively small CO_2e contribution overall from BC emissions, as compared to the CO_2e contributed from the gases (about 4 to 8% BC contribution relative to the other gases in 2002, with the fractions falling in the 2018 forecast; see Appendix I).

Approach

The principle goal of compiling the inventories and reference case projections presented in this document is to provide the State of Wyoming with a general understanding of Wyoming'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 Wyoming.

General Methodology

We prepared this analysis in close consultation with Wyoming agencies, in particular, with the WYDEQ 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[11] and its guidelines for States.[12] These inventory guidelines were developed based on the guidelines from the IPCC, the international organization responsible for developing coordinated methods for national GHG inventories.[13] 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.

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[14], we define reference case actions for the purposes of projections as those *currently in place or reasonably expected over the time period of analysis*.

- **Comprehensive Coverage of Gases, Sectors, State Activities, and Time Periods:** This analysis aims to comprehensively cover GHG emissions associated with activities in Wyoming. 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.

- **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.

[11] 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.
[12] http://yosemite.epa.gov/oar/globalwarming.nsf/content/EmissionsStateInventoryGuidance.html.
[13] http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
[14] "Reference case" is similar to the term "base year" used in criteria pollutant inventories. However, it also generally contains both a most current year estimate (e.g., 2002 or 2005), as well as estimates for historical years (e.g., 1990, 2000). Projections from this reference case are made to future years based on business-as-usual assumptions of future year source activity.

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

Source	Information provided	Use of Information in this Analysis
US EPA State Greenhouse Gas Inventory Tool (SGIT)	US EPA SGIT is a collection of linked spreadsheets designed to help users develop State GHG inventories. US EPA SGIT contains default data for each State for most of the information required for an inventory. The SGIT methods are based on the methods provided in the Volume 8 document series published by the Emissions Inventory Improvement Program (http://www.epa.gov/ttn/chief/eiip/techreport/volume08/index.html).	Where not indicated otherwise, SGIT is used to calculate emissions from residential/commercial/industrial fuel combustion, transportation, industrial processes, agriculture and forestry, and waste. We use SGIT emission factors (CO_2, CH_4 and N_2O per BTU consumed) to calculate energy use emissions.
US DOE Energy Information Administration (EIA) State Energy Data (SED)	EIA SED provides energy use data in each State, annually to 2003.	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 2003. 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. Wyoming is included in the Mountain Census region (AZ, CO, ID, MT, NM, NV, UT, and WY).	EIA AEO2006 is used to project changes in per capita (residential), per employee (commercial/industrial).
American Gas Association - Gas Facts	Natural gas transmission and distribution pipeline mileage.	Pipeline mileage from Gas Facts used with SGIT to estimate natural gas transmission and distribution emissions.
US EPA Landfill Methane Outreach Program (LMOP)	LMOP provides landfill waste-in-place data.	Waste-in-place data used to estimate annual disposal rate, which was used with SGIT to estimate emissions from solid waste.
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.

- **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.

- **Use of Consumption-Based Emissions Estimates:** To the extent possible, we estimated emissions that are caused by activities that occur in Wyoming. For example, we reported emissions associated with the electricity consumed in Wyoming. 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 Wyoming. This entails accounting for the electricity produced in Wyoming utilities to meet consumer demands outside of the State. Further refinement of this work could attempt to estimate other sectoral emissions on a consumption basis, such as accounting for emissions from transportation fuel used in Wyoming, 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 Industries;
- Appendix F. Agriculture;
- Appendix G. Waste Management; and
- Appendix H. Forestry. .

Appendix I contains a discussion of the inventory and forecast for black carbon. Appendix J provides additional background information from the US EPA on GHGs and global warming potential values.

Appendix A. Electricity Use and Supply

Overview

Wyoming's electric sector is dominated by coal generation, with much of this generation being exported to meet electricity demand in other states. This situation is projected to continue throughout the projection period of this analysis. As noted earlier, one of the key questions for the State to consider is how to treat GHG emissions that result from generation of electricity that is produced in Wyoming to meet electricity needs in other state. In other words, should the State consider the GHG emissions associated with the State's electricity consumption or its electricity production, or some combination of the two? Since this question still needs to be resolved, this section examines electricity-related emissions from both a production and consumption basis.

Emissions and Reference Case Projections

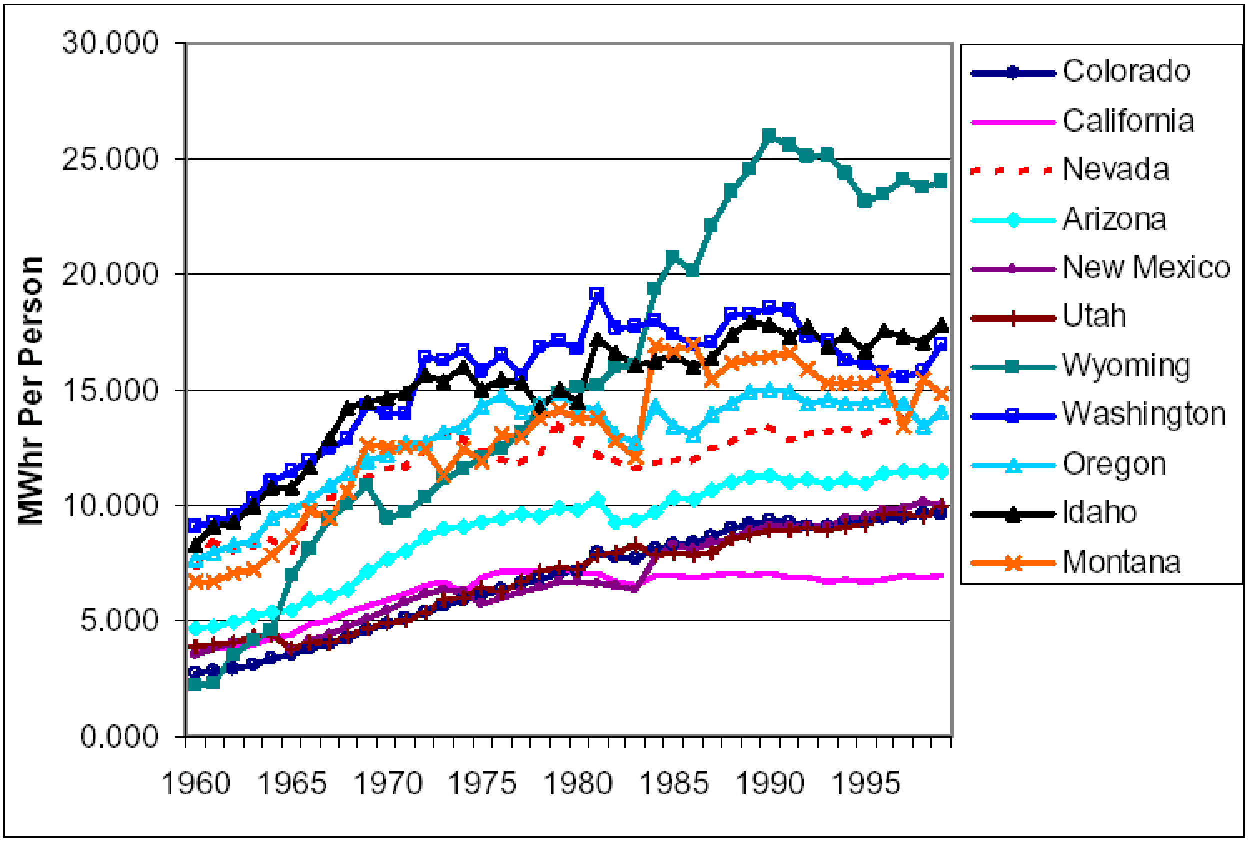
This appendix assesses Wyoming's electricity sector in terms of net consumption and production emissions, and describes the assumptions used to develop the reference case projections. It then describes inter-state electricity trade and potential approaches for allocating GHG emissions for the purpose of determining the State's inventory and reference case forecasts. Finally, key assumptions and results are summarized.

Electricity Consumption

At about 26,800 kWh/capita (2004 data), Wyoming has relatively high electricity consumption per capita. By way of comparison, the per capita consumption for the US was about 12,000 kWh per year.[15] Figure A1 shows Wyoming's rank compared to other western states from 1960-1999; since 1985, Wyoming's per capita consumption has been the highest of any western state. Many components influence a state's per capita electricity consumption, including the impact of weather on demand for cooling, the size and type of industries in the State, and the type and efficiency of equipment in the residential, commercial and industrial sectors. Wyoming's high electricity consumption per person appears to be mostly a result of the size and type of industries in the State and relatively low population.

[15] Census bureau for U.S. population, Energy Information Administration for electricity sales.

Figure A1. Electricity Consumption Per Capita in Western States, 1960-1999

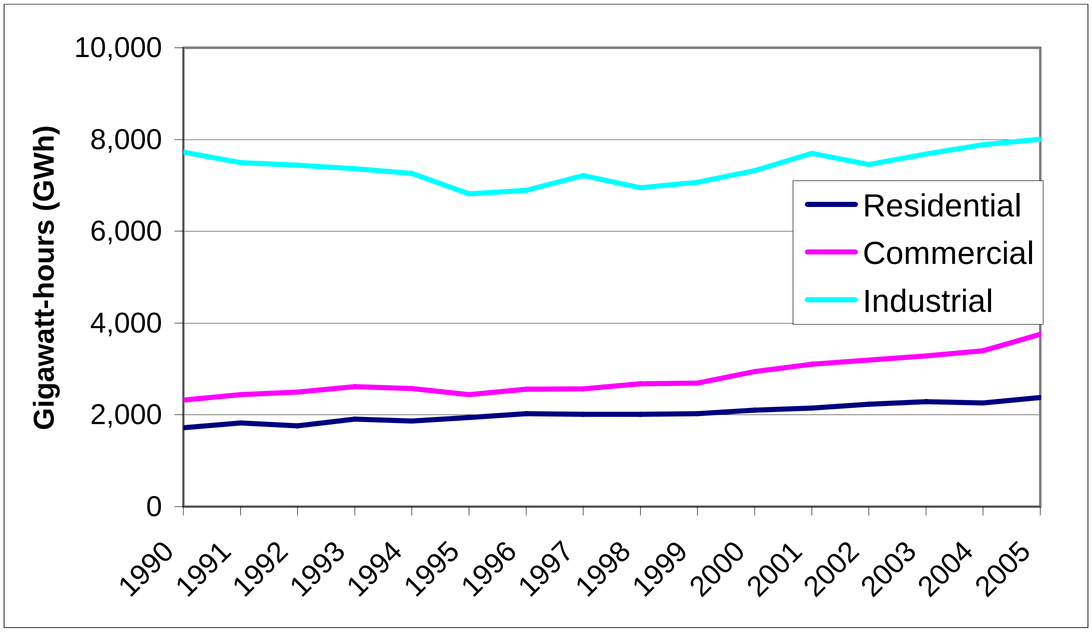


Source: Northwest Power Council, 5th Power Plan, Appendix A

As shown in Figure A2, electricity sales in Wyoming showed minor increases from 1990 through 2005. Overall, total electricity consumption increased at an average annual rate of 1.2% from 1990 to 2005, the same rate as the population growth rate for this period.[16] During this period, the residential sector grew by an average of 2.2% per year, the commercial sector by 3.3% per year, and the industrial sector by 0.2% per year.

[16] Population from Wyoming Department of Information and Administration, Economic Analysis Division, Wyoming Population Estimates and Forecasts, "Population for Wyoming, Counties, Cities, and Towns: 1990 to 2000" and "Population Estimates and Forecasts for Wyoming, Counties, Cities, and Towns for 2000-2020".

Figure A2. Electricity Consumption by Sector in Wyoming, 1990-2005[17]



Source: EIA State Energy Data (1990-2002) and EIA Electric Power Annual (2003-2005).

Projections for electricity sales from 2006 through 2020 are based on the 2006 *Load Forecast* developed by Rocky Mountain Power (previously named PacifiCorp).[18] Since Rocky Mountain Power accounts for almost 60% of Wyoming's retail electricity sales, the projections from its load forecast are assumed to be representative of the whole state and have been applied to total electricity sales. Rocky Mountain Power's projected annual growth in electricity sales from 2005 through 2017 is 3.0% per year, a strong increase compared to the average growth from 1990-2005. Rocky Mountain Power projects that both industrial and commercial sales will grow significantly as a result of increased oil and gas activity in the State. Table A1 reports historic and projected annual average growth rates.

[17] Note from 1990-2002, the EIA data includes a category referred to as "other," which included lighting for public buildings, streets, and highways, interdepartmental sales, and other sales to public authorities, agricultural and irrigation sales where separately identified, electrified rail and various urban transit systems (such as automated guideway, trolley, and cable). To report total electricity in Figure A2, the sales from the "other" category are included with the commercial sector. The decision to include with commercial rather than the other sectors is based on comparing the trends of electricity sales from 2000-2002 with 2003 sales.

[18] Data from the 2006 Load Forecast for Wyoming are from one of Pacificorp's Public Input Meeting for the 2006 Integrated Resource Plan (April 20, 2006). http://www.utah-power.com/File/File64180.pdf. Accessed on November 14, 2006.

Table A1. Electricity Growth Rates, historic and projected

	Historic		Projections	
	1990-2000	2000-2005	2006-2010	2010-2020
Residential	2.0%	1.5%	2.0%	2.0%
Commercial	2.4%	2.9%	3.4%	3.4%
Industrial	-0.5%	1.5%	3.1%	3.1%
Total	**0.5%**	**1.9%**	**3.0%**	**3.0%**

Source: Historic from EIA data, projections from Rocky Mountain Power *2006 Load Forecast.*

Electricity Generation – Wyoming's Power Plants

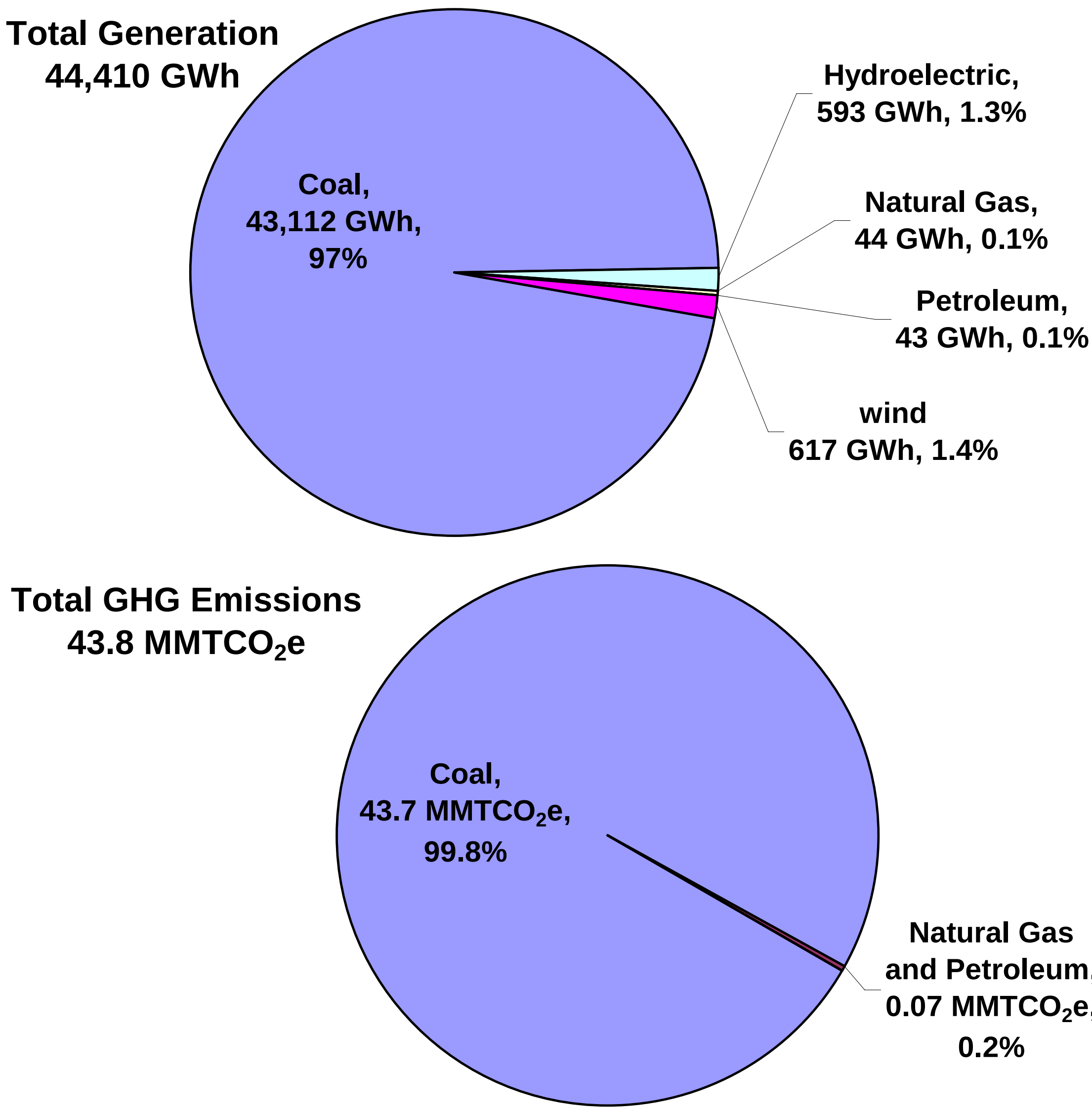
This section provides information on GHG emissions and other activity associated with power plants *located in Wyoming*. Since Wyoming is part of the interconnected Western Electricity Coordinating Council (WECC) region – electricity generated in Wyoming can be exported to serve needs in other states and electricity used in Wyoming can be generated in plants outside the state. For this analysis, we estimate emissions on both a *production-basis* (emissions associated with electricity produced in Wyoming, regardless of where it is consumed) and a *consumption-basis* (emissions associated with electricity consumed in Wyoming). This section describes production-based emissions while the subsequent section, *Electricity trade and the allocation of GHG emissions*, reports consumption-based emissions.

As displayed in Figure A3, coal figures prominently in electricity generation and accounts for almost 100% of the GHG emissions from power plants in Wyoming. Table A2 reports the emissions from the four plants in Wyoming with the highest GHG emissions. The two largest plants, Jim Bridger and Laramie River, account for about 67% of Wyoming's GHG emissions. Jim Bridger is jointly owned by Idaho Power (1/3) and Pacificorp/Rocky Mountain Power (2/3), while the Laramie River plant is jointly owned by six electric utilities (two in Wyoming, two in South Dakota, one in Colorado and one in Nebraska).[19]

We considered two sources of data in developing the historic inventory of GHG emissions from Wyoming power plants – EIA State Energy Data (SED), which need to be multiplied by GHG emission factors for each type of fuel consumed, and EPA data on CO_2 emissions by power plant. To calculate total GHG emissions from electricity production in Wyoming, we applied SGIT emission factors to EIA's SED. For CO_2 emissions from individual plants reported in Table A2, we used the EPA data.[20]

[19] Information from Idaho Power http://www.idahopower.com/energycenter/electricitybasics/generation/thermal.htm and Basin Electric Power Co-operative. http://www.basinelectric.com/EnergyResources/Electricity/BaseLoad/LRS.html, accessed on January 31, 2007.
[20] For total electric sector GHG emissions, we used the EIA's SED rather than EPA data because of comprehensiveness of the EIA-based data. The EPA data are limited to plants over 25 MW and only CO_2 emissions (EPA does not collect data on CH_4 or N_2O emissions). Through discussions with EPA we also learned that EPA data tend to be conservative (i.e., overestimate emissions) because the data are reported as part of a regulatory program, and that during early years of the data collection program, missing data points were sometimes assigned a large value as a placeholder. However, EPA provides easily accessible data for each power plant (over 25 MW), which would be much more difficult to extract from EIA data and the CO_2 emissions from the two sources differ by less

Figure A3. Electricity Generation and GHG Emissions from Wyoming Power Plants, 2004



Source: Generation data from EIA Electric Power Annual spreadsheets, GHG emissions calculated from EIA data on fuel consumption and EPA's SGIT GHG emission factors.

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than 2% in most years. Based on this information, we chose to report both data sources in Table A2 but rely on the EIA data for the inventory values of total GHG emissions for this sector.

Table A2. CO_2 Emissions from Individual Wyoming Power Plants, 1997-2002

(Million metric tons CO_2)	2000	2001	2002	2003	2004	2005
Dave Johnston	*6.7*	*6.1*	*6.4*	*6.0*	*6.4*	*6.5*
Jim Bridger	*16.9*	*16.7*	*15.1*	*14.8*	*15.2*	*14.7*
Laramie River	*13.1*	*13.0*	*12.8*	*13.6*	*13.7*	*13.9*
Naughton	*5.5*	*5.3*	*5.2*	*4.8*	*5.3*	*5.5*
Other Plants	*1.0*	*1.9*	*2.2*	*3.5*	*2.8*	*3.3*
Total CO_2 emissions	**43.1**	**43.1**	**41.6**	**42.7**	**43.5**	**44.0**

Source: US EPA Clean Air Markets database for named plants (http://cfpub.epa.gov/index.cfm). Total emissions calculated from fuel use data provided by SED (US DOE Energy Information Administration). "Other Plants" accounts for both the emissions from plants that are not reported individually and any adjustments to the data to calibrate to the Total Emissions.
Note: The emissions reported in the above table are CO_2 only. CH_4 and N_2O emissions were not included in the power plant data from the US EPA Clean Air Markets.

Table A3 shows the growth in generation by fuel type between 1990 and 2004 from power plants in Wyoming. Overall generation grew by 13% over the 15 years, with most of the growth from increased coal generation. Hydro generation shows a decrease between 1990 and 2004, but the table masks the considerable year-by-year variation from this resource. In the 15-year period, hydro generation ranged between a low of 584 GWh in 2003 and a high of 1,381 GWh in 1997. Wind power has grown rapidly in recent years.

Table A3. Growth in Electricity Generation in Wyoming 1990-2004

	Generation (GWh)		Growth
	1990	2004	
Coal	38,681	43,112	11%
Hydroelectric	645	593	-8%
Natural Gas	7	44	556%
Wind	0	617	n/a
Petroleum	46	43	-5%
Total	39,378	44,410	13%

Source: EIA data, generation from electric sector, excludes electricity generation from combined heat and power plants in the industrial and commercial sectors.

Future Generation and Emissions

Estimating future generation and GHG emissions from Wyoming power plants requires estimation of new power plant additions and production levels from new and existing power plants. There are, of course, large uncertainties, especially related to the timing and nature of new power plant construction.

The future mix of plants in Wyoming remains uncertain as the trends in type of new builds are influenced by many factors. Since 2000, new power plants in Wyoming have been a mix of coal and wind; new plant proposals also rely on these two resources. Table A4 presents data on new and proposed plants in Wyoming. Note that proposed plants may not necessarily be built; while others not yet on the drawing boards could well appear prior to 2020.

Individual proposed plants are not modeled in the reference case projections, but the mix of types of proposed plants are considered when developing assumptions.

Table A4. New and Proposed Power Plants in Wyoming

	Plant Name	Fuel	Status	Capacity MW	Illustrative Annual Generation GWh	Illustrative Annual Emissions $MMTCO_2e$	Notes
New plants	Pleasant Valley	Wind	Online 2003	144	378	0.0	
	Wygen II	coal	under construction	90	670	0.6	Black Hills Corp, Plans to be operational Jan 2008
Proposed plants	Tierra Wind	wind	Permiting begun	30	92	0.0	Has power purchase agreement with Cheyenne Fuel and Power. On-line 2008
	Two Elk I	coal	Permit awarded construction stopped	280	2,085	1.7	Plans to finish construction by 2010
	Mountain Wind	wind		60	184	0.0	Has power purchase agreement with PacifiCorp. On-line 2008
	Pine Draw	wind		182	558	0.0	Expected On-line 2010
	Bridger Butte Wind Project	wind		201	616	0.0	
	Dry Fork Station	coal	Permit awarded	422	3,142	2.6	Basin Electric, plans to finish construction by fall 2010
	Two Elk II	coal	Permiting begun	750	5,585	4.6	Anticipated as either a nominal 750 MW Supercritical Pulverized Coal or a nominal 600 MW Integrated Gasification Combined Cycle facility.
	Medicine Bow	coal, coal-to-liquids refinery with cogeneration	proposed	200	1,489	1.2	First phase includes 10,000 barrel per day refinery, plans for 2010
	Wygen III	coal	proposed	90	670	0.6	Same plant design as Wygen II
	White Mountain	wind	proposed	239	734	0.0	towers

Sources: Wyoming Department of Environmental Quality, industrial siting department website (http://deq.state.wy.us/isd/isdnews.htm) and personal communication with Todd Parfitt. Personal communication Dave Piroutek, Wyoming Public Service Commission.
California Energy Commission website, proposed new plants http://www.energy.ca.gov/electricity/WECC_PROPOSED_GENERATION.XLS.
North American Power Group new projects, http://www.napg-ltd.com/projects.html
Rentech Inc. Press Release, January 17, 2007 http://www.rentechinc.com/pdfs/01-17-06-Rentech-Signs-CTL-Agreement-with-DKRW.pdf .
Generation estimates based on capacity factors of 0.85 for base load coal and 0.35 for wind. Emissions estimates based on heat rates of 9,000 BTU/kWh of coal.

Given the many factors affecting electricity-related emissions and a diversity of assumptions by stakeholders within the electricity sector, developing a "reference case" projection for the most likely development of Wyoming's electricity sector is particularly challenging. Therefore, to develop an initial projection, simple assumptions were made, relying to the extent possible on widely-reviewed and accepted modeling assessments.

The reference case projections assume:

- Generation from power plants in Wyoming grows at 3.0% per year from 2008-2010, following growth rate in electricity sales

- Generation from power plants in Wyoming grows at 1.7% per year from 2010 to 2015 and 1.6% from 2015 to 2020. This reflects the generation growth rate for the combined Northwest Power Pool and Rocky Mountains region in Annual Energy Outlook 2006 (AEO2006). These assumptions lead to about 2100 MW of new power plant capacity by 2020.
- Generation from existing non-hydro plants is based on holding generation at 2005 levels. Generation from existing hydro-electric plants is assumed to be 957 GWh per year, the average generation from the last ten years. New plants and changes to existing plants due to plant renovations and overhauls that result in higher capacity factors are counted as new generation (thus the mix of new generation discussed below would also apply to plant upgrades).
- Generation from new power plants built between 2007 and 2010 will be a mix of 85% coal and 15% wind. This mix is roughly based on the mix of proposed new plants, Table A4.
- Generation from new power plants built between 2011 and 2020 will be a mix of 83% coal, 5% natural gas, and 12% wind. This mix of proposed plants is based on information in Table A4 on proposed new plants, combined with regional projections from the EIA AEO2006.

Electricity Trade and Allocation of GHG Emissions

Wyoming is part of the interconnected Western Electricity Coordinating Council (WECC) region - a vast and diverse area covering 1.8 million square miles and extending from Canada through Mexico, including all or portions of 14 western states. The inter-connected region allows electricity generators and consumers to buy and sell electricity across regions, taking advantage of the range of resources and markets. Electricity generated by any single plant enters the interconnected grid and may contribute to meeting demand throughout much of the region, depending on sufficient transmission capacity. Thus, it is challenging to define which emissions should be allocated to Wyoming, and secondly in estimating these emissions both historically and into the future. Some utilities track and report electricity sales to meet consumer demand by fuel source and plant type; however, tracing sales to individual power plants may not be possible.

In 2004, Wyoming had 35 entities involved in providing electricity to state customers. The State’s five private utilities serve approximately 61% of the customers, and provide 67% of the electricity sales. The State’s 16 electric cooperatives serve 29% of the customers and the same fraction of sales. One federal and 13 public utilities account for the remaining 10% of customers and 4% of sales. The top 5 providers of retail electricity in the State are reported in Table A5.

Table A5. Retail Electricity Providers in Wyoming (2004)

	Ownership Type	2004 GWh
Top 5 providers of Retail Electricity, ranked by retail sales		
Pacificorp	Investor-Owned	7,786
Powder River Energy	Cooperative	1,918
Cheyenne Light Fuel & Power	Investor-Owned	865
High Plains Power, Inc	Cooperative	793
Lower Valley Energy, Inc	Cooperative	554
Total Sales, Top Five Providers		11,916
Total, all Wyoming		13,565

Source: EIA state electricity profiles

Since almost all states are part of regional trading grids, many states that have developed GHG inventories have grappled with the problem of how to account for electric sector emissions, when electricity flows across state borders. Several approaches have been developed to allocate GHG emissions from the electricity sector to individual states for inventories.

In many ways the simplest approach is *production-based* – emissions from power plants within the state are included in the state's inventory. The data for this estimate are publicly available and unambiguous. However, this approach is problematic for states that import or export significant amounts of electricity. Under a production-based approach, characteristics of Wyoming electricity consumption would not be fully captured since only emissions from in-state generation would be considered.

An alternative is to estimate *consumption-based* or *load-based* GHG emissions, corresponding to the emissions associated with electricity consumed in the state. The load-based approach is currently being considered by states that import significant amounts of electricity, such as California, Oregon, and Washington.[21] By accounting for emissions from imported electricity, states can account for increases or decreases in fossil fuel consumed in power plants outside of the State, due to demand growth, efficiency programs, and other actions in the state. The difficulty with this approach is properly accounting for the emissions from imports and exports. Since the electricity flowing into or out of Wyoming is a mix of all plants generating on the inter-connected grid, it is impossible to physically track the sources of the electrons.

The approach taken in this initial inventory is a simplification of the consumption-based approach. This approach, which one could term "*Net-Consumption-based*," estimates consumption-based emissions as in-state (production-based) emissions times the ratio of total in-state electricity consumption to in-state generation (net of losses). This method does not account for differences in the type of electricity that is imported or exported from the State, and as such, it provides a simplified method for reflecting the emissions impacts of electricity consumption in the State. The calculation also ignores "gross" imports – since Wyoming plants have contracts to

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

out-of-state entities, some of the in-state electricity generation will be exported and gross imports will be greater than net imports. More sophisticated methods – for example, based on individual utility information on resources used to meet loads – can be considered for further improvements to this approach. Estimating the mix of electricity generation for the imports/export of a state is possible and several states are developing data collection approaches to do this. Washington State has developed regular fuel disclosure reporting.[22]

Summary of Assumptions and Reference Case Projections

As noted, projecting generation sources, sales, and emissions for the electric sector out to 2020 requires a number of key assumptions, including economic and demographic activity, changes in electricity-using technologies, regional markets for electricity (and competitiveness of various technologies and locations), access to transmission and distribution, the retirement of existing generation plants, the response to changing fuel prices, and the fuel/technology mix of new generation plants. The key assumptions described above are summarized in Table A6.

Table A6. Key Assumptions and Methods for Electricity Projections for Wyoming

Electricity sales	Average annual growth of 3.0% from 2006 to 2020, based on growth rates in Rocky Mountain Power *2006 Load Forecast*.
Electricity generation	3.0% per year from 2008-2010, based on consumption growth and proposed plants and 1.7% per year from 2010 to 2020, based on regional growth rates in AEO2006.
Transmission and Distribution losses	10% losses are assumed, based on average statewide losses, 1994-2000, (data from the US EPA Emission & Generation Resource Integrated Database[23])
New Generation Sources (2006-2010)	The mix of new generation in this period roughly tracks the mix of proposed new plants in Wyoming (Table A4). 85% coal and 15% wind
New Generation Sources (2011-2020)	The mix of new generation in this period is based on regional projections from the AEO2006 combined with the mix of proposed new plants in Wyoming (Table A4). 83% coal 5% natural gas 12% wind
Heat Rates	The assumed heat rates for new gas and coal generation are 7000 Btu/kWh and 9000 Btu/kWh, respectively, based on estimates used in similar analyses.[24]
Operation of Existing Facilities	Existing non-hydro facilities are assumed to continue to operate as they were in 2005. Existing hydro facilities are assumed to generate 957 GWh per year the average generation over the period 1996-2005. Improvements in existing facilities that lead to higher capacity factor and more generation are captured under the new generation sources.

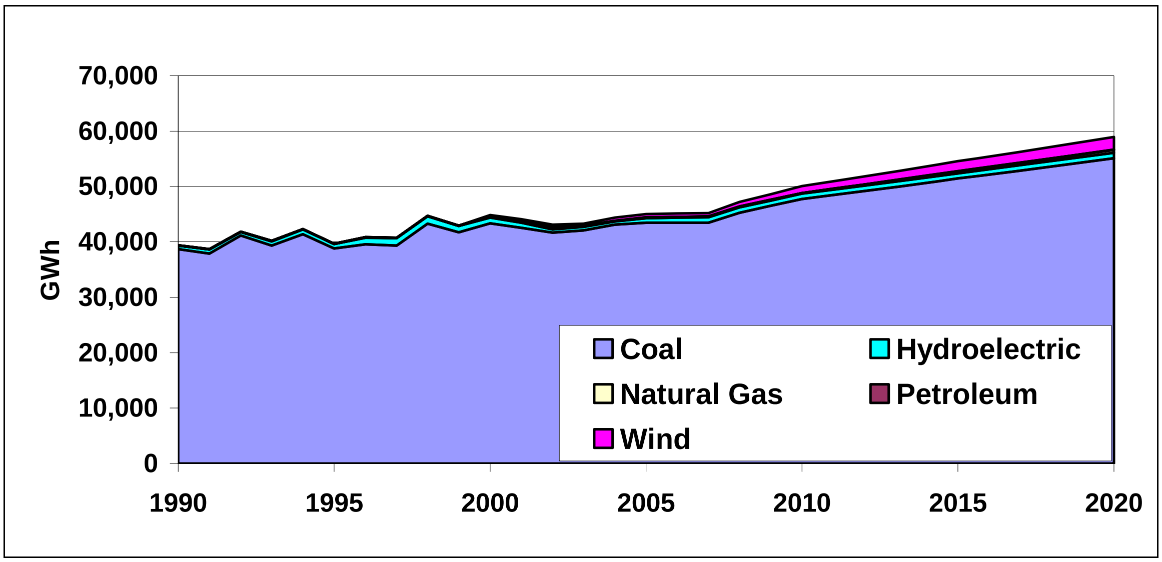
[22] http://www.cted.wa.gov/site/539/default.aspx
[23] http://www.epa.gov/cleanenergy/egrid/index.htm.
[24] See, for instance, the Oregon Governor's Advisory Group On Global Warming http://egov.oregon.gov/ENERGY/GBLWRM/Strategy.shtml.

Results

Figure A4 shows historical sources of electricity generation in the state by fuel source, along with projections to the year 2020 based on the assumptions described above. Based on the assumptions for new generation, coal continues to dominate new generation throughout the forecast period (2006-2020). Wind generation show high growth, relative to levels in 2005. Overall electricity generation grows at 1.8% per year from 2005 to 2020.

GHG emission estimates were calculated by multiplying the energy consumption by GHG emission factors by fuel. Energy consumption for 2006 to 2020 was calculated based on changes to future generation and heat rate properties described in table A6. The EPA SGIT software provided GHG emission factors by fuel for each state, consistent with factors used for EPA's national GHG inventory report.[25]

Figure A4. Electricity Generated by Wyoming Power Plants 1990-2020



Source: 1990-2005 EIA data, 2006-2020 CCS calculations based on assumptions described above, generation from petroleum and natural gas resources are too small to be visible in the chart

Figure A5 illustrates the GHG emissions associated with the mix of electricity generation shown in Figure A4. From 2005 to 2020, the emissions from Wyoming electricity generation are projected to grow at 1.4% per year, lower than the growth in electricity generation, due to an increased fraction of generation from wind. As a result, the emission intensity (GHG emissions per MWh) of Wyoming electricity is expected to decrease from 0.98 $MtCO_2$/MWh in 2005 to 0.92 $MtCO_2$/MWh in 2020.

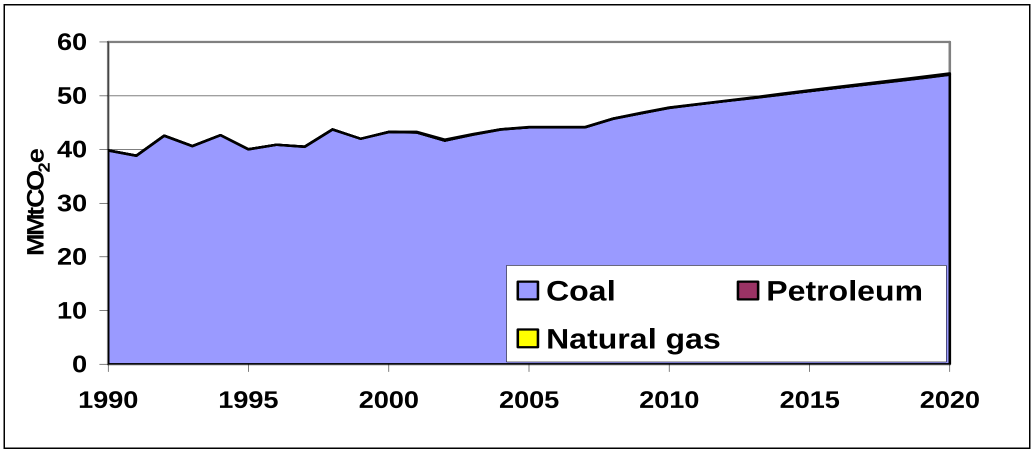
Figure A6 shows the "net-consumption-based" emissions from 1990 to 2020. Total emissions are much lower than the production-based emissions due to the GHG emissions associated with net electricity exports. Consumption-based emissions increase by 2.6% per year from 2006 to 2020.

[25] SGIT http://www.epa.gov/climatechange/emissions/state_guidance.html, National GHG inventory http://www.epa.gov/climatechange/emissions/usinventoryreport.html

The higher growth, relative to production-based emissions, results from higher growth in electricity consumption in the State compared to electricity generation.

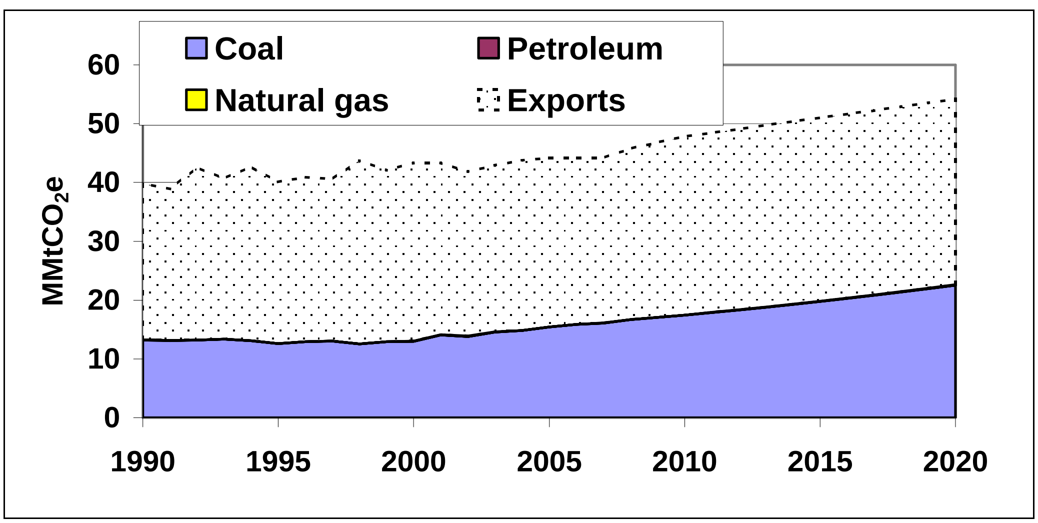
Following these figures, Table A7 summarizes the GHG emissions for Wyoming's electric sector from 1990 to 2020. During this time period, emissions are projected to increase by 49% on a production-basis and 139% on a consumption-basis. The consumption-based emissions have a stronger growth rate due to the higher growth rate of electricity consumption compared to electricity production.

Figure A5. Wyoming GHG Emissions Associated with Electricity Production (Production-Basis)



Source: CCS calculations based on approach described in text.
Note: Wyoming's electric generation GHG emissions from natural gas and petroleum sources are less than 0.05 MMTCO$_2$e and too small to be visible in the chart.

Figure A6. Wyoming GHG Emissions Associated with Electricity Use (Net Consumption-Basis), Showing Exports



Source: CCS calculations based on approach described in text.
Note: Wyoming's electric generation GHG emissions from natural gas and petroleum sources are less than 0.05 MMTCO$_2$e and too small to be visible in the chart.

Table A7. Wyoming GHG Emissions from Electric Sector, Production and Consumption-based estimates, 1990-2020

(Million Metric Tons CO2e)	1990	2000	2005	2010	2020
Electricity Production	**39.8**	**43.3**	**44.2**	**47.8**	**54.2**
Coal	39.8	43.2	44.1	47.7	53.9
CO_2	39.6	43.0	43.9	47.5	53.6
CH_4 and N_2O	0.2	0.2	0.2	0.2	0.3
Natural Gas	0.0	0.1	0.1	0.1	0.2
CO_2	0.0	0.1	0.1	0.1	0.2
CH_4 and N_2O	0.0	0.0	0.0	0.0	0.0
Petroleum	0.0	0.0	0.0	0.0	0.0
CO_2	0.0	0.0	0.0	0.0	0.0
CH_4 and N_2O	0.0	0.0	0.0	0.0	0.0
Elecricity Net Imports (negative for exports)	**-26.6**	**-30.3**	**-28.7**	**-30.4**	**-31.5**
Electricity Consumption-based Emissi	**13.2**	**13.0**	**15.4**	**17.4**	**22.6**

Note: Values that are less than 0.05 $MMTCO_2e$ are listed as 0.0 in table A7.

Key Uncertainties

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

- Future projections for electricity consumption. In particular, electricity growth rates are highly dependent on uncertain projections for oil and gas development.
- Amount and mix of new generation. Wyoming's mix of new generation will depend, in part, on policies in states that import Wyoming's electricity. Both new renewable generation policies and restrictions on mercury emissions could impact new plant development in the State.

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

Overview

Activities in the RCI[26] sectors produce carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions when fuels are combusted to provide space heating, process heating, and other energy applications. Carbon dioxide accounts for over 99% of these emissions on a million metric tons (MMt) of CO_2 equivalent (CO_2e) basis in Wyoming. 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.[27] Direct use of oil, natural gas, coal, and wood in the RCI sectors accounted for an estimated 10.2 $MMtCO_2e$ of gross greenhouse gas (GHG) emissions in 2005.[28]

Emissions and Reference Case Projections

Emissions from direct fuel use were estimated using the United States Environmental Protection Agency's (US EPA) State Greenhouse Gas Inventory Tool (SGIT) software and the methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for RCI fossil fuel combustion.[29] The default data used in SGIT for Wyoming are from the United States Department of Energy (US DOE) Energy Information Administration's (EIA) *State Energy Data* (SED). The SGIT default data for Wyoming were revised using the most recent data available, which includes: (1) 2002 SED information for all fuel types;[30] (2) 2003 SED information for coal, and for wood and wood waste;[31] (3) 2003 and 2004 SED information for natural gas;[6] (4) 2003 and 2004 SED information for petroleum (distillate oil, kerosene and liquefied petroleum

[26] The industrial sector includes emissions associated with agricultural energy use and fuel used by the fossil fuel production industry.
[27] 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 transmission and distribution, 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 fossil fuel production and distribution are provided in Appendix E.
[28] 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.
[29] GHG emissions were calculated using SGIT, with reference to *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.
[30] EIA *State Energy Data 2002*, Data through 2002, released June 30, 2006, (http://www.eia.doe.gov/emeu/states/state.html?q_state_a=co&q_state=WYOMING).
[31] EIA *State Energy Data 2003 revisions for all fuels, and first release of 2004 information for natural gas and petroleum*, (http://www.eia.doe.gov/emeu/states/_seds_updates.html).

gas) consumption;[6] (5) 2004 electricity consumption data from the EIA's *State Electricity Profiles*;[32] and (6) 2005 natural gas consumption data from the EIA's *Natural Gas Navigator*.[33] 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. The carbon storage assumptions for these products are explained in detail in the EIIP guidance document.[34] The fossil fuel categories for which the EIIP methods are applied in the SGIT software to account for carbon storage include the following categories: asphalt and road oil, coking coal, distillate fuel, feedstocks (naphtha with a boiling range of less than 401 degrees Fahrenheit), feedstocks (other oils with boiling ranges greater than 401 degrees Fahrenheit), LPG, lubricants, miscellaneous petroleum products, natural gas, pentanes plus,[35] petroleum coke, residual fuel, still gas, and waxes. Data on annual consumption of the fuels in these categories as chemical industry feedstocks were obtained from the EIA SED.

Reference case emissions from direct fuel combustion were estimated based on fuel consumption forecasts from EIA's *Annual Energy Outlook 2006* (AEO2006),[36] with adjustments for Wyoming's projected population[37] and employment growth. Wyoming employment data for the manufacturing (goods-producing) and non-manufacturing (commercial or services-providing) sectors were obtained from the Wyoming Department of Information and Administration.[38] Regional employment data for the same sectors were obtained from EIA for the EIA's Mountain region.[39]

Table B1 shows historic and projected growth rates for electricity sales by sector. Table B2 shows historic and projected growth rates for energy use by sector and fuel type. For the residential sector, the rate of population growth is expected to be about 0.6% annually between 2004 and 2020; this demographic trend is reflected in the growth rates for residential fuel consumption. Based on the Wyoming Department of Information and Administration's 10-year

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[32] EIA *Electric Power Annual 2005 - State Data Tables*, (http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html).
[33] EIA *Natural Gas Navigator* (http://tonto.eia.doe.gov/dnav/ng/ng_cons_sum_dcu_SWY_a.htm).
[34] EIIP, Volume VIII: Chapter 1 "Methods for Estimating Carbon Dioxide Emissions from Combustion of Fossil Fuels", August 2004.
[35] A mixture of hydrocarbons, mostly pentanes and heavier fractions, extracted from natural gas.
[36] EIA AEO2006 with Projections to 2030, (http://www.eia.doe.gov/oiaf/aeo/index.html).
[37] Wyoming Department of Information and Administration, Economic Analysis Division, Wyoming Population Estimates and Forecasts. Population data for 1990 - 2000 from "Annual Population for Wyoming, Counties, and Municipalities: 1990 to 2000," File Name = c&sc90_00 (http://eadiv.state.wy.us/pop/c&sc90_00.htm). Population data for 2001 - 2005 from "Estimates of Wyoming and County Population: July 1, 2005," Table 1: Annual Estimates of the Population for Counties of Wyoming: April 1, 2000 to July 1, 2005 (http://eadiv.state.wy.us/pop/CO-05EST.htm). Population data 2006 - 2020 from "Population Estimates and Forecasts for Wyoming, counties, cities, and towns for 2000 - 2020," File Name = wyc&sc20.xls (http://eadiv.state.wy.us/pop/pop.asp).
[38] Wyoming Department of Information and Administration, Economic Analysis Division, "Ten Year Outlook - Wyoming Economic and Demographic Forecast: 2005 to 2014," Published in October 2005 (http://eadiv.state.wy.us/wef/wef.asp). Annual growth rates calculated from data provided in Table 2 for Wyoming Nonagricultural Wage & Salary Employment by Industry (North American Industry Classification System).
[39] AEO2006 employment projections for EIA's Mountain region obtained through special request from EIA (dated September 27, 2006).

forecast (2004 to 2014), commercial and industrial employment are projected to increase at compound annual rates of 1.5% and 0.4%, respectively, and these growth rates are reflected in the growth rates in energy use shown in Table B2 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.

Table B1. Electricity Sales Annual Growth Rates, Historical and Projected

Sector	1990-2004*	2000-2005†	2006-2020†
Residential	2.0%	1.5%	2.0%
Commercial	3.2%	2.9%	3.4%
Industrial	0.1%	1.5%	3.1%
Total	**1.0%**	**1.9%**	**3.0%**

* 1990-2004 compound annual growth rates calculated from Wyoming electricity sales by year from EIA state electricity profiles (Table 8), http://www.eia.doe.gov/cneaf/electricity/st_profiles/e_profiles_sum.html.
† Compound annual growth rates for total and for all three sectors taken from forecast for the energy supply sector (see Appendix A).

Table B2. Historic and Projected Average Annual Growth in Energy Use in Wyoming by Sector and Fuel: 1990-2020

	1990-2004*	2005-2010**	2010-2015†	2015-2020†
Residential				
natural gas	-0.2%	1.4%	1.1%	0.9%
Petroleum	2.6%	0.0%	0.4%	0.1%
Wood	-3.8%	-0.1%	-1.5%	-1.0%
Coal	-6.0%	-0.2%	-2.0%	-2.0%
Commercial				
natural gas	0.3%	0.9%	2.7%	2.1%
Petroleum	-3.0%	-1.8%	1.0%	0.6%
Wood	-0.3%	-0.3%	0.2%	-0.1%
Coal	-2.2%	-0.4%	0.2%	-0.1%
Industrial				
natural gas	-3.2%	0.5%	-0.5%	-0.5%
Petroleum	1.9%	1.5%	0.9%	0.3%
Wood	-12.5%	2.1%	1.3%	1.2%
Coal	-1.9%	0.1%	-0.8%	-0.9%

* Compound annual growth rates calculated from EIA SED historical consumption by sector and fuel type for Wyoming. Latest year for which EIA SED information was available for each fuel type is 2003 for coal and wood/wood waste, 2004 for petroleum, and 2005 for natural gas. Petroleum includes distillate fuel, kerosene, and liquefied petroleum gases for all sectors plus residual oil for the commercial and industrial sectors.
† Figures for growth periods starting after 2004 are calculated from AEO2006 projections for EIA's Mountain region, adjusted for Wyoming'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.

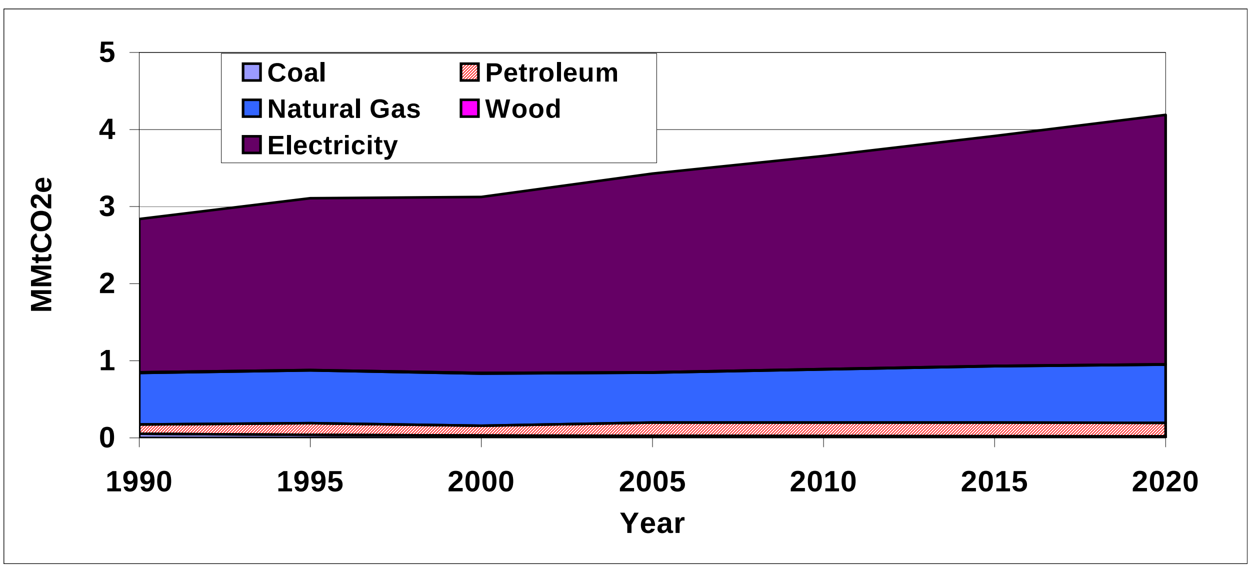
These estimates of growth relative to population and employment reflect expected responses of the economy — as simulated by the EIA's National Energy Modeling System — to changing fuel and electricity prices and changing technologies, as well as to structural changes within each sector (such as shifts in sub-sectoral shares and in energy use patterns).

Results

Figures B1, B2, and B3 show historic and projected emissions for the RCI sectors in Wyoming 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 use ranges from 11% in 1990 to 13% from 1995 through 2020. The commercial sector's share of total RCI emissions from direct fuel use and electricity use was 13% in 1990, increased to 18% in 2005, and is projected to increase to 21% by 2020. The industrial sector's share of total RCI emissions from direct fuel use and electricity use was 76% in 1990, declined to 69% in 2005, and is projected to decline further to 66% by 2020. These results indicate that the industrial sector accounts for a high share of total RCI emissions in Wyoming.

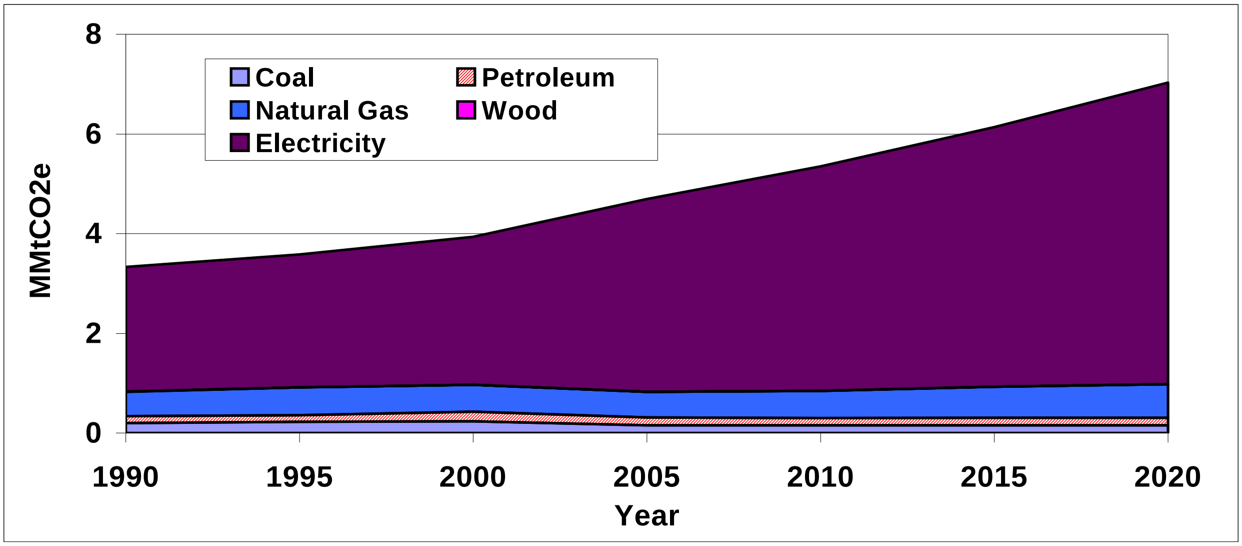
Emissions associated with the generation of electricity to meet RCI demand from 1990 through 2020, accounts for about, on average, 74% of the emissions for the residential sector, 80% of the emissions for the commercial sector, and 51% of the emissions for the industrial sector. From 1990 to 2020, natural gas consumption is the next highest source of emissions for all three sectors accounting for about 20% of total emissions in the residential sector, 12% for the commercial sector, and 15% for the industrial sector.

Figure B1. Residential Sector GHG Emissions from Fuel Consumption



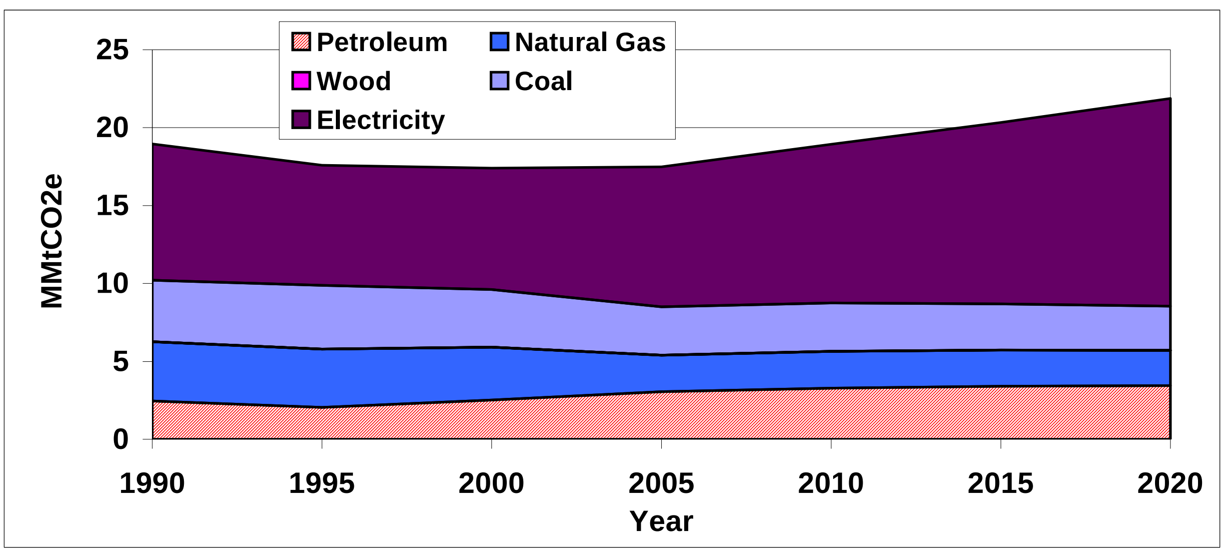
Source: CCS calculations based on approach described in text.
Note: Emissions associated with wood and coal combustion are too small to be seen on this graph.

Figure B2. Commercial 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.

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.

For the residential sector, emissions from electricity and direct fossil fuel use in 1990 were about 2.8 $MMtCO_2e$, and are estimated to increase to about 4.2 $MMtCO_2e$ by 2020. Emissions associated with the generation of electricity to meet residential energy consumption demand accounted for about 70% of total residential emissions in 1990 and are estimated to increase to 77% of total residential emissions by 2020. In 1990, natural gas consumption accounted for about 24% of total residential emissions and is estimated to account for about 18% of total residential emissions by 2020. Residential-sector emissions associated with the use of coal, petroleum, and wood in 1990 were about 0.18 $MMtCO_2e$ combined, and accounted for about

6.4% of total residential emissions. By 2020, emissions associated with the consumption of these three fuels are estimated to be 0.20 $MMtCO_2e$ and to account for 4.8% of total residential sector emissions.

For the 15-year period from 2005 to 2020, residential-sector GHG emissions associated with the use of electricity, natural gas, and petroleum are expected to increase at average annual rates of about 1.5%, 1.0%, and 0.1% respectively. Emissions associated with the use of wood and coal are expected to decline annually by about -1.0% and -1.5%, respectively. Total GHG emissions for this sector increase by an average of about 1.4% annually over the 15-year period.

For the commercial sector, emissions from electricity and direct fuel use in 1990 were about 3.3 $MMtCO_2e$, and are estimated to increase to about 7.0 $MMtCO_2e$ by 2020. Emissions associated with the generation of electricity to meet commercial energy consumption demand accounted for about 75% of total commercial emissions in 1990, and are estimated to increase to about 86% of total commercial emissions by 2020. In 1990, natural gas consumption accounted for about 15% of total commercial emissions, and is estimated to account for about 10% of total commercial emissions by 2020. Commercial-sector emissions associated with the use of coal, petroleum, and wood in 1990 were about 0.34 $MMtCO_2e$ combined, and accounted for about 10% of total commercial emissions. For 2020, emissions associated with the consumption of these three fuels are estimated to be 0.31 $MMtCO_2e$, and to account for 4.4% of total commercial sector emissions.

For the 15-year period 2005 to 2020, commercial-sector GHG emissions associated with the use of electricity, natural gas, and petroleum are expected to increase at average annual rates of about 3.0%, 1.9%, and 0.01% respectively. Emissions associated with the use of wood and coal are expected to decline annually by about -0.15% and -0.18%, respectively. Total GHG emissions for this sector increase by an average of about 2.7% annually over the 15-year period.

For the industrial sector, emissions in 1990 were about 19 $MMtCO_2e$, and are estimated to increase to about 22 $MMtCO_2e$ by 2020. Emissions associated with the generation of electricity to meet industrial energy consumption demand accounted for about 46% of total industrial emissions in 1990, and are estimated to increase to about 61% of total industrial emissions by 2020. In 1990, natural gas consumption accounted for about 20% of total industrial emissions and is estimated to account for about 10% of total industrial emissions by 2020. Industrial sector emissions associated with the use of coal, petroleum, and wood in 1990 were about 6.4 $MMtCO_2e$ combined and accounted for about 34% of total industrial emissions. For 2020, emissions associated with the consumption of these three fuels are estimated to be 6.3 $MMtCO_2e$, and to account for 29% 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 wood are expected to increase at average annual rates of about 2.7%, 0.8%, and 1.4%, respectively. Emissions associated with the use of natural gas and coal are expected to decline annually by about -0.2% and -0.6%, respectively. Total GHG emissions for this sector increase by an average of about 1.5% annually over the 15-year period.

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 Mountain modeling region scaled for Wyoming 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 Wyoming, 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, and thereby affect emissions estimates.
- The exception to the AEO2006 assumption of no large changes in prices or fuels consumption is the AEO2006 reference-case projections for industrial coal consumption. The AEO2006 model's forecast for the EIA's Mountain region assumes that new coal-to-liquids plants would be constructed near active coal mines when low-sulfur distillate oil prices reach high enough levels to make coal-to-liquids processing economic. Plants are assumed to be co-production plants with generation capacity of 758 MW and the capability of producing 33,200 barrels of liquid fuel per day. The technology assumed is similar to an integrated gasification combined cycle (electricity generation) plant, first converting the coal feedstock to gas, and then subsequently converting the synthetic gas to liquid hydrocarbons using the Fisher-Tropsch process. As a result, AEO2006 projections assume a rather significant increase in coal consumption by the coal-to-liquids industrial sector starting in 2011. For the EIA's Mountain region, this sector accounts for 17.5% of total coal consumption in 2011 and 63% of total coal consumption in 2020, with an annual growth rate of 26% from 2011 to 2020.[40] This increase in coal consumption, associated with the installation of coal-to-liquids plants starting in 2011, was excluded from the industrial coal consumption forecasts for Wyoming because it is considered to represent technology that is beyond the "business-as-usual" assumptions associated with the reference case projections for the industrial coal consumption sector. It is worth noting that currently a13,000 bbl/day coal-to-liquids (CTL) plant is proposed for Wyoming: the Medicine Bow project.[41] While a lack of existing commercial CTL plants makes estimation of emissions from these plants challenging and uncertain, it is estimated that the proposed Medicine Bow plant alone could add approximately 1.8 $MMTCO_2e$ to Wyoming's annual emissions.[42] Given the uncertainties surrounding

[40] Coal Market Module of the National Energy Modeling System 2006, as described in *Assumptions to the Annual Energy Outlook 2006, Coal Market Module*, Report #: DOE/EIA-0554(2006), March 2006 (http://www.eia.doe.gov/oiaf/aeo/assumption/index.html).
[41] Announcement on Marketwatch, January 12, 2007. Accessed at <http://www.marketwatch.com/news/story/medicine-bow-fuel-power/story.aspx?guid=%7BC2651EE1-8150-4E92-AD9A-CFDAA656379C%7D&sid=42740&symb> on January 29, 2007.
[42] This estimate could be lower than actual emissions from the CTL plant as it assumes that the CO_2 is used in enhanced oil recovery (EOR), as outlined in the Marketwatch announcement. This estimate assumes 43.5% of the

commercial CTL production, these emissions have not been included in the reference-case inventory presented here.

CO_2 is sequestered due to losses underground during EOR, based on an average of the range reported in IEA. 2004. *Prospects for* CO_2 *Capture and Storage*, p. 81, which reports the proportion retained in EOR varying between 20%–67%. Greenhouse gas emissions intensity estimate provided by Diane Kearney at EIA. Model plant based on methodology described in D. Gray and G. Tomlinson, Coproduction: A Green Coal Technology, Technical Report MP 2000-28 (Mitretek, March 2001). Assumes 40% of emissions attributed to the cogeneration plant, i.e. no use of cogeneration would likely result in higher CTL emissions.

Appendix C. Transportation Energy Use

Overview

The transportation sector is one of the largest sources of GHG emissions in Wyoming. Carbon dioxide accounts for about 88 percent of transportation GHG emissions from fuel use. Most of the remaining GHG emissions from the transportation sector are due to N_2O emissions from gasoline engines.

Emissions and Reference Case Projections

GHG emissions for 1990 through 2002 were estimated using SGIT and the methods provided in the EIIP guidance document for the sector.[43,44] For onroad vehicles, the CO_2 emission factors are in units of lb/MMBtu and the CH_4 and N_2O emission factors are both in units of grams/VMT. Key assumptions in this analysis are listed in Table C1. The default data within SGIT were used to estimate emissions, with the most recently available fuel consumption data (2002) from EIA SED added.[45] The default VMT data in SGIT were replaced with state-level annual VMT from the Wyoming Department of Transportation (WYDOT).[46] State-level VMT was allocated to vehicle types using the default vehicle mix data in SGIT.

Onroad vehicle gasoline and diesel emissions were projected based on VMT forecasts provided by WYDOT[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 2002 Wyoming estimates of VMT by vehicle type. 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 WYDOT estimates for total VMT in the State for each year to yield the vehicle type VMT estimates and compound annual average growth rates. These are displayed in Tables C2. Gasoline and diesel consumption by key sectors — transportation, commercial, and industrial —are shown in Table C3.

[43] CO_2 emissions were calculated using SGIT, with reference to Emission Inventory Improvement Program, Volume VIII: Chapter. 1. "Methods for Estimating Carbon Dioxide Emissions from Combustion of Fossil Fuels", August 2004.
[44] CH_4 and N_2O emissions were calculated using SGIT, with reference to Emission Inventory Improvement Program, Volume VIII: Chapter. 3. "Methods for Estimating Methane and Nitrous Oxide Emissions from Mobile Combustion", August 2004.
[45] Energy Information Administration, State Energy Consumption, Price, and Expenditure Estimates (SED), http://www.eia.doe.gov/emeu/states/_seds.html
[46] Dave Clabaugh, Highway Statistical Engineer, Wyoming Department of Transportation.

Table C1. Key Assumptions and Methods for the Transportation Inventory and Projections

Vehicle Type and Pollutants	Methods
Onroad gasoline, diesel, natural gas, and LPG vehicles – CO_2	**Inventory (1990 – 2002)** EPA SGIT and fuel consumption from EIA SED **Reference Case Projections (2003 – 2020)** Gasoline and diesel fuel projected using VMT projections from WYDOT, adjusted by fuel efficiency improvement projections from AEO2006. Other onroad fuels projected using Mountain Region fuel consumption projections from EIA AEO2006 adjusted using state-to-regional ratio of population growth.
Onroad gasoline and diesel vehicles – CH_4 and N_2O	**Inventory (1990 – 2002)** EPA SGIT, onroad vehicle CH_4 and N_2O emission factors by vehicle type and technology type within SGIT were updated to the latest factors used in the US EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003.* State total VMT replaced with VMT provided by WYDOT, VMT allocated to vehicle types using default data in SGIT. **Reference Case Projections (2003 – 2020)** VMT projections from WYDOT.
Non-highway fuel consumption (jet aircraft, gasoline-fueled piston aircraft, boats, locomotives) – CO_2, CH_4 and N_2O	**Inventory (1990 – 2002)** EPA SGIT and fuel consumption from EIA SED. **Reference Case Projections (2003 – 2020)** Aircraft projected using aircraft operations projections from Federal Aviation Administration (FAA) and jet fuel efficiency improvement projections from AEO2006. Rail and marine gasoline projected based on historical data.

Table C2. Wyoming Vehicle Miles Traveled Compound Annual Growth Rates

Vehicle Type	2002-2005	2005-2010	2010-2015	2015-2020
Heavy Duty Diesel Vehicle	4.51%	3.21%	2.92%	2.88%
Heavy Duty Gasoline Vehicle	3.21%	1.69%	2.38%	2.45%
Light Duty Diesel Truck	6.01%	6.76%	6.77%	6.99%
Light Duty Diesel Vehicle	6.01%	6.76%	6.77%	6.99%
Light Duty Gasoline Truck	1.79%	1.77%	1.77%	1.73%
Light Duty Gasoline Vehicle	1.79%	1.77%	1.77%	1.73%
Motorcycle	1.79%	1.77%	1.77%	1.73%

Onroad gasoline and diesel fuel consumption was 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 EIA's *Annual Energy Outlook* (AEO). These projections suggest onroad fuel consumption growth rates of 1.0% per year for gasoline and 3.2% per year for diesel between 2002 and 2020.

Gasoline consumption estimates for 1990-2002 were adjusted by subtracting ethanol consumption. While the historical ethanol consumption suggests continued growth, projections for ethanol consumption in Wyoming were not available. Therefore, ethanol consumption was assumed to remain at the 2002 level (0.4% of total gasoline) in the reference case projections. Biodiesel and other biofuel consumption were not considered in this inventory because historical and projection data were not available.

For the aircraft sector, emission estimates for 1990 to 2002 are based on SGIT methods and fuel consumption from EIA. Emissions were projected from 2002 to 2020 using general aviation and commercial aircraft operations for 2002 to 2020 from the Federal Aviation Administration's (FAA) Terminal Area Forecast System[47] 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-2002 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 Wyoming, which was obtained from the FAA source noted above. These projections resulted in compound annual growth rates of 0.6% for aviation gasoline and -0.4% for jet fuel.

For the rail and marine sectors, 1990 – 2004 estimates are based on SGIT methods and fuel consumption from EIA. Emissions from these sources were projected based on the historical 1990-2004 data, which result in compound annual growth rates of -0.6% for rail and 4.7% for marine gasoline.

Fuel consumption data from EIA includes nonroad gasoline and diesel fuel consumption in the commercial and industrial sectors. Therefore, nonroad emissions are included in the RCI emissions in this inventory (see Appendix B). Table C3 shows how EIA divides gasoline and diesel fuel consumption between the transportation, commercial, and industrial sectors.

Table C3. 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

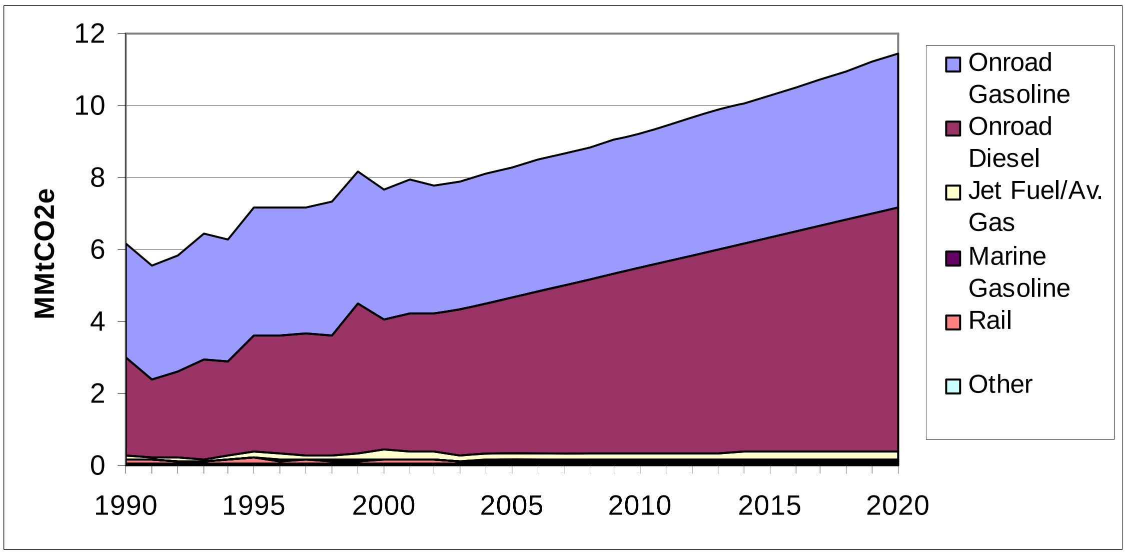
[47] Terminal Area Forecast, Federal Aviation Administration, http://www.apo.data.faa.gov/main/taf.asp.

Results

As shown in Figure C1, onroad gasoline and diesel consumption accounts for the largest share of transportation GHG emissions. Emissions from onroad gasoline vehicles increased by about 35% from 1990-2002 to cover almost 46% of total transportation emissions in 2002. GHG emissions from onroad diesel fuel consumption increased by 148% from 1990 to 2002, and by 2002 accounted for 49% of GHG emissions from the transportation sector. Emissions from all other categories combined (aviation, marine gasoline, locomotives, natural gas and LPG, and oxidation of lubricants) contributed less than 5% of total transportation emissions in 2002.

GHG emissions from all onroad vehicles combined are projected to increase by 49% between 2002 and 2020, due to a 43% increase in VMT during this period and projected fuel efficiency improvements. Most of this growth is predicted to occur in the diesel sector, with onroad gasoline consumption projected to increase by only 19%, and emissions from onroad diesel consumption projected to increase by 77% between 2002 and 2020. Emissions from aviation fuels are projected to increase by 4% between 2002 and 2020.

Figure C1. Transportation GHG Emissions by Fuel, 1990-2020



Source: CCS calculations based on approach described in text.

Key Uncertainties

Projections of Vehicle Miles of Travel (VMT) and Biofuels Consumption
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-specific VMT growth rates for the state. Also, onroad gasoline and diesel growth rates may be slightly overestimated because increased consumption of biofuels between 2005 and 2020 was not taken into account (due to a lack of data).

Uncertainties in Aviation Fuel Consumption
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.

The fuel consumption associated with international air flights should not be included in the state inventory; however, data were not available to subtract this consumption from total jet fuel estimates. 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.

Appendix D. Industrial Processes

Overview

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

- Carbon Dioxide (CO_2) from:
  - Production of cement, lime, and soda ash
  - Consumption of limestone, dolomite, and soda ash;
- Sulfur hexafluoride (SF_6) from transformers used in electric power transmission and distribution (T&D) systems; and
- Hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs) from consumption of substitutes for ozone-depleting substances (ODS) used in cooling and refrigeration equipment.

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

- Nitrous oxide (N_2O) from nitric and adipic acid production;
- HFCs), PFCs, and SF_6 from semiconductor manufacture;
- PFCs from aluminum production;
- HFCs from HCFC-22 production; and
- SF_6 from magnesium production and processing.

Emissions and Reference Case Projections

GHG emissions for 1990 through 2005 were estimated using the United States Environmental Protection Agency's (US EPA) State Greenhouse Gas Inventory Tool (SGIT) software and the methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for this sector.[48] Table D1 identifies for each emissions source category the information needed for input into SGIT to calculate emissions, the data sources used for the analysis described here, and the historical years for which emissions were calculated based on the availability of data.

Table D2 lists the data sources used to quantify activities related to industrial process emissions, the annual compound growth rates implied by estimates of future activity used, and the years for which the reference case projections were calculated.

[48] GHG emissions were calculated using SGIT, with reference to the Emission Inventory Improvement Program, Volume VIII: Chapter. 6. "Methods for Estimating Non-Energy Greenhouse Gas Emissions from Industrial Processes", August 2004. This document is referred to as "EIIP" below.

Table D1. Approach to Estimating Historical Emissions

Source Category	Time Period	Required Data for SGIT	Data Source
Cement Manufacturing - Clinker Production	1990 - 2002	Metric tons (Mt) of clinker produced each year.	US Geological Survey (USGS) in *Cement: Annual Report.* Note: USGS aggregates production for groups of states for confidentiality purposes. In the SGIT, aggregated production is divided by the number of states for which production is aggregated to estimate production for a given state. The number of states included in an aggregate total may vary from one year to the next. For example, the USGS generally aggregates clinker production from Wyoming, Colorado, Nebraska, and South Dakota. SGIT divides this aggregated production by four to estimate Wyoming's clinker production. This is a limitation in SGIT and may result in overestimating or underestimating production for a given state.
Cement Manufacturing - Masonry Cement Production	1990, 1992 and 1996 - 2000	Mt of masonry cement produced each year.	USGS in *Cement: Annual Report.* Note: Data limitations are the same as described for clinker production. Data are not available for some years; in those cases, data for the closest year to that for which data were missing was used as a surrogate to fill in production data for missing years (e.g., 1990 production used for 1991, 1992 production used for 1993 and 1994, 1996 production used for 1995, and 2000 production used for 2001 and 2002.
Lime Manufacture	1991 - 2002	Mt of high-calcium and dolomitic lime produced each year.	USGS in *Lime: Minerals Yearbook*. Note: Data limitations are the same as described for clinker production. In SGIT, USGS production data aggregated for Wyoming, Colorado, and Montana is divided by three to estimate Wyoming's lime production. Default production data are not available in SGIT for 1990; data for 1991 were used for 1990 as a surrogate to fill in production data missing for 1990.
Soda Ash Manufacture	1990 - 2002	Mt of soda ash produced each year.	One plant in Wyoming produces soda ash. The default SGIT methods and activity data for this plant in Wyoming were used to estimate emissions.
Limestone and Dolomite Consumption	1994 - 2002	Consumption of limestone and dolomite by industrial sectors.	For default limestone data, the state's total limestone consumption (as reported by USGS) is multiplied by the ratio of national limestone consumption for industrial uses to total national limestone consumption. Additional information on these calculations, including a definition of industrial uses, is available in Chapter 6 of the EIIP guidance document. Default limestone production data are not available in SGIT for 1990 - 1993; data for 1994 were used for 1990 – 1993 as a surrogate to fill in production data missing for these years. SGIT contains default dolomite production data for only 1998 (31,189 Mt) and 1999 (13,643 Mt). Given the uncertainty associated with the default data and also the lack of data for 1990-1997 and 2000-2002, emissions associated with dolomite consumption for 1998 and 1999 were not calculated in SGIT.

Table D1. Approach to Estimating Historical Emissions (Continued)

Source Category	Time Period	Required Data for SGIT	Data Source
Soda Ash	1990 - 2005	Consumption of soda ash used in consumer products such as glass, soap and detergents, paper, textiles, and food. Emissions based on state's population and estimates of emissions per capita from the US EPA national GHG inventory.	*USGS Minerals Yearbook, 2004: Volume I, Metals and Minerals*, (http://minerals.usgs.gov/minerals/pubs/commodity/soda_ash/). For population data, see references for ODS substitutes.
ODS Substitutes	1990 - 2002	Based on state's population and estimates of emissions per capita from the US EPA national GHG inventory.	-- Wyoming Department of Information and Administration, Economic Analysis Division, Wyoming Population Estimates and Forecasts. Population data for 1990 - 2000 from "Annual Population for Wyoming, Counties, and Municipalities: 1990 to 2000," File Name = c&sc90_00 (http://eadiv.state.wy.us/pop/c&sc90_00.htm). Population data for 2001 - 2005 from "Estimates of Wyoming and County Population: July 1, 2005," Table 1: Annual Estimates of the Population for Counties of Wyoming: April 1, 2000 to July 1, 2005 (http://eadiv.state.wy.us/pop/CO-05EST.htm). -- US 1990-2000 population from US Census Bureau (http://www.census.gov/popest/archives/EST90INTERCENSAL/US-EST90INT-01.html). -- US 2000-2005 population from US Census Bureau (http://www.census.gov/population/projections/SummaryTabA1.xls).
Electric Power T&D Systems	1990 - 2002	Emissions from 1990 to 2002 based on the national emissions per kilowatt-hour (kWh) and state's electricity use.	National emissions per kWh from US EPA 2005 *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003* (http://www.epa.gov/climatechange/emissions/usgginv_archive.html).

Table D2. Approach to Estimating Projections

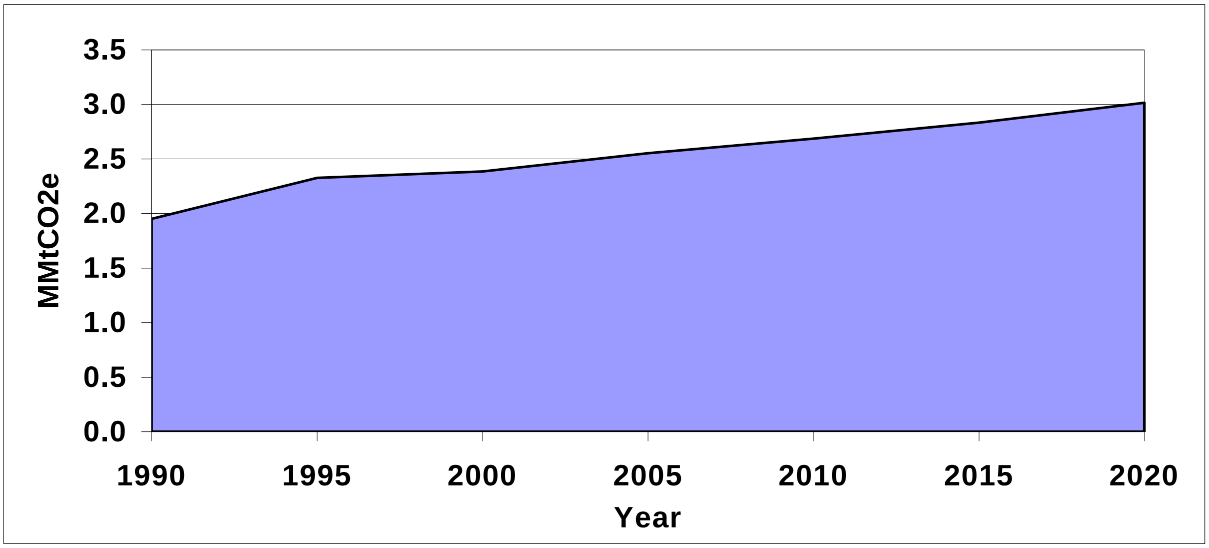
Source Category	Time Period	Projection Assumptions	Data Source	Annual Growth Rates (%) 2000 to 2005	2005 to 2010	2010 to 2015	2015 to 2020
Cement Manufacturing - Clinker and Masonry Cement Production	2003 - 2020	Compound annual growth rate for Wyoming's goods-producing sector. The goods-producing sector includes employment in the natural resources and mining, construction, and manufacturing sectors.	Wyoming Department of Information and Administration, Economic Analysis Division, "Ten Year Outlook - Wyoming Economic and Demographic Forecast: 2005 to 2014," Published in October 2005 (http://eadiv.state.wy.us/wef/wef.asp). Annual growth rates calculated from data provided in Table 2 for Wyoming Nonagricultural Wage & Salary Employment by Industry (North American Industry Classification System).	2.5	0.4	0.4	0.4
Lime Manufacture	2003 - 2020	Ditto	Ditto	2.5	0.4	0.4	0.4
Limestone Consumption	2003 - 2020	Ditto	Ditto	2.5	0.4	0.4	0.4
Soda Ash Manufacture and Consumption	2003 - 2020	Growth between 2004 and 2009 is projected to be about 0.5% per year for US production. Assumed growth is same for 2010 – 2020.	*Minerals Yearbook, 2005: Volume I, Soda Ash*, (http://minerals.usgs.gov/minerals/pubs/commodity/soda_ash/soda_myb05.pdf).	0.5	0.5	0.5	0.5
ODS Substitutes	2003 - 2020	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).	15.8	7.9	5.8	5.3
Electric Power T&D Systems	2003 - 2020	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).	3.3	-6.2	-9.0	-2.8

Results

Figures D1 and D2 show historic and projected emissions for the industrial processes sector from 1990 to 2020. Total gross GHG emissions for the sector were about 2.4 million metric tons (MMt) of carbon dioxide equivalent (CO_2e) in 2000 and are estimated to increase to about 3

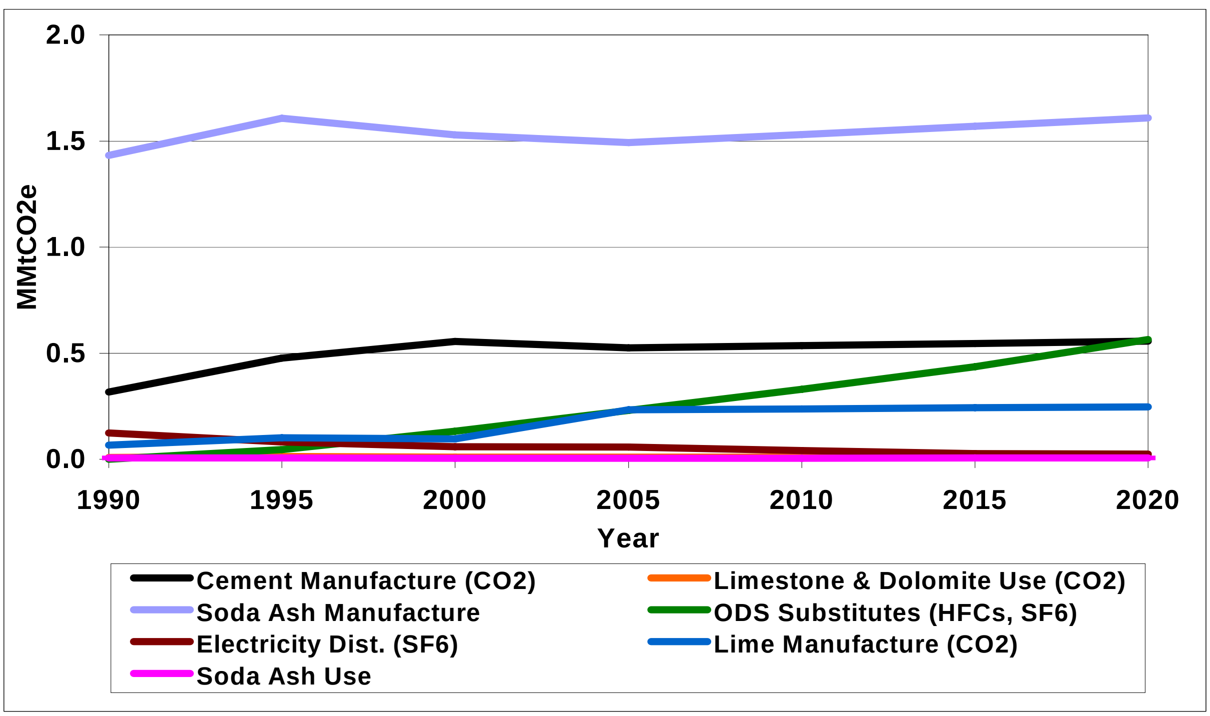
$MMTCO_2e$ in 2020. Emissions from the overall industrial processes category are expected to grow by about 1.1% annually from 2005 through 2020, as shown in Figures D1 and D2, with emissions growth primarily associated with increasing use of HFCs and PFCs in refrigeration and air conditioning equipment.

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



Source: CCS calculations based on approach described in text.

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



Source: CCS calculations based on approach described in text.

Substitutes for Ozone-Depleting Substances (ODS)

The problem of substances that deplete the atmosphere's protective ozone layer was recognized and addressed by international and US law in the late l980s and l990s. In compliance with the Montreal Protocol and the Clean Air Act Amendments of 1990,[49] HFCs and PFCs, strong greenhouse gases, 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.) 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 carbon-equivalent basis. Emissions from the use of ODS substitutes in Wyoming were calculated using the default methods in SGIT (see dark green line in Figure D2). Emissions have increased from 0.001 $MMtCO_2e$ in 1990 to about 0.13 $MMtCO_2e$ in 2000, and are expected to increase at an average rate of 7.6% per year from 2000 to 2020 due to increased substitutions of these gases for ODS. The projected rate of increase for these emissions is based on projections for national emissions from the US EPA report referenced in Table D2.

Electricity Distribution

Emissions of SF_6 from electrical equipment nationwide have experienced declines since the early 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 Wyoming from 1990 to 2002 were estimated based on the estimates of emissions per kWh from the US EPA GHG inventory and Wyoming's electricity consumption estimates provided in SGIT. 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 Wyoming. The decline in SF_6 emissions in the future reflects expectations of future actions by the electric industry to reduce these emissions. Relative to total industrial non-combustion process emissions, SF_6 emissions from electrical equipment are low (about 0.12 $MMtCO_2e$ in 1990 and 0.02 $MMtCO_2e$ in 2020), and therefore, appear at the bottom of the graph because of scaling effects in Figure D2.

Clinker Production for Cement Manufacture

Clinker production releases CO_2 when calcium carbonate ($CaCO_3$) is heated in a cement kiln to form lime (calcium oxide) and CO_2 (see Chapter 6 of the EIIP guidance document). Emissions are calculated by multiplying annual clinker production and annual production of masonry cement by emission factors for these processes. Information on clinker and masonry cement production in Wyoming was not available; therefore, the default data provided in SGIT were used to calculate emissions (see black line in Figure D2). The growth rate for Wyoming's goods-producing (manufacturing) sector was used to project emissions to 2020. As shown in Figure D2, emissions increase slightly from 0.53 $MMtCO_2e$ in 2005 to 0.56 $MMtCO_2e$ 2020, reflecting an overall average annual increase of about 0.4% over that time period.

[49] 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.

Lime Manufacture

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 Chapter 6 of the EIIP guidance document).

Information on lime production in Wyoming was not readily available; therefore, the default data provided in SGIT were used to calculate emissions (see dark blue line in Figure D2). The growth rate for Wyoming's goods-producing (manufacturing) sector was used to project emissions to 2020. As shown in Figure D2, emissions increase slightly from 0.23 $MMtCO_2e$ in 2005 to 0.25 $MMtCO_2e$ 2020, reflecting an overall average annual increase of about 0.4% over that time period.

Limestone and Dolomite Consumption

Limestone and dolomite are basic raw materials 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.[50] Historical data for Wyoming were not available from the USGS; consequently, the default data provided in SGIT were used to calculate emissions for Wyoming (see orange line in Figure D2). The employment growth rate for Wyoming's goods-producing sector was used to project emissions from 2003 through 2020.

Relative to total industrial non-combustion process emissions, emissions associated with limestone and dolomite consumption are low (about 0.008 $MMtCO_2e$ in 1990 and 0.010 $MMtCO_2e$ in 2020), and therefore, appear at the bottom of the graph in Figure D2 due to scaling effects. Note that for this sector, SGIT did not contain default consumption data for Wyoming for 1990 through 1993, and therefore, emissions for these years were estimated using the default production data for 1994. In addition, SGIT provided dolomite consumption data for only 1998 and 1999. The dolomite consumption data 1998 and 1999 were not used to estimate emissions because of uncertainties associated with how the production data for these two years were developed for use in SGIT.

Soda Ash Manufacture

Under the soda ash production method used in Wyoming, trona (an ore from which natural soda ash is made) is calcined in a rotary kiln and chemically transformed into a crude soda ash that requires further processing. Carbon dioxide and water are generated as a by-product of the calcination process (see Chapter 6 of the EIIP guidance document). SGIT estimates historical

[50] 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).

emissions (see purple line in Figure D2) using default production data for the single plant currently operating in Wyoming. The emissions for this one plant account for over 70% of Wyoming's total industrial non-combustion process emissions in 1990, 60% in 2000, and is estimated to account for over 50% of total emissions in 2020. Emissions are about 1.4 $MMtCO_2e$ in 1990, increase to about 1.6 $MMtCO_2e$ in 1995, and decline to about 1.5 $MMtCO_2e$ in 2005. According to the USGS, this industry is expected to grow at an annual rate of 0.5% from 2004 through 2009 for the US as a whole. Information on growth trends for years later than 2009 was not available; therefore, the same 0.5% annual growth rate was applied for estimating emissions to 2020. Application of this annual growth rate starting in 2003 results in emissions increasing to about 1.6 $MMtCO_2e$ in 2020.

Soda Ash Consumption
Commercial soda ash (sodium carbonate) is used in many consumer products such as glass, soap and detergents, paper, textiles, and food. CO_2 is also released when soda ash is consumed (see Chapter 6 of the EIIP guidance document). SGIT estimates historical emissions (see dark pink line in Figure D2) based on the state's population and national per capita emissions from the US EPA national GHG inventory. According to the USGS, this industry is expected to grow at an annual rate of 0.5% from 2004 through 2009 for the US as a whole. Information on growth trends for years later than 2009 was not available; therefore, the same 0.5% annual growth rate was applied for estimating emissions to 2020. Relative to total industrial non-combustion process emissions, emissions associated with soda ash consumption are low (about 0.0049 $MMtCO_2e$ in 1990 and 0.0051 $MMtCO_2e$ in 2020), and therefore, cannot be seen in the graph due to scaling effects in Figure D2.

Key Uncertainties

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

- Historical clinker and masonry cement production for the cement industry is uncertain because of the reliance on the SGIT method that divides aggregated clinker and masonry cement production (obtained from the USGS) for select states evenly between the states. In SGIT, production for Wyoming, Colorado, Nebraska, and South Dakota is aggregated and divided evenly between the four states. Future work on this category should focus on obtaining actual clinker and masonry cement production data for 1990 through 2005 from plants located in Wyoming.
- Historical production data for lime manufacturing is uncertain because of the reliance on the SGIT method that divides aggregated lime production (obtained from the USGS) for select states evenly between the states. In SGIT, production for Wyoming, Colorado, and Montana is aggregated and divided evenly between the three states. Future work on this category should focus on obtaining actual lime production data for 1990 through 2005 from plants located in Wyoming.
- For dolomite consumption, the default data in SGIT were only available for 1998 and 1999. Future work should include the collection of actual data for all historical years so that emissions associated with dolomite consumption can be included in the inventory.

- Production data for the one soda ash manufacturing plant in Wyoming should be reviewed by the plant to either verify or improve upon the default production data in SGIT.
- 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. This dependence of future emissions is particularly acute for Wyoming, where so large a fraction of recent-year emissions from the industrial processes category are from a single soda ash plant. Future emissions depend on the competitiveness of Wyoming manufacturers in these industries, and the specific nature of the production processes used in Wyoming.
- The projected largest source of growth in future industrial emissions in Wyoming, HFCs and PFCs used in cooling applications, is subject to several uncertainties as well. First, historical emissions are based on national estimates; Wyoming-specific estimates are currently unavailable. In addition, 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.
- Greenhouse gases are emitted from several additional industrial processes that are not covered in the EIIP guidance documents, due in part to a lack of sufficient state data on non-energy uses of fossil fuels for these industrial processes. These sources include:

  - Iron and Steel Production (CO_2 and CH_4);
  - Ammonia Manufacture and Urea Application (CO_2, CH_4, N_2O);
  - Aluminum Production (CO_2);
  - Titanium Dioxide Production (CO_2);
  - Phosphoric Acid Production (CO_2);
  - CO_2 Consumption (CO_2);
  - Ferroalloy Production (CO_2);
  - Petrochemical Production (CH_4); and
  - Silicon Carbide Production (CH_4).

  The CO_2 emissions from the above CO_2 sources (other than CO_2 consumption and phosphoric acid production) result from the non-energy use of fossil fuels. Although the US EPA estimates emissions for these industries on a national basis, US EPA has not developed methods for estimating the emissions at the state level due to data limitations. If state-level data on non-energy uses of fuels become available, future work should include an assessment of emissions for these other categories.

Appendix E. Fossil Fuel Industries

Overview

This appendix reports the greenhouse gas (GHG) emissions that are released during the production, processing, transmission, and distribution of fossil fuels. Known as fugitive emissions, these are methane (CH_4) and carbon dioxide (CO_2) emissions released via leakage and venting at coal mines, oil and gas fields, processing facilities, and pipelines. Nationally, fugitive emissions from natural gas systems, petroleum systems, and coal mines accounted for 2.8% of total US GHG emissions in 2004.[51] Emissions associated with energy consumed by these processes are included in Appendix B for the Residential, Commercial, and Industrial sectors.

Emissions and Reference Case Projections

Oil and Gas Production

Wyoming currently ranks 7th in crude oil production among US states, totaling 141,000 barrels (bbls) per day and accounting for about 3% of US production.[52] Proved crude oil reserves sit at 628 million barrels, which is similarly about 3% of US totals. Oil production in the State was at its peak in the first year of EIA reported production (1981) at 358,000 bbls per day. For more than two decades production has steadily declined.[53] Wyoming has five petroleum refineries, with a combined crude oil distillation capacity of 153,000 bbls per day.[54]

The natural gas industry has been growing in Wyoming, with the State currently producing over 15 times the amount of natural gas that it consumes. For example, in 2005, Wyoming consumed just 108 billion cubic feet (Bcf) of natural gas while it produced 1,639 Bcf,[55] the highest natural gas production ever reported in the State.

Wyoming places third in the nation for both coal bed methane (CBM) proved reserves and for CBM production, with total CBM production for the State at about 65% of the production of each of the two leading CBM producing states, Colorado and New Mexico.[56] In 2005, CBM accounted for 20% of total natural gas production in the State.[57] The highest annual production reported for Wyoming CBM is 344 Bcf in 2003, which was 22% of total natural gas production.[58] While the production and transport systems for CBM and conventional natural gas are similar, CBM development generally requires more wells to produce a comparable amount of

[51] "The *U.S. Inventory of Greenhouse Gas Emissions and Sinks*", US EPA, 2005. Greenhouse gas emissions calculated on a carbon dioxide equivalent basis.
[52] "Petroleum Profile: Wyoming", US DOE Energy Information Administration website, January 2007, Accessed at <http://tonto.eia.doe.gov/oog/info/state/wy.html>
[53] "Petroleum Navigator", US DOE Energy Information Administration website, January 2007, Accessed at < http://tonto.eia.doe.gov/dnav/pet/hist/mcrfpwy2a.htm>
[54] "Petroleum Profile: Wyoming", US DOE Energy Information Administration website, January 2007, Accessed at < http://tonto.eia.doe.gov/oog/info/state/wy.html >
[55] "Natural Gas Navigator", US DOE Energy Information Administration website, January 2007, Accessed at < http://tonto.eia.doe.gov/dnav/ng/ng_cons_sum_dcu_SWY_a.htm> & http://tonto.eia.doe.gov/dnav/ng/ng_prod_whv_dcu_SWY_a.htm
[56] "Natural Gas Navigator", US DOE Energy Information Administration website, January 2007, Accessed at < http://tonto.eia.doe.gov/dnav/ng/ng_enr_cbm_a_EPG0_r52_Bcf_a.htm >
[57] ibid
[58] ibid

gas. Therefore, CBM will generally have slightly higher fugitive emissions per unit of natural gas produced. These differences are accounted for in the inventory.

Wyoming has the third largest oil shale deposits of any US state. While commercial oil shale production is a number of years away, high oil prices have brought renewed interest. The Wyoming portion of the Green River oil shale resource is estimated to be about 300 billion barrels of oil, while Utah holds up to 320 billion barrels, and Colorado holds approximately 1 trillion barrels.[59] As of 2005, Anadarko Petroleum is the only company to have submitted an application to the BLM for an oil shale research, development and demonstration lease in Wyoming.[60] A 2005 study projected a 12 to 16 year lag before the pilot tests initiated over the next few years lead to a production growth phase.[61] Given the large uncertainty surrounding future production from oil shale in Wyoming, especially in the 2006-2020 timeframe, this analysis does not include a specific estimate for oil shale production or for total GHG emissions from this process. While a high-level review of oil shale research projects was conducted, meaningful GHG emission intensity estimates could not be provided within the time constraints of this project.

Also of note is the recent announcement from Medicine Bow Fuel and Power of plans to develop a coal-to-liquids processing facility in Wyoming. The proposed output from the Medicine Bow facility is 13,000 bbls per day of liquid fuels (primarily diesel) plus onsite power generation.[62] See Appendix B for a discussion of the potential GHG emissions resulting from energy consumption at coal-to-liquids facilities in Wyoming. Note that any fugitive emissions resulting from commercial coal-to-liquids development are not included in this inventory.

Oil and Gas Industry Emissions
Emissions of CH_4 and entrained CO_2 can occur at many stages of production, processing, transmission, and distribution of oil and gas. With over 33,000 active gas and oil wells in the State, 45 operational gas processing plants, 5 oil refineries, and over 9,000 miles of gas pipelines[63], there are significant uncertainties associated with estimates of Wyoming's GHG emissions from this sector. This is compounded by the fact that there are no regulatory requirements to track CO_2 or CH_4 emissions. Therefore, estimates based on emissions measurements in Wyoming are not possible at this time.
The State Greenhouse Gas Inventory Tool (SGIT) developed by the US EPA facilitates the development of a rough estimate of state-level GHG emissions.[64] Methane emission estimates are calculated by multiplying emissions-related activity levels (e.g. miles of pipeline, number of

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[59] Utah Oil Shale database, compiled by Michael D. Vanden Berg, John R. Dyni, and David E. Tabet, 2006.
[60] Bureau of Land Management News "Nominations for Oil Shale Research Leases Demonstrate Significant Interest in Advancing Energy Technology", September 20, 2005
Accessed at <http://www.ut.blm.gov/NewsReleases/sep20a.html>
[61] Bartis, James T. et al, Oil Shale development in the United States : prospects and policy issues. 2005. Rand Corporation. Prepared for the National Energy Technology Laboratory of the U.S. Department of Energy.
[62] MarketWatch announcement online, January 12, 2007, Accessed at < http://www.marketwatch.com/news/story/medicine-bow-fuel-power/story.aspx?guid=%7BC2651EE1-8150-4E92-AD9A-CFDAA656379C%7D&sid=42740&symb=?>.
[63] Data from EIA, Gas Facts, and Wyoming Oil and Gas Conservation Commission.
[64] Methane emissions were calculated using SGIT, with reference to Emission Inventory Improvement Program, Volume VIII: Chapter. 5. "Methods for Estimating Methane Emissions from Natural Gas and Oil Systems", March 2005.

compressor stations) by aggregate industry-average emission factors. Key information sources for the activity data are the Wyoming Oil and Gas Conservation Commission[65], the US DOE EIA[66] and the American Gas Association's annual publication *Gas Facts*.[67] Methane emissions were estimated using SGIT, with reference to the EIIP guidance document.

Wyoming has a few reservoirs that contain up to 65% CO_2 in produced natural gas.[68] This CO_2 is processed and used primarily in enhanced oil recovery (EOR) operations, where it is injected into producing oil fields to increase reservoir pressure, thereby increasing oil recovery. The Oil and Gas Conservation Commission reports volumes of gas vented during natural gas processing. Two facilities account for over 96% of the total reported vent gas volumes: the largest portion from ExxonMobil's LaBarge Shute Creek gas plant, with Burlington Resource's Lost Cabin facility next.[69]

Projections of CH_4 emissions from oil and gas systems are developed based on the following key drivers:

- Natural Gas Consumption – See Appendix B, Residential, Commercial and Industrial Sector for assumptions used in projecting natural gas consumption in Wyoming. Based on those assumptions, Wyoming's natural gas consumption is projected to increase at an average annual rate of 0.4% until 2020.[70]
- Production **–** The *Wyoming State Government Revenue Forecast* contains production projections for coal, oil and natural gas out to 2012. Following that, growth rates for oil and gas production are based on regional results from US DOE EIA's *Annual Energy Outlook 2006* ("US DOE regional projections"), where these data are available. Simple assumptions were made for oil refining and transport growth rates. Any input from reviewers on oil and gas growth rates is appreciated.

Table E1 provides an overview of data sources and approach used to project future emissions.

[65] Wyoming Oil and Gas Conservation Commission, January 2007, <http://wogcc.state.wy.us>
[66] "Petroleum Navigator" and "Natural Gas Navigator", US DOE Energy Information Administration website, January 2007, Accessed at http://www.eia.doe.gov
[67] American Gas Association "Gas Facts, A Statistical Record of the Gas Industry" Referenced annual publications from 1992 to 2004.
[68] Personal communication, Rodney De Bruin, Wyoming State Geological Survey, January 25, 2007.
[69] As reported by the Wyoming Oil and Gas Conservation Commission, Exxon's LaBarge Shute Creek facility vented approximately 80% of total reported vent volume between 2004 and 2006, while the Lost Cabin facility vented approximately 14% of the total over the same period.
[70] Based on US DOE regional projections (see Appendix B).

Table E1. Approach to Estimating Historical and Projected Methane Emissions from Natural Gas and Oil Systems

	Approach to Estimating Historical Emissions		**Approach to Estimating Projections**
Activity	***Required Data for SGIT***	***Data Source***	***Projection Assumptions***
Natural Gas Drilling and Field Production	Number wells	EIA	Emissions estimated based on Wyoming State Government projections for natural gas production until 2012,[71] then follow US DOE regional projections until 2020, which average 0.8% annual growth.[72]
	Miles of gathering pipeline	Gas Facts[73]	
Natural Gas Processing	Number gas processing plants	EIA[74]	Emissions follow trend of natural gas processing volume, which continues to grow at 4.9% annually until 2012, then follows US DOE natural gas production trends to 2020, as above.[75]
	Venting of Entrained Gas	Wyoming Oil and Gas Conservation Commission[76]	Projections follow recent vent gas trends (decline of 0.4% per year) until 2020.[77]
Natural Gas Transmission	Miles of transmission pipeline	Gas Facts[73]	Emissions follow trend of State gas production, as above.
	Number of gas transmission compressor stations	EIIP[78]	

[71] Natural gas production projections for 2006 to 2012 from *Wyoming State Government Revenue Forecast Fiscal Year 2007 – Fiscal Year 2012*. Accessed at http://eadiv.state.wy.us/creg/GreenCREG_Jan07.pdf January 25 2007. Emissions calculated assuming emission intensity stays constant at 2004 levels.
[72] Based on US DOE Annual Energy Outlook 2006, natural gas production projection for Rocky Mountain region. Accessed at http://www.eia.doe.gov/oiaf/aeo/supplement/sup_ogc.xls.
[73] No Gas Facts available for 1991 and 1993, so a linear relationship was assumed to extrapolate from the previous and subsequent year.
[74] EIA reported data for 1995 and 2004.
[75] Growth assumption based on EIA reported gas processing data, with an average annual growth of 4.9% in gas processing volume between 1990 and 2005.
[76] Gas plants with largest vent gas volumes identified by Rodney De Bruin, Wyoming State Geological Survey, January 25, 2007. Confirmed by Wyoming Oil and Gas Conservation Commission online reports of monthly vent gas volume from Wyoming gas plants, accessed at <http://wogcc.state.wy.us/GasPlantProd.cfm>. Data confirmed by Cindy Roman, Oil and Gas Conservation Commission, January 30, 2007. Based on 2006 data from LaBarge Chute Creek plant (which emitted 83% of total State reported vent gas in 2006), assume that 84% of vented gas is CO_2, and 1% is CH_4 each year. Used PV=mRT to calculate GHG emissions on metric tons CO_2 equivalent basis. Gas plants with largest vent gas volumes identified by Rodney De Bruin, Wyoming State Geological Survey, January 25, 2007.
[77] Calculated vented greenhouse gas emissions from Wyoming gas plants on a metric tons CO_2 equivalent basis declined at an average annual rate of 0.41% between 2000 and 2006.
[78] Number of gas transmission compressor stations = miles of transmission pipeline x 0.006 EIIP. Volume VIII: Chapter 5, March 2005.

Table E1. Approach to Estimating Historical and Projected Methane Emissions from Natural Gas and Oil Systems (continued)

	Number of gas storage compressor stations	EIIP[79]	
	Number of LNG storage compressor stations	Unavailable, assumed negligible.	
Natural Gas Distribution	Miles of distribution pipeline	Gas Facts[73]	Distribution emissions follow State gas consumption trend – projected annual growth rate of 0.4% until 2020.[80]
	Total number of services	Gas Facts	
	Number of unprotected steel services	Ratio estimated from 2003 data[81]	
	Number of protected steel services	Ratio estimated from 2002 data[81]	
Oil Production	Annual production	EIA[82] and Wyoming Oil and Gas Conservation Commission	Emissions estimated based on Wyoming State Government projections for oil production until 2012,[83] then follow US DOE regional projections until 2020, which average 1.4% annual growth.[84]
Oil Refining	Annual amount refined	EIA[85]	Emissions projected to follow trend of 0.1% annual growth in State oil refining.[86] Assumes no new refineries are built in Wyoming prior to 2020.
Oil Transport	Annual oil transported	Unavailable, assumed oil refined = oil transported	Emissions follow trend of State oil refining, as above.

79 Number of gas storage compressor stations = miles of transmission pipeline x 0.0015 EIIP. Volume VIII: Chapter 5, March 2005.
80 Based on US DOE regional projections and electric sector growth assumptions (see Appendix A and B).
81 Gas Facts reported unprotected and protected steel services for 2002-3, but only total services for other years. Therefore the ratio of unprotected and protected steel services in 2003 was assumed to be the ratio for all other years (0.4284 for protected services and 0.0047 for unprotected services). This yields more congruent results than the EIIP guidance of using multipliers of 0.2841 for protected steel services, and 0.0879 for unprotected steel services.
82 Data extracted from the Petroleum Supply Annual for each year.
83 Natural gas production projections for 2006 to 2012 from *Wyoming State Government Revenue Forecast Fiscal Year 2007 – Fiscal Year 2012*. Accessed at http://eadiv.state.wy.us/creg/GreenCREG_Jan07.pdf, January 25 2007. Emissions calculated assuming emission intensity stays constant at 2004 levels.
84 Based on US DOE Annual Energy Outlook 2006, oil production projection for Rocky Mountain region. Accessed at http://www.eia.doe.gov/oiaf/aeo/supplement/sup_ogc.xls.
85 Refining assumed to be equal to the total input of crude oil into PADD IV times the ratio of Wyoming's refining capacity to PADD IV's total refining capacity. No data for 1995 and 1997, so linear relationship assumed from previous and subsequent years.
86 Based on EIA reported data, average growth in crude oil refined annually was 0.1% between 1990 and 2004.

Note that potential improvements to production, processing, and pipeline technologies resulting in GHG emissions reductions have not been accounted for in this analysis.

As noted above, this analysis also does not include a specific estimate for oil shale production. Note that any commercial development of oil shale in the region would result in increased CO_2 equivalent (CO_2e) emissions from oil production, refining and transportation, and that no emissions from oil shale facilities are included in current forecasts. As production of oil from oil shale is expected to be energy-intensive, and therefore GHG emissions-intensive, any future oil shale development could have significant GHG implications.[87]

Coal Production Emissions

Methane occurs naturally in coal seams, and is typically vented during mining operations for safety reasons. Coal mine CH_4 emissions are usually considerably higher, per unit of coal produced, from underground mining than from surface mining.

Wyoming's 18 operational coal mines, only one of which is underground, produced 404.3 million short tons of coal in 2005.[88] As reported in this inventory, CH_4 emissions from coal mines are as reported by the EPA, and include emissions from surface and underground coal mines, as well as post-mining activities.[89]

With increasing coal production in the state, coal mine CH_4 emissions grew fairly consistently between 1990 and 2004, at an average annual rate of 5.8%. Projections of future coal mine CH_4 emissions through 2012 are based on the 2007 Wyoming State Government Revenue Forecast coal production projections.[90] As a simple projection, coal mine CH_4 emissions are then projected to hold flat from 2012 until 2020. While we will be reviewing these estimates with the Wyoming Division of Oil, Gas and Mining, we welcome any input from reviewers in this regard.

Results

Table E2 displays the estimated CH_4 and vented CO_2 emissions from the fossil fuel industry in Wyoming from 1990 to 2005, with projections to 2020. Emissions from this sector grew by 101% from 1990 to 2005 and are projected to increase by a further 10% between 2005 and 2020. The natural gas industry is the major contributor to both GHG emissions and emissions growth, with CH_4 emissions from coal mining second. That said, it is worth noting that a significant portion of the emissions attributed to the natural gas industry are due to vented gas from a few processing plants, which process gas largely used for injection in enhanced oil recovery operations.

[87] For indications of potential GHG emission intensity of oil shale development see "Strategic Significance of America's Oil Shale Resource", U.S. Department of Energy, March 2004. Accessed on January 20, 2007 at < http://www.fossil.energy.gov/programs/reserves/npr/NPR_Oil_Shale_Program.html>
[88] EIA Coal Data Accessed at < http://www.eia.doe.gov/cneaf/coal/page/acr/table1.html >
[89] Emissions from EPA *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2004* (April 2006) http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2006.html
[90] Coal production projections for 2006 to 2012 from *Wyoming State Government Revenue Forecast Fiscal Year 2007 – Fiscal Year 2012*. Accessed at http://eadiv.state.wy.us/creg/GreenCREG_Jan07.pdf January 25 2007. Emissions calculated assuming emission intensity stays constant at 2004 levels.

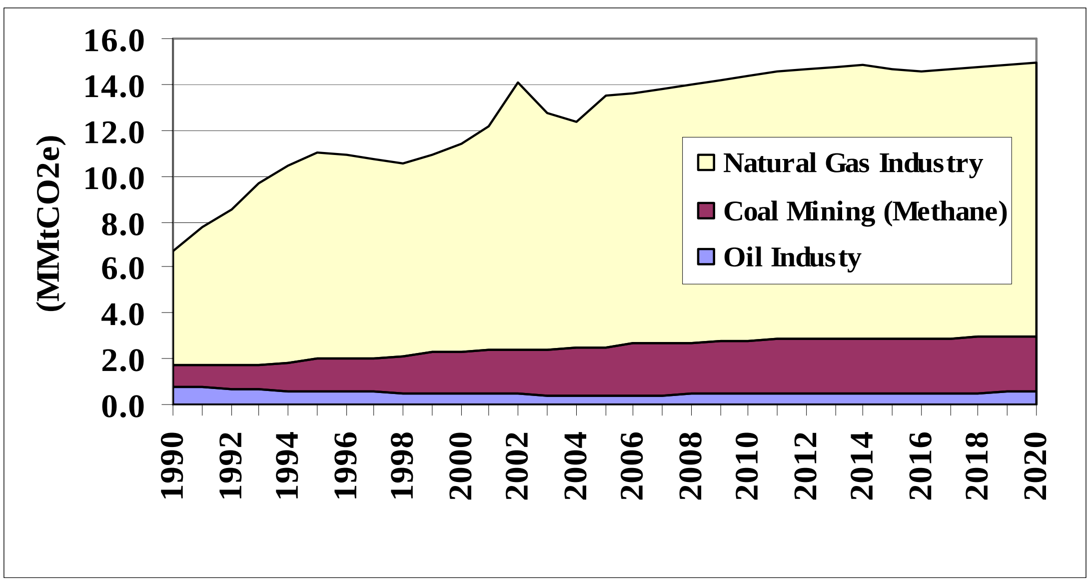
Table E2. Methane Emissions and Projections from the Fossil Fuel Industry

(Million Metric Tons CO2e)	1990	1995	2000	2005	2010	2015	2020
Fossil Fuel Industry	**6.7**	**11.0**	**11.4**	**13.5**	**14.4**	**14.7**	**14.9**
Natural Gas Industry	5.0	9.0	9.2	11.0	11.6	11.8	12.0
Production (CH_4)	0.2	0.3	0.8	1.6	2.3	2.5	2.6
Processing (CO_2 & CH_4)	4.1	7.9	7.7	8.2	7.6	7.6	7.5
Methane Emissions (CH_4)	*1.4*	*1.4*	*1.3*	*1.2*	*1.6*	*1.7*	*1.8*
Vented Gas (CO_2 & CH_4)	*2.6*	*6.5*	*6.4*	*6.9*	*6.0*	*5.9*	*5.7*
Transmission (CH_4)	0.6	0.7	0.6	1.1	1.6	1.6	1.7
Distribution (CH_4)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Oil Industry	0.8	0.6	0.5	0.4	0.5	0.5	0.5
Production (CH_4)	0.7	0.6	0.5	0.4	0.5	0.5	0.5
Refineries (CH_4)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal Mining (CH_4)	1.0	1.4	1.8	2.1	2.3	2.4	2.4

The value 0.00 in the above table indicates emissions less than 0.005 MMtCO2e.

Figure E1 displays the CH_4 emissions from coal mining and natural gas and oil systems, on an $MMtCO_2e$ basis.

Figure E1. Fossil Fuel Industry Emission Trends ($MMtCO_2e$)



Source: CCS calculations based on approach described in text.

Key Uncertainties

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

- Current levels of fugitive emissions. These are based on industry-wide averages, and until estimates are available for local facilities significant uncertainties remain.
- Projections of future production of fossil fuels. These industries are difficult to forecast with the mix of drivers: economics, resource supply, demand, and regulatory procedures. The assumptions used for the projections, based on recent trends or State production trends in the near-term, and AEO2006 growth rates through 2020, do not include any significant changes in energy prices, relative to today's prices. Large price swings, resource limitations, or changes in regulations could significantly change future production and the associated GHG emissions.
- Other uncertainties include the volume of GHGs vented from gas processing facilities in the future, any commercial oil shale or coal-to-liquids production, and potential emissions-reducing improvements in oil and gas production, processing, and pipeline technologies.

We welcome any comments from reviewers in Wyoming on sources of estimates for the above uncertainties.

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 related to agricultural practices (combustion of fossil fuels to power agricultural equipment) are included in the residential, commercial, and industrial (RCI) fuel consumption 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 breakdown food and emit CH_4 as a by-product. More CH_4 is produced in ruminant livestock than in other animals because of digestive activity in the large fore-stomach to break down grasses and other high-fiber feeds. 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 (or oxygen-free) anaerobic conditions. Under aerobic conditions, N_2O emissions are the dominant GHG emissions of concern. Emissions estimates from manure management are based on estimates of the volumes of manure that are stored and treated in 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 inventories of emissions from agricultural soils.

The management of agricultural soils can result in N_2O emissions and in fluxes of carbon dioxide (CO_2) that make soils net emitters or net sinks of carbon. 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 and sewage sludge application to soils, nitrogen fixation, and cultivation of histosols (high organic soils, such as wetlands or peatlands). 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 and is transported off-site before entering the nitrification/denitrification cycle. Methane and N_2O emissions also result when crop residues are burned. Methane emissions occur during rice cultivation; however, rice is not grown in Wyoming.

The net flux of CO_2 in or out of 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. Conversely, soil disturbance from the cultivation of histosols releases large stores of carbon from the soil to the atmosphere. Finally, the practice of adding limestone and dolomite to agricultural soils results in CO_2 emissions.

Emissions and Reference Case Projections

Methane and Nitrous Oxide

GHG emissions for 1990 through 2005 were estimated using SGIT and the methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for the sector.[91] In general, the SGIT methodology applies emission factors developed for the US to activity data for the agriculture sector. Activity data include livestock population 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.[92]

Data on crop production in Wyoming from 1990 to 2005 and on the number of animals in the state from 1990 to 2002 were obtained from the United States Department of Agriculture (USDA), National Agriculture Statistical Service (NASS) and incorporated as defaults in SGIT.[93] Future reference case emissions from enteric fermentation and manure management were estimated based on the annual growth rate in emissions (million metric ton [MMt] carbon dioxide equivalent [CO_2e] basis) associated with historical livestock populations in Wyoming for 1990 to 2002. The default data in SGIT accounting for the percentage of each livestock category using each type of manure management system was used for this inventory. Default SGIT assumptions were available for 1990 through 2002.

Data on fertilizer usage came from *Commercial Fertilizers*, a report from the Fertilizer Institute. Data on crop production in Wyoming from 1990 to 2005 from the USDA NASS were used to calculate N_2O emissions from crop residues and crops that use nitrogen (i.e., nitrogen fixation) and CH_4 emissions from agricultural residue burning through 2005. Emissions for the other agricultural crop production practices categories (i.e., synthetic and organic fertilizers) were calculated through 2002.

Data were not available to estimate nitrogen released by the cultivation of histosols (i.e., the number of acres of high organic content soils). However, as discussed in the following section for soil carbon, the Natural Resources Ecology Laboratory at Colorado State University estimated zero CO_2 emissions for organic soils in Wyoming for 1997, suggesting that the area of cultivated high organic content soils was either very small or zero in Wyoming. Therefore, N_2O emissions from cultivated histosol soils were also assumed to be zero.

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[91] GHG emissions were calculated using SGIT, with reference to Emission Inventory Improvement Program, 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.

[92] Revised 1996 1ntergovermental Panel on Climate Change 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/).

[93] USDA, NASS (http://www.nass.usda.gov/Statistics_by_State/Wyoming/index.asp).

Agricultural residue burning is conducted in Wyoming. 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 and burned, the resultant dry matter, and the carbon/nitrogen content of the dry matter. For Wyoming, the default SGIT method was used to calculate emissions because activity data in the form used in the SGIT were not readily available. Future work on this category should include an assessment to refine the SGIT default assumptions.

Table F1 shows the annual growth rates applied to estimate the reference case projections by agricultural sector. Emissions from enteric fermentation and agricultural soils were projected based on the annual growth rate in historical emissions ($MMtCO_2e$ basis) for these categories in Wyoming for 1990 to 2002 (1990 to 2005 for crop residues and nitrogen fixing crops).

Table F1. Growth Rates Applied for the Agricultural Sector

Agricultural Category	Growth Rate	Basis for Annual Growth Rate*
Enteric Fermentation	1.4%	Historical emissions for 1990-2002.
Manure Management	1.8%	Historical emissions for 1990-2002.
Agricultural Burning	0.0%	Assumed no growth.
Agricultural Soils – Direct Emissions		
Fertilizers	2.0%	Historical emissions for 1990-2002.
Crop Residues	1.3%	Historical emissions for 1990-2005.
Nitrogen-Fixing Crops	1.1%	Historical emissions for 1990-2005.
Histosols	0.0%	No historical data available.
Livestock	1.5%	Historical emissions for 1990-2002.
Agricultural Soils – Indirect Emissions		
Fertilizers	2.0%	Historical emissions for 1990-2002.
Livestock	1.5%	Historical emissions for 1990-2002.
Leaching/Runoff	1.7%	Historical emissions for 1990-2002.

* Compound annual growth rates shown in this table were calculated using the growth rate in historical emissions ($MMtCO_2e$ basis) from 1990 through the most recent year of data. These growth rates were applied to forecast emissions from the latest year of data to 2020.

The growth rates for enteric fermentation and manure management are driven by livestock populations and waste management methods. From 1990 through 2002, dairy cattle populations declined by about 5.6% annually on average, this rate of decline has remained roughly constant and applies to the most recent five years (1997 through 2002) for which data are available in SGIT. The average annual growth rate for beef cattle during the 12-year period from 1990 through 2002 was about 1.5%, but has slowed to -1.2% during the 1997 through 2002 period. The annual average growth rate for the swine population in Wyoming was about 15.7% from 1990 through 2002, but the growth rate has significantly slowed to about 4% during the 1997 through 2002 period. The growth rates shown in Table F1 are calculated using the trend in emissions from 1990 through 2002 associated with the historical livestock populations and default SGIT assumptions on manure management systems used in Wyoming. Future work should include an evaluation to improve the growth rates used for the reference case projections. Such an evaluation should also include an assessment to improve the growth rates for forecasting emissions associated with the use of fertilizers containing nitrogen. Use of fertilizers that contain nitrogen in Wyoming indicated a 12-year average annual growth rate of 8.5%; however, the growth rate for the 1997 to 2002 period is about -1.1%.

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 *U.S. Inventory of Greenhouse Gas Emissions and Sinks*[94] and the *U.S. Agriculture and Forestry Greenhouse Gas Inventory*. The estimates are based on the IPCC 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 *U.S. Agriculture and Forestry Greenhouse Gas Inventory*. 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 at present.

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 Wyoming, Table F2 shows a summary of the latest estimates available from the USDA, which are for 1997.[95] These data show that changes in agricultural practices are estimated to result in a net sink of 0.92 $MMtCO_2e$/yr in Wyoming. Since data are not yet available from USDA to make a determination of whether the emissions are increasing or decreasing, the net sink of 0.92 $MMtCO_2e$/yr is assumed to remain constant.

Results

As shown in Figure F1, gross GHG emissions from agricultural sources range between about 4.09 and 5.97 $MMtCO_2e$ from 1990 through 2020, respectively. In 1990, enteric fermentation accounted for about 40% (1.63 $MMtCO_2e$) of total agricultural emissions and is estimated to account for about 41.5% (2.48 $MMtCO_2e$) of total agricultural emissions in 2020. The manure management category, which shows the second highest rate of growth relative to the other categories, accounted for 2.1% (0.09 $MMtCO_2e$) of total agricultural emissions in 1990 and is estimated to account for about 2.5% (0.15 $MMtCO_2e$) of total agricultural emissions in 2020. The agricultural soils category shows 1990 emissions accounting for 58% (2.37 $MMtCO_2e$) of total agricultural emissions and 2020 emissions estimated to be about 56% (3.34 $MMtCO_2e$) of total agricultural emissions. Including the CO_2 sequestration from soil carbon changes, the historic and projected emissions for the agriculture sector on a net basis would range between about 3.17 and 5.05 $MMtCO_2e$/yr from 1990 through 2020, respectively.

[94] *U.S. 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.

[95] *U.S. 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.

Table F2. 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
0.51	(0.07)	0.00	(0.62)	(0.04)	(0.29)	0.00	(0.37)	(0.04)	0.00	(0.92)

Based on USDA 1997 estimates. Parentheses indicate net sequestration.

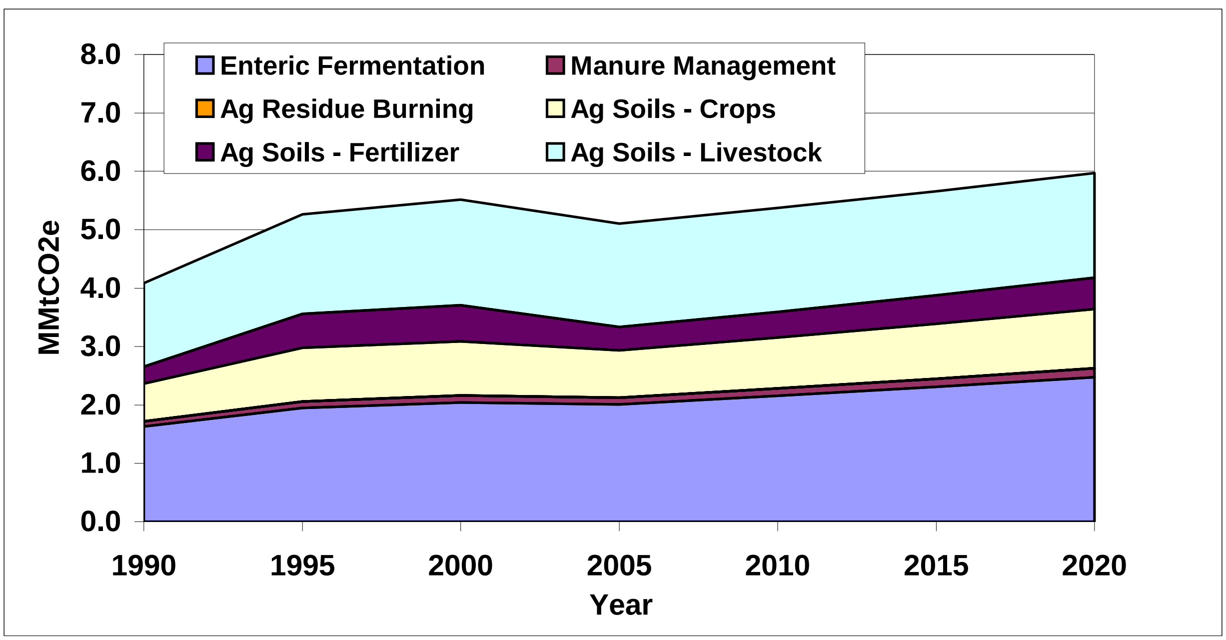
[1] Losses from annual cropping systems due to plow-out of pastures, rangeland, hayland, set-aside lands, and perennial/horticultural cropland (annual cropping systems on mineral soils, e.g., corn, soybean, cotton, and wheat).

[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.

Figure F1. Gross GHG Emissions from Agriculture



Source: CCS calculations based on approach described in text.
Notes: Ag Soils – Crops category includes: incorporation of crop residues and nitrogen fixing crops (no cultivation of histosols estimated in Wyoming); emissions for agricultural residue burning are too small to be seen in this chart. Soil carbon sequestration is not shown (see Table F2).

Agricultural burning emissions were estimated to be very small based on the SGIT activity data (<0.001 $MMtCO_2e$/yr from 1990 to 2002). This agrees with the USDA Inventory which also reports a low level of residue burning emissions (0.02 $MMtCO_2e$).

The only standard IPCC source categories missing from this report are N_2O emissions from cultivation of histosols and CO_2 emissions from limestone and dolomite application. Estimates for Wyoming were not available; however, the USDA's national estimate for soil liming is about 9 $MMtCO_2e$/ yr.[96]

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 that are dependent on several variables, including manure production levels, volatile solids contents of manures, and CH_4 formation potential). Each of these factors has some level of uncertainty. Also, 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. 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 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 2020, the current size of the CO_2 sink could be appreciably affected. As mentioned above, emission estimates for soil liming have not been developed for Wyoming.

Another contributor to uncertainty in the emission estimates is the projection assumptions. This inventory assumes that the average annual rate of change in future year emissions will follow the historical average annual rate of change from 1990 through the most recent year of data. For example, the historical data for 1990 through 2002 show an increase in the use of fertilizers; however, the 5-year trend (-1.1%) for 1997 through 2002 suggests that there may be a leveling-off in fertilizer use trends perhaps due to recent efficiency gains that my be close to reaching their full technical potential.

[96] *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2001*. Global Change Program Office, Office of the Chief Economist, US Department of Agriculture.

Appendix G. Waste Management

Overview

GHG emissions from waste management include:

- Solid waste management – methane (CH_4) emissions from municipal and industrial solid waste landfills (LFs), 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 combustion of solid waste in incinerators or waste to energy plants; and
- Wastewater management – CH_4 and N_2O from municipal wastewater and CH_4 from industrial wastewater (WW) treatment facilities.

Inventory and Reference Case Projections

Solid Waste Management

For solid waste management, we used EPA's State Greenhouse Gas Inventory Tool (SGIT). CCS usually uses US EPA Landfill Methane Outreach Program (LMOP) landfills database[97] as a starting point for municipal solid waste (MSW) landfill data. However, the LMOP database included only one landfill for Wyoming, the Cheyenne Landfill. WYDEQ was unable to provide additional data for Wyoming landfills; therefore, SGIT default state-level annual MSW waste emplacement was used to estimate emissions. The default waste emplacement for 2001 agrees with the annual MSW disposal estimated in the Wyoming Business Council's Biomass Inventory (542,031 tons).[98] SGIT estimates emissions from landfills based on the annual 30-year waste-in-place (waste that has been landfill for up to 30 years), estimated from the annual waste emplacement data.

SGIT uses different emission formulas for estimating emissions for small and large landfills. Instead of using the default assumption that 86% of total waste is disposed in large landfills (defined as larger than 1.1 million tons of waste-in-place), Cheyenne Landfill was assumed to be the only large landfill and emplacement data for Cheyenne Landfill in the LMOP database was used to estimate the annual large landfill WIP. Table G1 shows the estimated waste-in-place for each year for large and small landfills.

The LMOP database indicates that the Cheyenne landfill does not have a landfill gas collection system and LFGTE plant or flare. All other landfills in the state were assumed to also be uncontrolled. Growth rates were estimated by using the historic (1990-2005) growth rates of emissions, resulting in a compound annual growth rate of 4.15%.

[97] LMOP database is available at: http://www.epa.gov/lmop/proj/index.htm. Updated version of the database provided by Rachel Goldstein, Program Manager, EPA Landfill Methane Outreach Program, October 2006.
[98] Wyoming Biomass Inventory, Wyoming Business Council, 2002, http://www.wyomingbusiness.org/business/energy.aspx. The report estimates that 682,008 tons of municipal solid waste were generated in 2001. The estimate of 542,031 tons sent to landfills was calculated by subtracting the amount of waste estimated to go to balefills, to the Thayne incinerator, and diverted for recycling or compost.

Table G1. Wyoming Annual 30-Year Waste-in-Place (tons)

Year	Total State WIP	Large Landfill (Cheyenne) WIP	Small Landfill WIP
1990	6,701,470	2,994,140	3,707,330
1991	6,889,552	3,124,320	3,765,232
1992	7,071,787	3,254,500	3,817,287
1993	7,248,620	3,384,680	3,863,940
1994	7,591,429	3,514,860	4,076,569
1995	7,961,569	3,645,040	4,316,529
1996	8,331,858	3,775,220	4,556,638
1997	8,692,594	3,905,400	4,787,194
1998	9,047,571	3,905,400	5,142,171
1999	9,395,142	3,905,400	5,489,742
2000	9,737,770	3,905,400	5,832,370
2001	10,152,349	3,905,400	6,246,949
2002	10,644,313	3,905,400	6,738,913
2003	11,132,397	3,905,400	7,226,997
2004	11,615,800	3,905,400	7,710,400
2005	12,090,925	3,905,400	8,185,525

CCS used the SGIT default for industrial solid waste landfills. This default is based on national data indicating that industrial landfilled waste is emplaced at approximately 7 percent of the rate of MSW emplacement. We assumed that this additional industrial waste emplacement occurs beyond that already addressed in the emplacement rates for MSW sites described above. Due to a lack of data, no controls were assumed for industrial waste landfilling. For industrial landfills, the overall growth rate in MSW emissions from 1990 to 2005 (4.15 %/yr) was used to project emissions to 2020 (based on the assumption that industrial waste landfilling will continue to grow at the same rate as MSW landfilling overall).

Solid Waste Combustion

The Wyoming Business Council's Biomass Inventory indicates that there is one solid waste incinerator operating in Wyoming (Thayne incinerator in Lincoln County). The report indicates that in 2001, 1,168 cubic yards of incinerator ash were landfilled. Assuming that the incinerator ash is 10% of the original waste volume[99] and the waste density is 800 lbs/cubic yard, CCS estimated that 4,672 tons of waste was combusted in 2001. SGIT contains default waste combustion throughputs of 5,680 tons in 2000 and 3,125 tons in 2001 (0 for all other years). This default data was replaced with the estimate of 4,670 tons combusted annually for 2000-2005. These estimates have a significant level of uncertainty; however, this level of combustion activity represents less than 1% of total emissions from the waste management sector.

[99] Waste-to-Energy Research and Technology Council (WTERT), http://www.seas.columbia.edu/earth/wtert/wtertfaq.html.

Wastewater Management
GHG emissions from municipal wastewater treatment were also estimated. For municipal wastewater treatment, emissions are calculated in EPA's SGIT based on state population, assumed biochemical oxygen demand (BOD) and protein consumption per capita, and emission factors for N_2O and CH_4. The key SGIT default values are shown in Table G2. Revised values for the amount of BOD anaerobically treated and the percentage of state residents on septic were provided by WYDEQ. According to the contact at WYDEQ, most of the CH_4 produced by municipal wastewater plants is either flared or captured by the aerobic layer of facultative lagoons; therefore, a control efficiency of 80% was applied to municipal wastewater CH_4 emissions.[100] Municipal wastewater emissions were based on population projections for 2005-2020[101] for a growth rate of 0.57% per year.

For industrial wastewater emissions, SGIT provides default assumptions and emission factors for three industrial sectors: Fruits & Vegetables, Red Meat & Poultry, and Pulp & Paper. However, the contact at WYDEQ indicated that there are no large plants in these industries operating in Wyoming.[4]

Table G2. SGIT Key Default Values for Municipal Wastewater Treatment and Revised Values Provided by WYDEQ

Variable	Default Value	WYDEQ Value
BOD	0.065 kg /day-person	
Amount of BOD anaerobically treated	16.25%	25%
CH_4 emission factor	0.6 kg/kg BOD	
Wyoming residents not on septic	75%	50%
Water treatment N_2O emission factor	4.0 g N_2O/person-yr	
Biosolids emission factor	0.01 kg N_2O-N/kg sewage-N	

Source: US EPA State Greenhouse Gas Inventory Tool – Wastewater Module; methodology and factors taken from US EPA, Emission Inventory Improvement Program, Volume 8, Chapter 12, October 1999: www.epa.gov/ttn/chief/eiip/techreport/volume08/.

Results

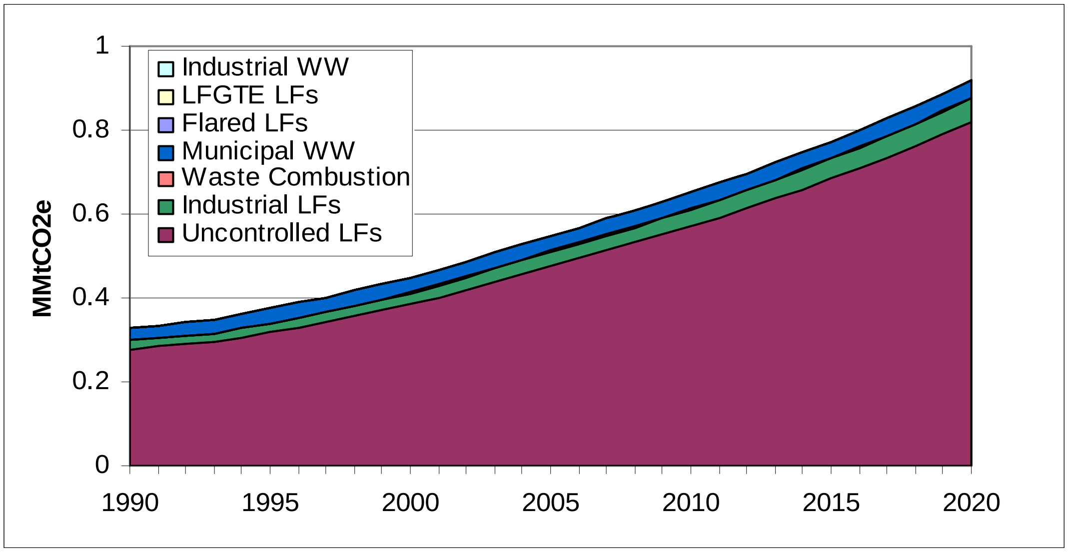
Figure G1 shows the emission estimates for the waste management sector. Overall, the sector accounts for 0.55 $MMtCO_2e$ in 2005. By 2020, emissions are expected to grow to 0.92 $MMtCO_2e$/yr. The growth in emissions is driven by the solid waste management sector, in particular uncontrolled municipal landfills. In 2005, almost 87 percent of the emissions came from the municipal landfills sector. By 2020, the contribution from these sites is expected to be about 89 percent.

Only about 7 percent of the waste management sector emissions were contributed by municipal wastewater treatment systems. By 2020, municipal wastewater treatment is expected to

[100] Lou Harmon, Program Principal/SE District Engineer, Wyoming Department of Environmental Quality – Water Quality Division.
[101] Wyoming Department of Administration and Information, Economic Analysis Division, http://eadiv.state.wy.us/pop/pop.asp.

contribute about 4 percent of the waste management sector emissions with the reduction due to the large increase projected for the solid waste sector.

Figure G1. Wyoming GHG Emissions from Waste Management



Source: CCS calculations based on approach described in text.
Notes: LF – landfill; WW – wastewater; LFGTE – landfill gas to energy; emissions for solid waste combustion were estimated to be negligible.

Key Uncertainties

Emissions from landfills were based on default annual disposal data, which is more uncertain than landfill specific data. Landfill specific data would provide information on landfill openings and closures, relative sizes of landfills, and any controls that are present

For industrial landfills, these were estimated using national defaults (7 percent of the rate of MSW emplacement). It could be that the MSW emplacement data used to model the MSW emissions already captures industrial LF emplacement. As with overall MSW landfill emissions, industrial landfill emissions are projected to increase between 2005 and 2020. Hence, the industrial landfill inventory and forecast has a significant level of uncertainty and should be investigated further. If the existing municipal waste emplacement data are thought to include industrial wastes, then the industrial landfill emissions can be excluded from the inventory.

According to WYDEQ, almost all of wastewater biosolids are applied to soils. In this inventory, N_2O emissions associated with these biosolids are included in the wastewater sector. Since most of the emissions probably occur after land application, these emissions could be included in the agricultural soils sector instead. These emissions are estimated to equal 0.008 $MMtCO_2e$ in 2005. Other key uncertainties with the wastewater sector are associated with the application of SGIT default values for the parameters listed in Table G2 above (e.g. the fraction of BOD that is anaerobically decomposed). The SGIT defaults for emission factors used to estimate wastewater emissions were derived from national data.

Appendix H. Forestry

Overview

Forestland emissions refer to the net carbon dioxide (CO_2) flux[102] from forested lands in Wyoming, which account for about 18% of the state's land area.[103] The dominant forest type in Wyoming is Lodgepole pine which makes up about 32% of forested lands. Other common forest types are Fir-Spruce (17%) and Ponderosa pine (13%) forests.

Forestlands are net sinks of CO_2 in Wyoming. Through photosynthesis, carbon dioxide 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 carbon dioxide removals from and emissions to the atmosphere from the processes described above.

Inventory and Reference Case Projections

For over a decade, the United State 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 *U.S. Inventory of Greenhouse Gas Emissions and Sinks*.[104] The national estimates are compiled from state-level data. The Wyoming forest CO_2 flux data in this report come from the national analysis and are provided by the USFS.

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 (Mg per hectare) for a number of separate C pools.

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, Under-story, 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

[102] "Flux" refers to both emissions of CO_2 to the atmosphere and removal (sinks) of CO_2 from the atmosphere.
[103] Total forested acreage is 10.9 million acres. Acreage by forest type available from the USFS at: http://www.fs.fed.us/ne/global/pubs/books/epa/states/WY.htm. The total land area in Wyoming is 62.1 million acres (http://www.50states.com/wyoming.htm).
[104] *U.S. 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.

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).

Carbon pool data for two periods are used to estimate CO_2 flux for each pool. The data shown in Table H1 are based on the most recent estimates from the USFS, which are included in the 2005 estimates in EPA's national GHG inventory. Discussions with USFS have indicated that the soil carbon pool estimates carry a high level of uncertainty and in many cases might not be statistically different than zero.[105]

Table H1. Forest Carbon Flux Estimates for Wyoming

Forest Pool	Carbon Flux (MMtC)	Carbon Flux ($MMtCO_2$)
Live Tree (above ground)	-4.5	-16.5
Live Tree (below ground)	-1.7	-6.2
Standing Dead & Down Dead	-2.2	-8.1
Forest Floor	-1.2	-4.4
Soil Carbon	-1.2	-4.4
Harvested Wood Products	-0.08	-0.3
Totals	**-10.9**	**-39.9**
Totals (excluding soil carbon)	**-9.7**	**-35.5**

Totals may not sum exactly due to independent rounding.
Data source: Jim Smith, USFS, personal communications with S. Roe, CCS, October 2006 and February 2007.

In addition to the forest carbon pools, additional carbon stored as biomass is removed from the forest for the production of durable wood products. Carbon remains stored in the products pool or is transferred to landfills where much of the carbon remains stored over a long period of time. As shown in the table above, 0.3 $MMtCO_2$/yr is estimated to be sequestered annually in wood products.[106] 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.[107]

For the 1990 and 2000 historic emission estimates as well as the reference case projections, the forest area and carbon densities of forestlands were assumed to be at the same levels as those shown in the Table H1 above. Information is not currently available on the near term effects of climate change and their impacts on forest productivity. Hence, there is no change in the estimated future sinks for 2010 and 2020.

[105] Rich Birdsey, USFS, personal communication with CCS, May 2007.
[106] Jim Smith, USFS, personal communication with S. Roe, CCS, October 2006.
[107] 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.

In order to provide a more comprehensive understanding of GHG sources/sinks from the forestry sector, the CCS also developed some rough estimates of state-wide emissions for methane (CH_4) and nitrous oxide (N_2O) from wildfires and prescribed burns. A study published earlier this year in *Science* indicated an increasing frequency of wildfire activity in the western US driven by a longer fire season and higher temperatures.[108]

CCS used 2002 emissions data developed by the Western Regional Air Partnership (WRAP) to estimate CO_2e emissions for wildfires and prescribed burns.[109] The CO_2e from CH_4 emissions from this study were added to an estimate of CO_2e for N_2O to estimate a total CO_2e for fires (the carbon dioxide emissions from fires are captured within the carbon pool accounting methods described above). The N_2O estimate was made assuming that N_2O was 1% of the emissions of nitrogen oxides (NO_x) from the WRAP study. The 1% estimate is a common rule of thumb for the N_2O content of NO_x from combustion sources.

The results for 2002 are that wildfires and prescribed burns on forested lands contributed about 0.35 MMtCO_2e of CH_4 and N_2O. Over 90% of the CO_2e was contributed by CH_4 emissions. In 2002, there were about 155,000 acres burned by wildfires and prescribed burns in Wyoming. Note that this 2002 level of wildfire activity compares to about 358,000 acres burned in Wyoming in 1996.[110]

A comparison estimate was made using emission factors from a 2001 global biomass burning study[111] and the total tons of biomass burned from the 2002 WRAP fires emissions inventory. This estimate is 0.41 MMtCO_2e with about equal contributions from CH_4 and N_2O on a CO_2e basis. Given the large swings in fire activity from year to year and the current lack of data for multiple years, CCS did not include these estimates in with the annual forestry flux estimates presented in the emissions summaries of this report. However, on the basis of total acres burned in 1996 and 2002, it appears that forest fires contribute on the order of 0.4 – 0.8 MMtCO_2e annually in WY from CH_4 and N_2O emissions.

Key Uncertainties

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

[108] Westerling, A.L. et al, "Warming and Earlier Spring Increases Western US Forest Wildfire Activity", *Sciencexpress*, July 6, 2006.
[109] *2002 Fire Emission Inventory for the WRAP Region Phase II*, prepared by Air Sciences, Inc. for the Western Regional Air Partnership, July 22, 2005.
[110] *1996 Fire Emission Inventory*, Draft Final Report, prepared by Air Sciences, Inc. for the Western Regional Air Partnership, December 2002.
[111] M.O. Andreae and P. Merlet, "Emission of trace gases and aerosols from biomass burning", *Global Biogeochemical Cycles*, Vol. 15, No. 4, pp. 955-966, December 2001.

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.

Also, FIA surveys since 1999 include all dead trees on the plots, but data prior to that are variable in terms of these data. As shown in Table H1, the standing dead and down/dead pools contribute about 20% of the net estimated forest flux. 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. The effect of these changes in survey methods has not been estimated by the USFS. It is possible that changes in FIA sampling resulted in more forest area coming into the inventory sample in the second time period.

As mentioned above, CCS included the forestry estimates without the soil carbon pool in the emissions summary tables (see Tables ES-1 and Table 1) for this report, since the USFS has indicated a high level of uncertainty for this carbon pool. These uncertainties are likely to remain until additional data from measurements and potentially improved modeling methods are developed.

Appendix I. Inventory and Forecast for Black Carbon

Overview

This appendix summarizes the methods, data sources, and results of the development of an inventory and forecast for black carbon (BC) emissions in Wyoming. Black carbon is an aerosol (particulate matter or PM) species with positive climate forcing potential but currently without a global warming potential defined by the IPCC (see Appendix J for more information on black carbon and other aerosol species). BC is synonymous with elemental carbon (EC), which is a term common to regional haze analysis. An inventory for 2002 was developed based on inventory data from the Western Regional Air Partnership (WRAP) regional planning organization.[112] This appendix describes these data and methods for estimating mass emissions of BC and then transforming the mass emission estimates into CO_2 equivalents (CO_2e) in order to present the emissions within a GHG context.

In addition to the PM inventory data from WRAP, PM speciation data from EPA's SPECIATE database were also used: these data include PM fractions of elemental carbon (also known as black carbon) and primary organic aerosols (also known as organic material or OM). These data come from ongoing work being conducted by E.H. Pechan & Associates, Inc. (Pechan) for EPA on updating the SPECIATE database.[113] These new profiles have just recently been released by EPA. As will be further described below, both BC and OM emission estimates are needed to assess the CO_2e of black carbon emissions. While BC and OM emissions data are available from the WRAP regional haze inventories, CCS favored the newer speciation data available from EPA for the purposes of estimating BC and OM for most source sectors (BC and OM data from the WRAP were used only for the nonroad engines sector). In particular, better speciation data are now available from EPA for important BC emissions sources (e.g., most fossil fuel combustion sources).

After assembling the BC and OM emission estimates, the mass emission rates were transformed into their CO_2e estimates using information from recent global climate modeling. This transformation is described in later sections below.

Development of BC and OM Mass Emission Estimates
The BC and OM mass emission estimates were derived by multiplying the emissions estimates for particulate matter with an aerodynamic diameter of less than 2.5 micrometers ($PM_{2.5}$) by the appropriate aerosol fraction for BC and OM. The aerosol fractions were taken from Pechan's ongoing work to update EPA's SPECIATE database as approved by EPA's SPECIATE Workgroup members.

After estimating both BC and OM emissions for each source category, we used the BC estimate as described below to estimate the CO_2e emissions. Also, as described further below, the OM emission estimate was used to determine whether the source was likely to have positive climate forcing potential. The mass emission results for 2002 are shown in Table I1.

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[112] Tom Moore, Western Regional Air Partnership, data files provided to Steve Roe, CCS, December 2006.
[113] Version 4.0 of the SPECIATE database and report: http://www.epa.gov/ttn/chief/software/speciate/index.html#related.

Development of CO_2e for BC+OM Emissions

We used similar methods to those applied previously in Maine and Connecticut for converting BC mass emissions to CO_2e.[114] These methods are based on the modeling of Jacobson (2002)[115] and his updates to this work (Jacobson, 2005a).[116] Jacobson (2005a) estimated a range of 90:1 to 190:1 for the climate response effects of BC+OM emissions as compared to CO_2 carbon emissions (depending on either a 30-year or 95-year atmospheric lifetime for CO_2). It is important to note that the BC+OM emissions used by Jacobson were based on a 2:1 ratio of OM:BC (his work in these papers focused on fossil fuel BC+OM; primarily diesel combustion, which has an OM:BC ratio of 2:1 or less).

For Maine and Connecticut, ENE (2004) applied climate response factors from the earlier Jacobson work (220 and 500) to the estimated BC mass to estimate the range of CO_2e associated with BC emissions. Note that the analysis in the northeast was limited to BC emissions from onroad diesel exhaust. An important oversight from this work is that the climate response factors developed by Jacobson (2002, 2005a) are on the basis of CO_2 carbon (not CO_2). Therefore, in order to express the BC emissions as CO_2e, the climate response factors should have been adjusted upward by a factor of 3.67 to account for the molecular weight of CO_2 to carbon (44/12).

For this inventory, we started with the 90 and 190 climate response factors adjusted to CO_2e factors of 330 and 697 to obtain a low and high estimate of CO_2e for each sector. An example calculation of the CO_2e emissions for 10 tons of PM less than 2.5 microns ($PM_{2.5}$) from onroad diesel exhaust follows:

> BC mass = (10 short tons $PM_{2.5}$) x (0.613 ton EC/ton $PM_{2.5}$) = 6.13 short tons BC
>
> Low estimate CO_2e = (6.13 tons BC) (330 tons CO_2e/ton BC+OM) (3 tons BC+OM/ton BC) (0.907 metric ton/ton) = 5,504 metric tons CO_2e
>
> High estimate CO_2e = (6.13 tons BC) (697 tons CO_2e/ton BC+OM) (3 tons BC+OM/ton BC) (0.907 metric ton/ton) = 11,626 metric tons CO_2e
>
> NOTE: The factor 3 tons BC+OM/ton BC comes directly from the global modeling inputs used by Jacobson (2002, 2005a; i.e., 2 tons of OM/ton of BC).

For source categories that had an OM:BC mass emissions ratio >4.0, we zeroed out these emission estimates from the CO_2e estimates. The reason for this is that the net heating effects of OM are not currently well understood (overall OM is thought to have a negative climate forcing

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[114] ENE, 2004. Memorandum: "Diesel Black Carbon Calculations – Reductions and Baseline" from Michael Stoddard, Environment Northeast, prepared for the Connecticut Stakeholder Dialog, Transportation Work Group, October 23, 2003.

[115] Jacobson, 2002. Jacobson, M.Z., "Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming", *Journal of Geophysical Physical Research*, volume 107, No. D19, 4410, 2002.

[116] Jacobson, 2005a. Jacobson, M.Z., "Updates to 'Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming", *Journal of Geophysical Research Atmospheres*, February 15, 2005.

effect or a net cooling effect). Therefore, for source categories where the PM is dominated by OM (e.g., biomass burning), the net climate response associated with these emissions is highly uncertain and could potentially produce a net negative climate forcing potential. Further, OM:BC ratios of 4 or more are well beyond the 2:1 ratio used by Jacobson in his work.

Results

We estimate that BC mass emissions in Wyoming total about 4.1 $MMtCO_2e$ in 2002. This is the mid-point of the estimated range of emissions. The estimated range is 2.6 – 5.5 $MMtCO_2e$ (see Table I1). The primary contributing sectors in 2002 were rail (41%), nonroad diesel (27%), onroad diesel (14%), coal fired electricity generating units (12%), nonroad gasoline engines (2%), and RCI coal combustion (1%).

The nonroad diesel sector includes engine exhaust emissions used for construction/mining, commercial, industrial and agricultural purposes, and recreational vehicles. Agricultural engines contributed about 66% of the nonroad diesel total, while construction and mining engines contributed another 21%. For nonroad gasoline engines, primary contributors included recreational equipment (56%) and pleasure craft (25%).

Wildfires and miscellaneous sources such as fugitive dust from paved and unpaved roads contributed a significant amount of PM and subsequent BC and OM mass emissions (see Table I1); however the OM:BC ratio is >4 for these sources, so the BC emissions were not converted to CO_2e.

CCS also performed an assessment of the primary BC contributing sectors from the 2018 WRAP forecast. A drop in the future BC emissions for the onroad and nonroad diesel sectors is expected due to new engine and fuels standards that will reduce particulate matter emissions. For the nonroad diesel sector the estimated 1.1 $MMtCO_2e$ in 2002 drops to 0.3 $MMtCO_2e$ in 2018. For the onroad diesel sector, 0.6 $MMtCO_2e$ was estimated for 2002 dropping to 0.09 $MMtCO_2e$ in 2018. Emissions from the rail sector were nearly the same as in 2002. No significant reductions are expected in the other emission sectors. The development of emission estimates for each of the smaller source sectors was beyond the scope of this analysis.

Key Uncertainties

While the state of science in aerosol climate forcing is still developing, there is a good body of evidence supporting the net warming impacts of black carbon. Aerosols have a *direct* radiative forcing because they scatter and absorb solar and infrared radiation in the atmosphere. Aerosols also alter the formation and precipitation efficiency of liquid water, ice and mixed-phase clouds, thereby causing an *indirect* radiative forcing associated with these changes in cloud properties (IPCC, 2001).[117] There are also a number of other indirect radiative effects that have been modeled (e.g., Jacobson, 2002).

The quantification of aerosol radiative forcing is more complex than the quantification of radiative forcing by GHGs because of the direct and indirect radiative forcing effects, and the fact that aerosol mass and particle number concentrations are highly variable in space and time.

[117] IPCC, 2001. Climate Change 2001: The Scientific Basis, Intergovernmental Panel on Climate Change, 2001.

This variability is largely due to the much shorter atmospheric lifetime of aerosols compared with the important GHGs (i.e. CO_2). Spatially and temporally resolved information on the atmospheric concentration and radiative properties of aerosols is needed to estimate radiative forcing.

The quantification of indirect radiative forcing by aerosols is especially difficult. In addition to the variability in aerosol concentrations, some complicated aerosol influences on cloud processes must be accurately modeled. For example, the warm (liquid water) cloud indirect forcing may be divided into two components. The first indirect forcing is associated with the change in droplet concentration caused by increases in aerosol cloud condensation nuclei. The second indirect forcing is associated with the change in precipitation efficiency that results from a change in droplet number concentration. Quantification of the latter forcing necessitates understanding of a change in cloud liquid-water content. In addition to warm clouds, ice clouds may also be affected by aerosols.

To put the radiative forcing potential of BC in context with CO_2, the IPCC estimated the radiative forcing for a doubling of the earth's CO_2 concentration to be 3.7 watts per square meter (W/m^2). For BC, various estimates of current radiative forcing have ranged from 0.16 to 0.42 W/m^2 (IPCC, 2001). These BC estimates are for direct radiative effects only. There is a higher level of uncertainty associated with the direct radiative forcing estimates of BC compared to those of CO_2 and other GHGs. There are even higher uncertainties associated with the assessment of the indirect radiative forcing of aerosols.

Table I1. 2002 BC Emission Estimates

Sector	Subsector	Mass Emissions			CO2 Equivalents		Contribution to CO2e
		BC	OM	BC + OM	Low	High	
		Metric Tons			Metric Tons		%
Electricity Generating Units (EGUs)	Coal	321	458	779	317,429	670,448	12.1%
	Oil	0	0	0	277	585	0.0%
	Gas	0	32	32	0	0	0.0%
	Other	0	0	0	0	0	0.0%
Non-EGU Fuel Combustion (Residential, Commercial, and Industrial)							
	Coal	37	53	90	36,812	77,751	1.4%
	Oil	22	18	39	21,519	45,450	0.8%
	Gas	0	289	289	0	0	0.0%
	Other[a]	289	1,495	1,783	4,907	10,364	0.2%
Onroad Gasoline (Exhaust, Brake Wear, & Tire Wear)		21	82	103	7,688	16,238	0.3%
Onroad Diesel (Exhaust, Brake Wear, & Tire Wear)		415	175	590	369,864	781,198	14.1%
Aircraft		6	26	32	0	0	0.0%
Railroad[b]		1,092	358	1,450	1,080,713	2,282,597	41.3%
Other Energy Use	Nonroad Gas	56	158	214	55,496	117,214	2.1%
	Nonroad Diesel	712	234	946	705,272	1,489,620	27.0%
	Other Combustion[c]	0	1	1	0	0	0.0%
Industrial Processes		206	1,329	1,535	8,762	18,505	0.3%
Agriculture[d]		12	361	374	0	0	0.0%
Waste Management	Landfills	0	0	0	0	0	0.0%
	Incineration	8	16	23	7,610	16,073	0.3%
	Open Burning	39	500	539	0	0	0.0%
	Other	0	1	1	0	0	0.0%
Wildfires/Prescribed Burns		1,746	17,127	18,873	0	0	0.0%
Miscellaneous[e]		99	1,617	1,716	0	0	0.0%
Total		**5,081**	**24,330**	**29,410**	**2,616,348**	**5,526,044**	**100%**

[a] Industrial wood combustion.
[b] Railroad includes Locomotives and Railroad Equipment Emissions.
[c] Other Combustion includes Motor Vehicle Fire, Structure Fire, and Aircraft/Rocket Engine Fire & Testing Emissions.
[d] Agriculture includes Agricultural Burning, Agriculture/Forestry and Agriculture, Food, & Kindred Spirits Emissions.
[e] Miscellaneous includes Paved/Unpaved Roads and Catastrophic/Accidental Release Emissions.

Appendix J. 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[118] were developed prior to the publication of the TAR. Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. This excerpt of the U.S. *Inventory* addresses in detail the differences between emission estimates using these two sets of GWPs. Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends.

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

What is Climate Change?

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

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

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

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_{max}
CFC-11	4,600	3,600
CFC-12	10,600	9,900
CFC-113	6,000	5,200
HCFC-22	1,700	1,700
HCFC-123	120	100
HCFC-124	620	590
HCFC-141b	700	570
HCFC-142b	2,400	2,300
$CHCl_3$	140	0
CCl_4	1,800	660
CH_3Br	5	(500)
Halon-1211	1,300	(3,600)
Halon-1301	6,900	(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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