WASHINGTON STATE DEPARTMENT OF ECOLOGY

STATE OF WASHINGTON
DEPARTMENT OF COMMUNITY, TRADE AND ECONOMIC DEVELOPMENT

Washington State

Greenhouse Gas Inventory and Reference Case Projections, 1990-2020

December 2007

CCS
CENTER FOR CLIMATE STRATEGIES

[This page intentionally left blank.]

Executive Summary

Washington's anthropogenic GHG emissions and sinks (carbon storage) are estimated for the period from 1990 to 2020.[1] Historical GHG emission estimates (1990 through 2005, or most recent historical year) are developed using a set of generally-accepted principles and guidelines for state GHG emission estimates, with adjustments for Washington-specific data and context, as appropriate. The initial reference case emission projection (2006-2020) is 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.

Relying on the State projections of population and employment growth, utilities' projections of electricity use, and input from Washington staff from CTED, Ecology and other departments, a simple reference case projection was developed for GHG emissions through 2020.

The reference case projection, by design, does not account for the significant policy actions required by Governor Gregoire's Washington Climate Change Challenge (Executive Order 07-02) or any of the recommendations from Washington's Climate Advisory Team (CAT). Therefore, the Reference Case projections in this report should be viewed as a "no recent policy" baseline, against which the benefits of policies, both those recently enacted and those to be recommended by the Climate Advisory Team (CAT), can be assessed.

Washington's Historical and Projected GHG Emissions

Overview

Table ES-1 provides a summary of historical (1990, 2000 and 2005) and projected (2010 and 2020) GHG emissions for Washington. Activities in Washington accounted for about 95 million metric tons (MMt) of *gross* carbon dioxide equivalent[2] (CO_2e) emissions in 2005. This is equal to about 1% of the total U.S. gross GHG emissions.[3] This table also shows if gross emissions are adjusted for estimated forestry and agriculture sequestration, the *net* emissions result may considerably lower (perhaps as low as 65 MMtCO2e in 2005). As discussed in Appendix H, the GHG emission estimates for forestry sinks are subject to a significant degree of uncertainty.

[1] The Center for Climate Strategies (CCS) prepared this report in collaboration with the Washington State Department of Ecology (Ecology) and the Washington Department of Community, Trade and Economic Development (CTED) for the Washington Climate Advisory Team (CAT). It relies heavily on past and ongoing emissions inventory work by CTED and Ecology. It contains some updates and adjustments to the figures presented in CTED's 2006 report, *Washington's Greenhouse Gas Emissions: Sources and Trends* (2006), as well as an emissions projection for the purposes of guiding the CAT process.

[2] This analysis includes the six gases included in the U.S. Greenhouse Gas Inventory: carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). Emissions of these GHGs are presented using a common metric, CO2 equivalence (CO2e), which indicates the relative contribution of each gas to global average radiative forcing on a Global Warming Potential (GWP) weighted basis. In order to be consistent with the US EPA National GHG inventory, the GWP values in this report are from the Second Assessment Report (SAR) of the Intergovernmental Panel on Climate Change (IPCC).

[3] Gross U.S. emissions in 2005 were 7,260 $MMtCO_2e$ (U.S. EPA, *U.S. Inventory of Greenhouse Gas Emissions and Sinks 1990-2005*).

Figure ES-1 shows the State's emissions per capita and per unit of economic output. On a per capita basis, Washington residents emit about 15 metric tons (Mt) of CO_2e annually. This is much lower than the national average of 25 MtCO_2e/yr. This is because of the state's abundance of hydroelectricity. Per capita emissions in Washington have varied between 15 and 18 MtCO2e since 1990, largely in the electric and industrial sectors. On the other hand, economic growth exceeded emissions growth throughout the 1990-2005 period (leading to declining GHG emissions per unit of state product). The trends in Washington's emissions per gross state product parallel those for the nation on average, in this time period.

As illustrated in Table ES-1 and figure ES-2, Washington's total GHG emissions have varied significantly between 1990 and 2005, with a general increase from 1990 to 2000 being followed by significant decreases in 2001 and 2002 then increases starting again in 2003 through 2005. The strong decreases reflect energy price swings and resulting impacts on the manufacturing sector in 2001 and 2002. Under the reference case projections, Washington's gross GHG emissions continue the growth of the last few years and are projected to climb to 122 MMtCO_2e per year by 2020, about 38% above 1990 levels.

The principal source of Washington's GHG emissions is transportation, accounting for 47% of total State gross GHG emissions in 2005. The next largest contributors to total gross GHG emissions are fossil fuel combustion in the residential, commercial, and industrial sectors (20%) and electricity consumption from these sectors (20%).

Electricity Consumption

As shown in Table ES-1, Washington's electricity emissions increased strongly between 1990 and 2000, followed by a decrease from 2000 levels by 2005. Much of the year to year variation is due to changes in hydro-electric generation, based on variation in local and regional water levels. Although the reference case includes projections for new wind plants, it also includes growth in generation from natural gas facilities. Overall emissions from electricity consumption are projected to grow by about 6 MMtCO_2e between 2005 and 2020.

Consumption-based Approach vs. Production-based Approach

It is important to note that Table ES-1 shows Washington electricity emissions on a consumption-based (or "load-based") approach, i.e. based on the emissions of electricity sources delivered to Washington consumers, regardless of where those electricity generation facilities are located.

Another way to present electricity emissions is on a production-basis, i.e. the emissions associated with generating facilities located in the state of Washington, regardless of where this electricity is delivered.

Both approaches have been used for state-level GHG emissions analysis, and both are relevant depending upon the policy approaches that might be taken to reduce electricity emissions. Therefore, this report presents electricity emissions from both production and consumption perspectives. The difference in approaches are illustrated in Figure ES-3 as calculated by CTED based on data for 2002-2005 and Appendix A provides information on how the consumption-based approach was derived for other years in the inventory and projections.

Transportation

While transportation makes up a larger fraction of Washington's emissions – again, in large part as a result of the state's abundant hydroelectricity -- on a per capita basis, Washington consumes about the same amount of gasoline per capita as the US average. Per capita diesel fuel consumption in Washington is slightly lower than the national average. As shown in Figure ES-4, emissions associated with transportation are projected to be the largest contributor to future emissions growth from 2005 to 2020. The figure shows that transportation growth could add just over 12 $MMtCO_2e$ to Washington's emissions by 2020.

Residential, Commercial and Industrial sectors

GHG emissions associated with energy consumption in residential, commercial, and industrial (RCI) sectors, including emissions from electricity consumption, are projected to increase through 2020. Growth in the residential, commercial and industrial sectors (including the electricity they consume) could add about 11 $MMtCO_2e$ from 2005 to 2020 (5 $MMtCO_2e$ from increased direct use of fuels and 6 $MMtCO_2e$ from the emissions associated with electricity sold to RCI sectors), see figure ES-4.

Agriculture

Agricultural activities such as manure management, fertilizer use, and livestock (enteric fermentation) result in methane and nitrous oxide emissions that account for 6% of State GHG emissions in 2005. These emissions are projected to decrease by about 0.6 $MMtCO_2e$.

Industrial Processes

Industrial process emissions (including methane released from natural gas transmission and coal mining) comprise about 4% of State GHG emissions today. Emissions of PFCs from aluminum productions decreased from almost 6 $MMtCO_2e$ in 1990 to less than 0.5 $MMtCO_2e$ currently. The use of hydrofluorocarbons (HFCs) as substitutes for ozone-depleting substances (ODS) such as chlorofluorocarbons and hydrochlorofluorocarbons[4], now accounts for a majority of process emissions, and are growing rapidly (GHG emissions from ODS substitutes are projected to more than double between now and 2020).

Waste Management

Emissions from solid waste and wastewater management account for less than 3% of Washington's emissions currently, and are projected to increase by just over 1 $MMtCO_2e$ from 2005 to 2020.

For more discussion of historic Washington State GHG emissions trends, and the factors underlying these trends, see *Washington's Greenhouse Gas Emissions: Sources and Trends* (2006).[5]

---

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

[5] *Washington's Greenhouse Gas Emissions: Sources and Trends*, by Stacey Waterman-Hoey and Greg Nothstein, WA State Dept. of Community, Trade & Economic Development, Energy Policy Division, dated December 2006

Carbon Sinks

Estimates of carbon sinks within Washington's forests and agricultural soils have also been included in this report. For forests, the current estimates are based on data from the U.S. Forest Service and indicate that about 29 $MMtCO_2e$ are sequestered annually in Washington forest biomass. As described in Appendix H however, there is a significant degree of uncertainty in the size of the forest sink in Washington. The estimates presented here are believed to be at the high end of the possible range of sequestration estimates. Agricultural soils are estimated to store an additional 1.4 $MMtCO_2e$ annually.

Black Carbon

Emissions of aerosols, such as "black carbon" from fossil fuel combustion, may have significant climate impacts through their effects on radiative forcing. However, there are, as yet, no widely-accepted methodologies for reflecting the impacts of aerosol emissions in terms of global warming potential (i.e. on a CO2e basis)[6]; while some aerosols have overall warming effects, others have cooling impacts.

Appendix I to this report provides some preliminary estimates of aerosol emissions on a CO_2e basis, based on analysis for the Western Regional Air Partnership (WRAP). Given these very large uncertainties, black carbon emissions are not incorporated in the overall GHG emissions totals presented in this report.

Data Gaps and Unresolved Questions

Several data gaps and key unresolved questions regarding methodology and assumptions remain, particularly for the reference case projections. Areas for further review and refinement include:

- Estimates of the generation resources ("fuel mix") used to deliver electricity to Washington consumers.
- Key emissions drivers (such as transportation fuel use growth rates) used to estimate Washington's future GHG emissions.

[6] The Intergovernmental Panel on Climate Change (IPCC) provides global warming potential (GWP) estimates for the gases

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

(Million Metric Tons CO2e)	1990	2000	2005	2010	2020
Electricity, Net Consumption-based	**16.9**	**23.3**	**18.9**	**20.2**	**24.9**
Coal	16.8	17.4	15.2	15.9	18.4
Natural Gas	0.1	5.3	3.6	4.2	6.3
Petroleum	0.0	0.6	0.0	0.1	0.2
Biomass and Waste (CH_4 and N_2O)	0.0	0.0	0.0	0.0	0.0
Residential/Commercial/Industrial (RCI)	**18.6**	**20.3**	**19.4**	**21.3**	**24.3**
Coal	0.6	0.3	0.2	0.3	0.3
Natural Gas	8.6	11.4	10.3	11.0	12.7
Oil	9.1	8.4	8.5	9.7	11.0
Wood (CH4 and N2O)	0.2	0.2	0.3	0.4	0.4
Transportation	**37.5**	**45.9**	**44.5**	**48.5**	**56.9**
Onroad Gasoline	20.4	24.5	24.8	26.2	29.1
Onroad Diesel	4.1	7.6	7.5	8.8	12.0
Marine Vessels	2.6	2.9	3.0	3.3	4.1
Jet Fuel and Aviation Gasoline	9.1	10.0	7.8	8.1	8.5
Rail	0.8	0.3	0.8	0.8	0.8
Natural Gas, LPG, other	0.6	0.6	0.7	1.3	2.5
Fossil Fuel Industry	**0.5**	**0.7**	**0.9**	**1.0**	**1.1**
Natural Gas Industry (CH4)	0.4	0.7	0.9	0.9	1.0
Coal Mining (CH4)	0.0	0.0	0.0	0.0	0.0
Industrial Processes	**7.0**	**6.6**	**3.3**	**4.2**	**6.2**
Cement Manufacture (CO2)	0.2	0.5	0.5	0.5	0.5
Aluminum Production (CO2, PFC)	5.9	3.9	0.4	0.4	0.3
Limestone and Dolomite Use (CO2)	0.0	0.0	0.0	0.0	0.0
Soda Ash (CO2)	0.1	0.1	0.1	0.1	0.1
ODS Substitutes (HFC, PFC, and SF6)	0.0	1.6	2.1	3.0	5.1
Semiconductor Manufacturing (HFC, PFC, and SF6)	0.0	0.1	0.0	0.0	0.0
Electric Power T & D (SF6)	0.8	0.4	0.3	0.2	0.1
Waste Management	**1.5**	**2.2**	**2.4**	**2.8**	**3.6**
Solid Waste Management	1.0	1.5	1.8	2.0	2.7
Wastewater Management	0.5	0.6	0.7	0.8	0.9
Agriculture	**6.4**	**6.4**	**5.4**	**5.1**	**4.8**
Enteric Fermentation	2.0	1.8	1.6	1.5	1.3
Manure Management	0.7	0.9	0.9	1.0	1.2
Agricultural Soils	3.7	3.8	2.8	2.6	2.2
Total Gross Emissions	**88.4**	**105.4**	**94.8**	**103.0**	**121.9**
increase relative to 1990		*19%*	*7%*	*17%*	*38%*
Forestry and Land Use	-28.6	-28.6	-28.6	-28.6	-28.6
Agricultural Soils	-1.4	-1.4	-1.4	-1.4	-1.4
Net Emissions (including sinks*)	**58.4**	**75.4**	**64.8**	**73.0**	**91.9**

[a] Totals may not equal exact sum of subtotals shown in this table due to independent rounding. n/a = not available, GHG emissions from solid waste and wastewater management are not yet available due to updates to the approach for estimating emissions for these activities.
[b] Residential, Commercial and Industrial sectors.

Figure ES-1. Historical Washington and U.S. GHG Emissions, Per Capita and Per Unit Gross Product, 1990-2005

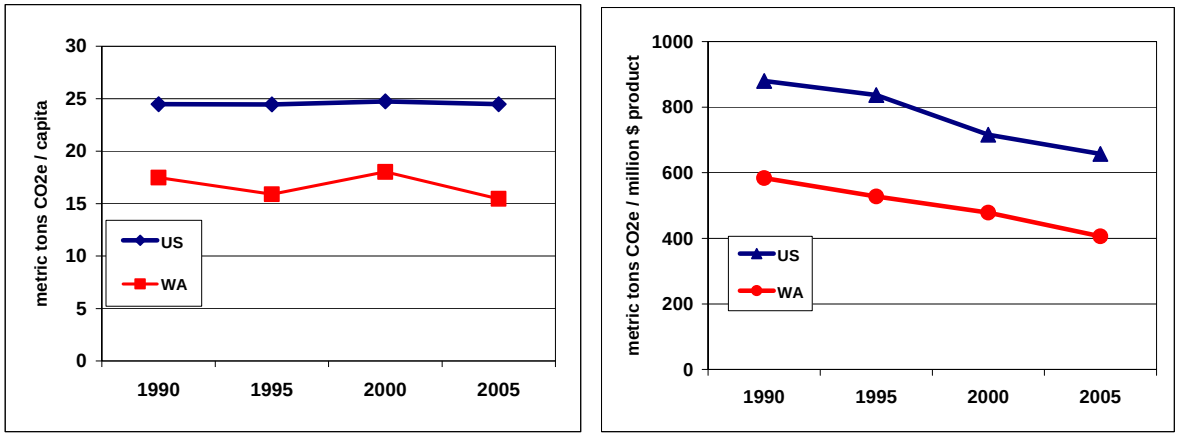


Figure ES-2. Washington Gross GHG Emissions by Sector, 1990-2020: Historical and Projected (consumption-based)

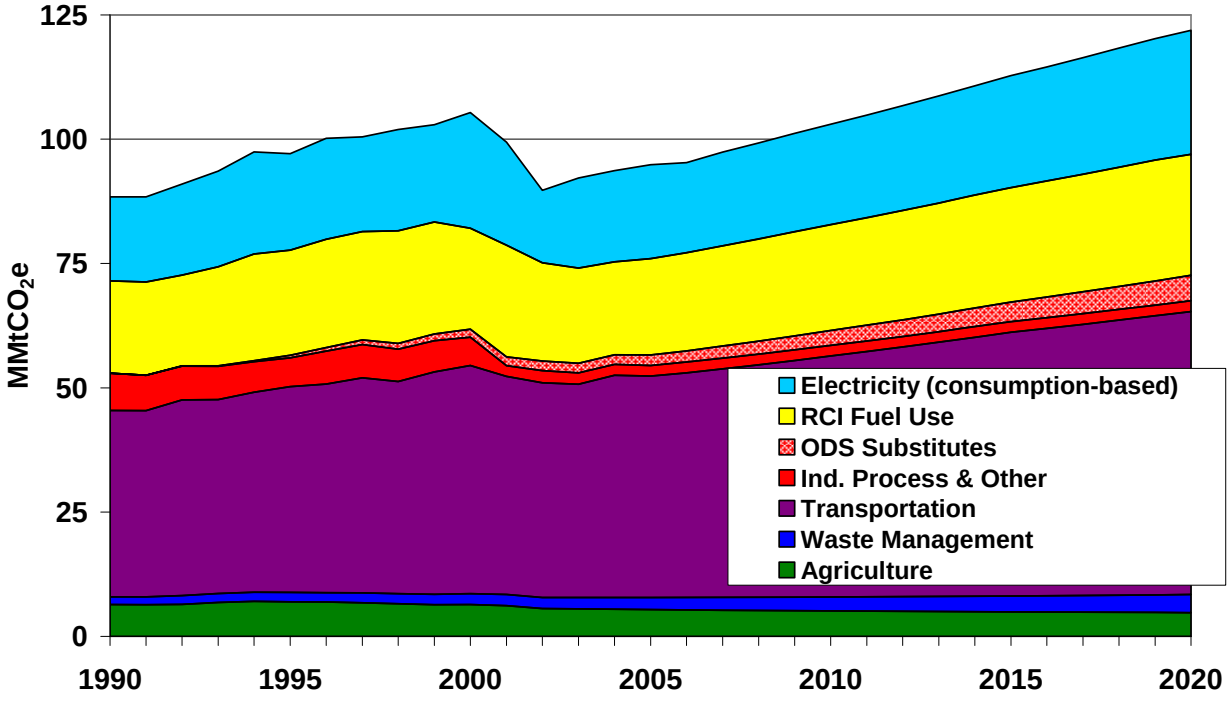
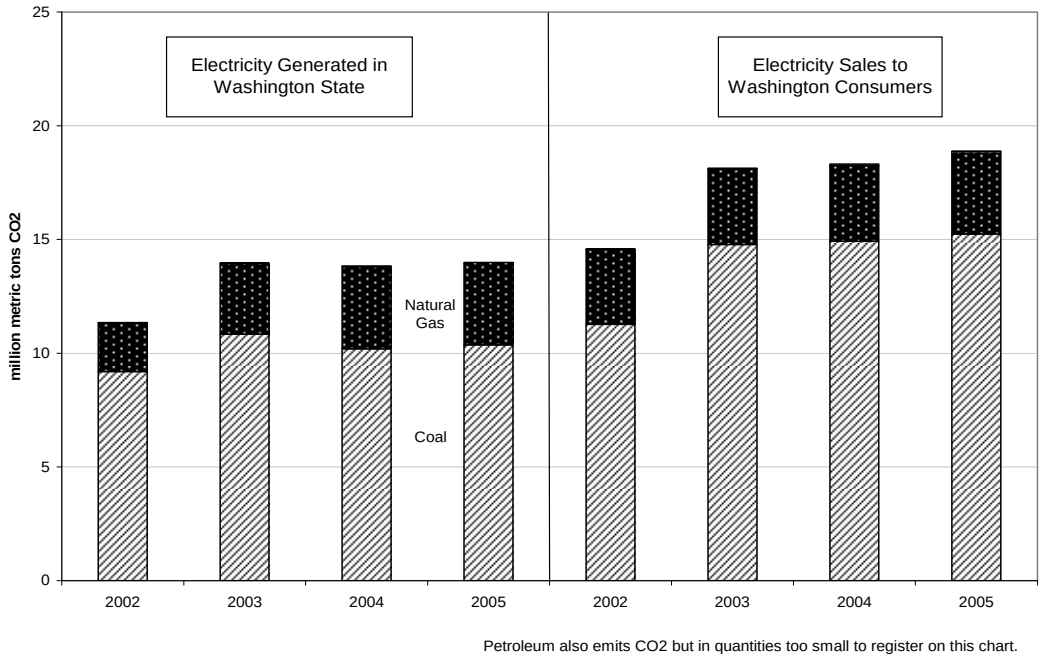


Figure ES-3. GHG Emissions from Washington Electric Sector 2002-2005, Production-based (Electricity Generated) and Consumption-based (Electricity Sales)



Source: CTED 2006

Figure ES-4. Sector Contributions to Emissions Growth in Washington, 1990-2020: Reference Case Projections

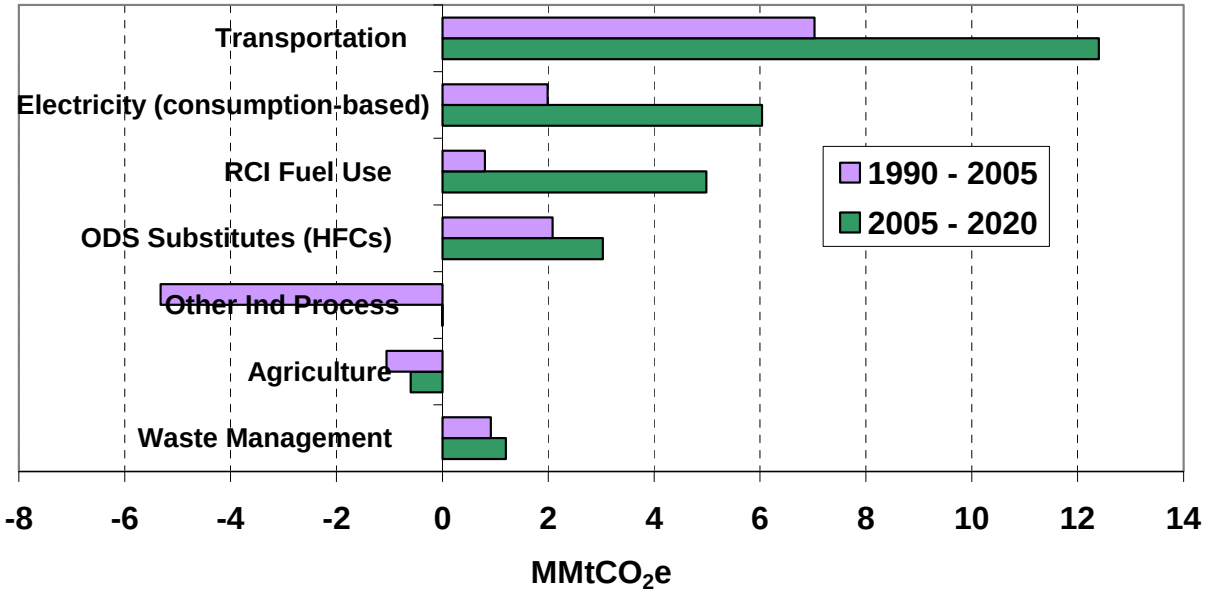


Table of Contents

Executive Summary 1
Washington's Historical and Projected GHG Emissions 1
Overview 1
Washington's GHG Contributions Per Capita ..... **Error! Bookmark not defined.**
Electricity Consumption 2
Transportation 3
Residential, Commercial and Industrial sectors 3
Agriculture 3
Industrial Processes 3
Waste Management 3
Carbon Sinks 4
Black Carbon 4
Data Gaps and Unresolved Questions 4
Table of Contents 1
Acronyms and Key Terms 4
Summary of Preliminary Findings 6
Introduction 6
Washington Greenhouse Gas Emissions: Sources and Trends 7
Historical Emissions 7
Overview 7
A Closer Look at Two of the Major Sources: Electricity and Transportation. 9
Emissions from Electricity Consumption 9
Emissions from Transportation 9
Reference Case Projections 10
Transportation 10
Residential, Commercial and Industrial, including electricity consumption 10
Agriculture 10
Industrial Processes 10
Key Uncertainties and Next Steps 13
Approach 13
General Methodology 13
General Principles and Guidelines 14
Appendix A. Electricity Use and Supply 1
Electricity Trade and Allocation of GHG Emissions 2
Electricity Generation – Washington's Power Plants 5
Electricity Consumption 7
Future Electricity Consumption 8
Future Electricity Generation 9
Summary of Assumptions and Reference Case Projections 11
Results 13
Consumption (Load) -based results 13
Production-based results 14
Summary of Results 16
Key Uncertainties 16

Appendix B. Residential, Commercial, and Industrial (RCI) Fossil Fuel Combustion 1
Overview 1
Data Sources and Approach 1
Results 3
Key Uncertainties 7
Appendix C. Transportation Energy Use 1
Overview 1
Inclusion of Maritime Transportation 1
Data Sources and Approach 1
On-road Vehicles 2
Aviation 5
Rail 5
Marine 5
Nonroad Engines 8
Results 9
Key Uncertainties 9
Appendix D. Industrial Processes 1
Overview 1
Data Sources and Approach 1
Results 3
Substitutes for Ozone-Depleting Substances (ODS) 4
Aluminum Production 4
Electricity Distribution 6
Semiconductor Manufacture 6
Clinker Production for Cement Manufacture 6
Limestone and Dolomite Consumption 6
Soda Ash Consumption 7
Key Uncertainties 7
Appendix E. Fugitive Emissions from Fossil Fuel Industries 1
Oil and Gas Production 1
Data Sources and Approach 1
Coal Production Emissions 3
Results 3
Key Uncertainties 4
Appendix F. Agriculture 1
Overview 1
Data Sources and Approach 2
Methane and Nitrous Oxide 2
Soil Carbon 3
Results 4
Key Uncertainties 6
Appendix G. Waste Management 1
Overview 1
Inventory and Reference Case Projections 1
Solid Waste Management 1
Wastewater Management 3

Results 4
Key Uncertainties 5
Appendix H. Forestry 1
Overview 1
Inventory and Reference Case Projections 1
Discussion 3
Forest Area Trends 3
Forest Carbon Density Trends 4
Interannual Variability 5
Wildfire and Non-CO2 Losses 5
Key Uncertainties 6
Appendix I. Inventory and Forecast for Black Carbon 1
Development of BC and OM Mass Emission Estimates 1
Development of CO_{2e} for BC+OM Emissions 2
Results and Discussion 3
Appendix J. Greenhouse Gases and Global Warming Potential 1
Values: Excerpts from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000 1
Introduction 1
What is Climate Change? 1
Greenhouse Gases 2
Water Vapor (H_2O) 3
Carbon Dioxide (CO2) 4
Methane (CH4) 4
Nitrous Oxide (N2O) 4
Ozone (O_3) 4
Halocarbons, Perfluorocarbons, and Sulfur Hexafluoride (SF_6). 5
Carbon Monoxide (CO) 5
Nitrogen Oxides (NO_x). 5
Nonmethane Volatile Organic Compounds (NMVOCs) 6
Aerosols 6
Global Warming Potentials 6
References 9

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

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_2 – Carbon Dioxide*

CO_2e – Carbon Dioxide Equivalent*

CRP – Federal Conservation Reserve Program

EC – Elemental Carbon

eGRID – U.S. EPA's Emissions & Generation Resource Integrated Database

EIA – U.S. DOE Energy Information Administration

EIIP – Emissions Inventory Improvement Project (US EPA)

FIA – Forest Inventory Analysis

GHG – Greenhouse Gases*

GSP – Gross State Product

GWh – Gigawatt-hour

GWP - Global Warming Potential*

HFCs – Hydrofluorocarbons*

HNO_3 – Nitric Acid

HWP – Harvested Wood Products

IPCC – Intergovernmental Panel on Climate Change*

kWh – Kilowatt-hour

LFGTE – Landfill Gas Collection System and Landfill-Gas-to-Energy

LMOP – Landfill Methane Outreach Program

LNG – Liquefied Natural Gas

LPG – Liquefied Petroleum Gas

Mg – Megagrams (equivalent to one metric ton)

Mt - Metric Ton (equivalent to 1.102 short tons)

MMt – Million Metric Tons

MPO – Metropolitan Planning Organization

MSW – Municipal Solid Waste

MW – Megawatt

N – Nitrogen

N_2O – Nitrous Oxide*

NO_2 – Nitrogen Dioxide*

NAICS – North American Industry Classification System

NASS – National Agricultural Statistics Service

NO_x – Nitrogen Oxides

NSCR – Non-selective Catalytic Reduction

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

SAR – Second Assessment Report

SCR- Selective Catalytic Reduction

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

TWh – Terawatt-hours

UNFCCC – United Nations Framework Convention on Climate Change

U.S. EPA – United States Environmental Protection Agency

U.S. 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*

WSDOT – Washington State Department of Transportation

WRAP – Western Regional Air Partnership

* - See Appendix J for more information

Summary of Preliminary Findings

Introduction

The Center for Climate Strategies (CCS) prepared this report for the Washington Department of Ecology (Ecology) under an agreement with the Western Governors' Association, and with input from the Departments of Ecology and Community, Trade and Economic Development. This report presents initial estimates of base year and projected Washington anthropogenic greenhouse gas (GHG) emissions and sinks 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 Washington, and, thereby, to inform future analysis and design of GHG mitigation strategies.

Historical GHG emissions estimates (1990 through 2005)[7] were developed using a set of generally accepted principles and guidelines for state GHG emissions inventories, as described in the Approach section below, relying to the extent possible on Washington-specific data and inputs. The initial reference case projections (2006-2020) are based on a set of 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 types of gases included in the U.S. Greenhouse Gas Inventory:

1. Carbon dioxide (CO_2),
2. Methane (CH_4),
3. Nitrous oxide (N_2O),
4. Hydrofluorocarbons (HFCs),
5. Perfluorocarbons (PFCs), and
6. 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. The final appendix to this report provides a more complete discussion of GHGs and GWPs. Emissions of black carbon 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 emission estimates reflect the *GHG emissions associated with the electricity sources used to meet Washington'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.* For many years, Washington power plants have tended to produce more electricity than is consumed in the State; emissions associated with exported electricity are excluded from the consumption-based emissions. This report covers both methods

[7] The last year of available historical data varies by sector; ranging from 2000 to 2005.

of accounting for emissions, but for consistency, all total results are reported as *consumption-based.*

Washington Greenhouse Gas Emissions: Sources and Trends

Table 1 provides a summary of GHG emissions estimated for Washington by sector for the years 1990, 2000, 2005, 2010, and 2020. 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 for each.

This report is divided into the following sections:

1. Historical emissions (1990 through 2005).
2. Forecasted reference-case projection-year emissions (2006 through 2020).
3. Key uncertainties and next steps.
4. General methodology, principles, and guidelines used to prepare 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 emissions for Washington.
- Appendix J provides background information on GHGs and climate-forcing aerosols.

Historical Emissions

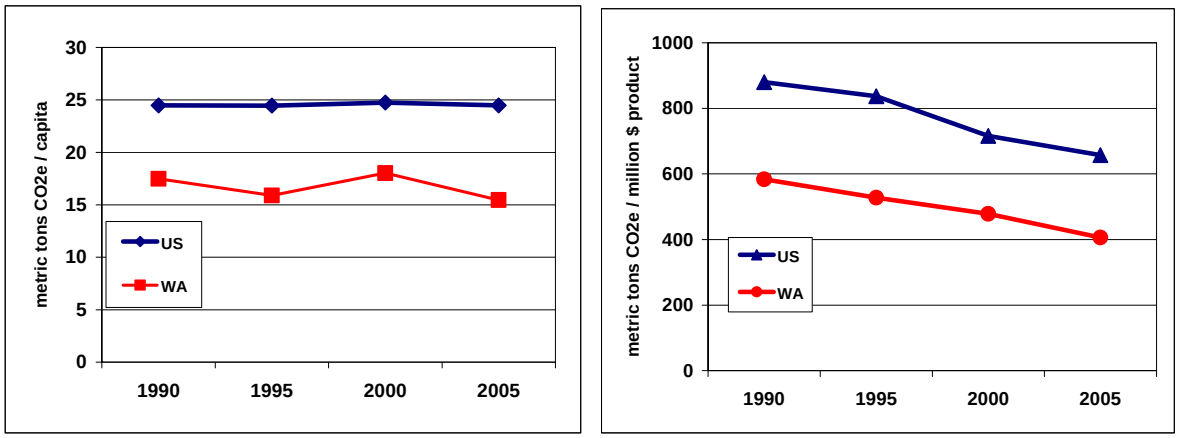
Overview

Our analyses suggest that in 2005, activities in Washington accounted for approximately 95 million metric tons (MMt) of *gross*[8] CO_2e emissions in 2005, an amount equal to 1% of total U.S. gross GHG emissions.[9] Washington's gross GHG emissions in 2005 were about 7% greater than emissions in 1990, following a 10% decrease from 2000 to 2005.

On a per capita basis, Washington emitted about 15 metric tons (Mt) of CO_2e per person in 2005, lower than the national average of 25 MtCO_2e/yr. Figure 1 illustrates the State's emissions per capita and per unit of economic output. Per capita emissions in Washington have varied between 15 and 18 MtCO2e per capita since 1990, largely in the electric and industrial sector. On the other hand, economic growth exceeded emissions growth throughout the 1990-2005 period (leading to declining GHG emissions per unit of state product). The trends in Washington's emissions per gross state product parallel those for the nation on average, in this time period.

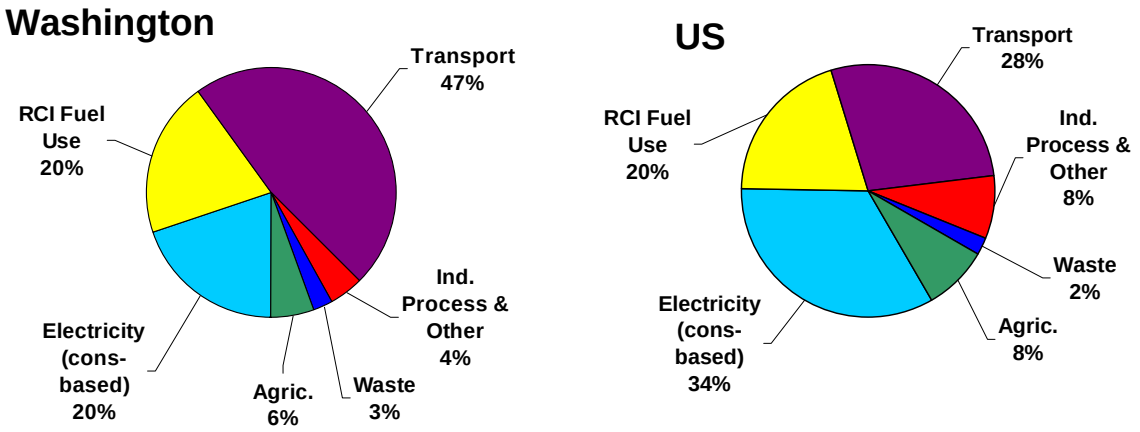
[8] Excluding GHG emissions removed due to forestry and other land uses and excluding GHG emissions associated with exported electricity.
[9] GHG emissions from solid waste and wastewater management are excluded from totals due to pending updates to the approach for estimating emissions for these activities.

Figure 1. Historical Washington and U.S. GHG Emissions, Per Capita and Per Unit Gross Product, 1990-2005



Electricity use, transportation and residential/commercial/industrial (RCI) fossil fuel combustion are the State's principal GHG emissions sources. A comparison of Washington and U.S. emissions for 2005 is shown in Figure 2 below, which shows that in Washington a much larger fraction of the GHG emissions are due to transportation activities. The large amount of hydro-electric generation in the State leads to lower contribution of the electric sector to total emissions, compared with the national average.

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



Forestry and agricultural soils in Washington are estimated to result in an annual net sink of almost 30 $MMtCO_2e$ in 2005.

The 1990-2004 historical emission estimates are comparable to estimates previously prepared by CTED.[10] The main difference is the use of consumption-based emissions for the electric sector.

[10] *Washington's Greenhouse Gas Emissions: Sources and Trends*, Stacey Waterman-Hoey and Greg Nothstein, WA State Dept. of Community, Trade & Economic Development, Energy Policy Division, December 2006.

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

Emissions from Electricity Consumption

As shown in Table 1, electricity use accounted for about 20% of Washington's gross GHG emissions in 2005 (19 $MMtCO_2e$), which was lower than the national share of emissions from electricity production (34%).[11] In total (across the residential, commercial and industrial sectors), Washington has a higher per capita use of electricity than the U.S. as a whole (13,000 kWh per person per year compared to 12,000 kWh/person-yr nationally). However, hydro-electric generation accounts for a large fraction of the electricity delivered to Washington's consumers. With no GHG emissions associated with this electricity source, Washington emits relatively low rates of GHGs per unit of electricity sold.

Consumption-based Approach vs. Production-based Approach

It is important to note that these preliminary electricity emissions estimates reflect the *GHG emissions associated with the electricity sources used to meet Washington demands,* corresponding to a *consumption-based* approach to emissions accounting (see Section 2). Another way to look at electricity emissions is to consider the *GHG emissions produced by electricity generation facilities in the State.* GHG emissions from Washington's electricity plants are estimated at about 14 $MMtCO_2e$ in 2005. The difference between the consumption-based and production-based emissions reflects, in part, that Washington imports more electricity from fossil fuel-based plants than it exports.

While GHG emissions associated with both electricity production and consumption have been estimated in this report, unless otherwise indicated, tables, figures, and totals in this report reflect electricity consumption-based emissions. The consumption-based approach can better reflect the emissions (and emissions reductions) associated with activities occurring in the State, particularly with respect to electricity use (and efficiency improvements), and is particularly useful for policy-making. 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.)

Emissions from Transportation

While transportation makes up a larger fraction of Washington's emissions – again, because of the state's abundant hydroelectricity – on a per capita basis, Washington consumes about the same amount of gasoline as the US average. Per capita diesel fuel consumption in Washington is slightly lower than the national average. GHG emissions from transportation fuel use have risen steadily since 1990 at an average rate of slightly over 1% annually. Gasoline-powered vehicles accounted for about 56% of transportation GHG emissions in 2005. On-road diesel vehicles accounted for 17% of emissions and air travel for another 17%. Marine, locomotives, and other sources [natural gas and liquefied petroleum gas (LPG) vehicles and lubricants] accounted for

---

http://www.cted.wa.gov/DesktopModules/CTEDPublications/CTEDPublicationsView.aspx?tabID=0&ItemID=4084&MId=863&wversion=Staging

[11] Unlike for Washington, for the U.S. as a whole, there is relatively little difference between the emissions from electricity use and emissions from electricity production, as the U.S. imports only about 1% of its electricity, and exports far less.

the remaining 10% of transportation emissions. As the result of Washington's population and economic expansion and an increase in total vehicle miles traveled during the 1990s, on-road gasoline use grew by 23% between 1990 and 2005. Meanwhile, on-road diesel use increased by 98% during this period, suggesting an even more rapid growth in freight movement within the State. Aviation fuel use declined from 1990-2005.

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 ES-1, under the reference case projections, Washington gross GHG emissions continue to grow steadily, climbing to 122 $MMTCO_2e$ by 2020, about 38% above 1990 levels.

Transportation

As shown in Figures 3 and 4, emissions associated with transportation are projected to be the largest contributor to future emissions growth from 2005 to 2020. The figure shows that transportation growth could add over 12 $MMtCO_2e$ to Washington's emissions by 2020.

Residential, Commercial and Industrial, including electricity consumption

Growth in energy consumption in the residential, commercial and industrial sectors could add about 5 MMtCO2e from increased direct use of fuels and 6 MMtCO2e from the emissions associated with electricity sold to RCI sectors, see figure 4.

Agriculture

Agricultural activities such as manure management, fertilizer use, and livestock (enteric fermentation) result in methane and nitrous oxide emissions are projected to decrease by about 0.6 $MMtCO_2e$.

Industrial Processes

Industrial process emissions (including methane released from natural gas transmission and coal mining) are projected to grow by 3 $MMtCO_2e$. Most of the growth is due to the use of hydrofluorocarbons (HFCs) as substitutes for ozone-depleting substances (ODS) such as chlorofluorocarbons and hydrochlorofluorocarbons.[12] GHG emissions from ODS substitutes are projected to more than double between now and 2020. Emissions from solid waste and wastewater management account for less than 3% of Washington's emissions currently, and are projected to increase by just over 1 MMTCO2e from 2005 to 2020.

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

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

(Million Metric Tons CO2e)	1990	2000	2005	2010	2020
Electricity, Net Consumption-based	**16.9**	**23.3**	**18.9**	**20.2**	**24.9**
Coal	16.8	17.4	15.2	15.9	18.4
Natural Gas	0.1	5.3	3.6	4.2	6.3
Petroleum	0.0	0.6	0.0	0.1	0.2
Biomass and Waste (CH_4 and N_2O)	0.0	0.0	0.0	0.0	0.0
Residential/Commercial/Industrial (RCI)	**18.6**	**20.3**	**19.4**	**21.3**	**24.3**
Coal	0.6	0.3	0.2	0.3	0.3
Natural Gas	8.6	11.4	10.3	11.0	12.7
Oil	9.1	8.4	8.5	9.7	11.0
Wood (CH4 and N2O)	0.2	0.2	0.3	0.4	0.4
Transportation	**37.5**	**45.9**	**44.5**	**48.5**	**56.9**
On-road Gasoline	20.4	24.5	24.8	26.2	29.1
On-road Diesel	4.1	7.6	7.5	8.8	12.0
Marine Vessels	2.6	2.9	3.0	3.3	4.1
Jet Fuel and Aviation Gasoline	9.1	10.0	7.8	8.1	8.5
Rail	0.8	0.3	0.8	0.8	0.8
Natural Gas, LPG, other	0.6	0.6	0.7	1.3	2.5
Fossil Fuel Industry	**0.5**	**0.7**	**0.9**	**1.0**	**1.1**
Natural Gas Industry (CH4)	0.4	0.7	0.9	0.9	1.0
Coal Mining (CH4)	0.0	0.0	0.0	0.0	0.0
Industrial Processes	**7.0**	**6.6**	**3.3**	**4.2**	**6.2**
Cement Manufacture (CO2)	0.2	0.5	0.5	0.5	0.5
Aluminum Production (CO2, PFC)	5.9	3.9	0.4	0.4	0.3
Limestone and Dolomite Use (CO2)	0.0	0.0	0.0	0.0	0.0
Soda Ash (CO2)	0.1	0.1	0.1	0.1	0.1
ODS Substitutes (HFC, PFC, and SF6)	0.0	1.6	2.1	3.0	5.1
Semiconductor Manufacturing (HFC, PFC, and SF6)	0.0	0.1	0.0	0.0	0.0
Electric Power T & D (SF6)	0.8	0.4	0.3	0.2	0.1
Waste Management	**1.5**	**2.2**	**2.4**	**2.8**	**3.6**
Solid Waste Management	1.0	1.5	1.8	2.0	2.7
Wastewater Management	0.5	0.6	0.7	0.8	0.9
Agriculture	**6.4**	**6.4**	**5.4**	**5.1**	**4.8**
Enteric Fermentation	2.0	1.8	1.6	1.5	1.3
Manure Management	0.7	0.9	0.9	1.0	1.2
Agricultural Soils	3.7	3.8	2.8	2.6	2.2
Total Gross Emissions	**88.4**	**105.4**	**94.8**	**103.0**	**121.9**
increase relative to 1990		*19%*	*7%*	*17%*	*38%*
Forestry and Land Use	-28.6	-28.6	-28.6	-28.6	-28.6
Agricultural Soils	-1.4	-1.4	-1.4	-1.4	-1.4
Net Emissions (including sinks*)	**58.4**	**75.4**	**64.8**	**73.0**	**91.9**

[a] Totals may not equal exact sum of subtotals shown in this table due to independent rounding. n/a = not available, , GHG emissions from solid waste and wastewater management are not yet available due to updates to the approach for estimating emissions for these activities.
[b] Residential, Commercial and Industrial sectors.

Figure 3. Washington Gross GHG Emissions by Sector, 1990-2020: Historical and Projected (consumption-based)

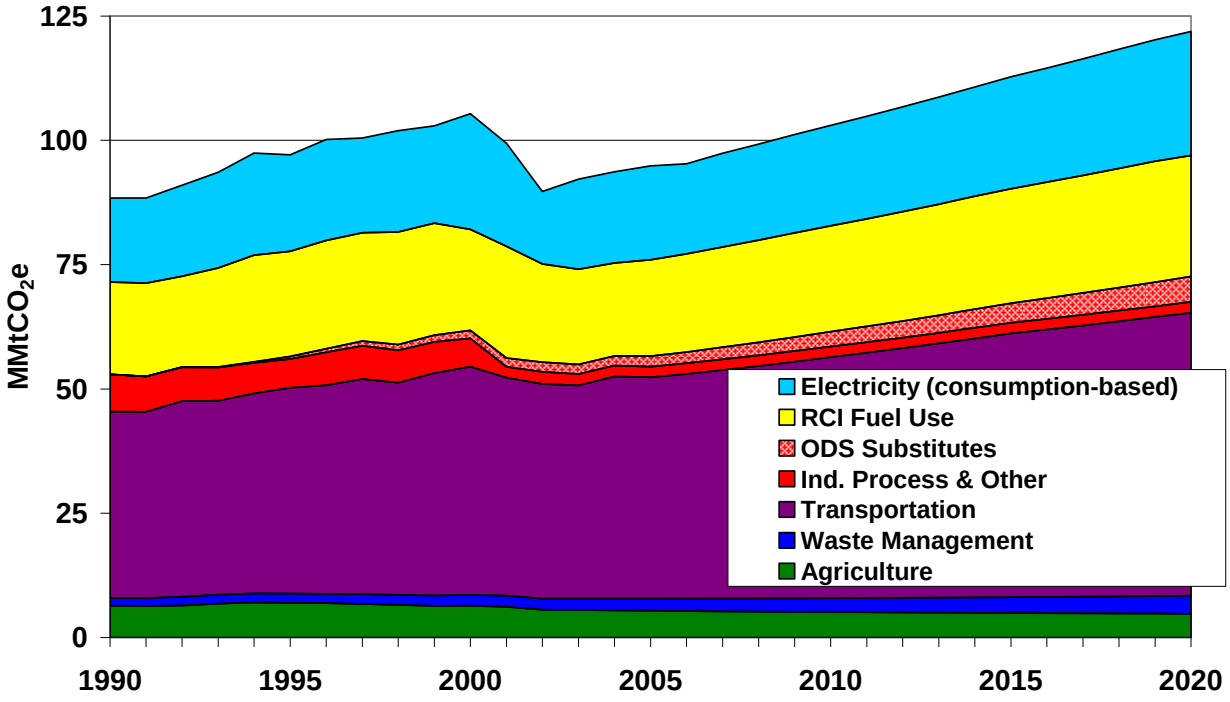
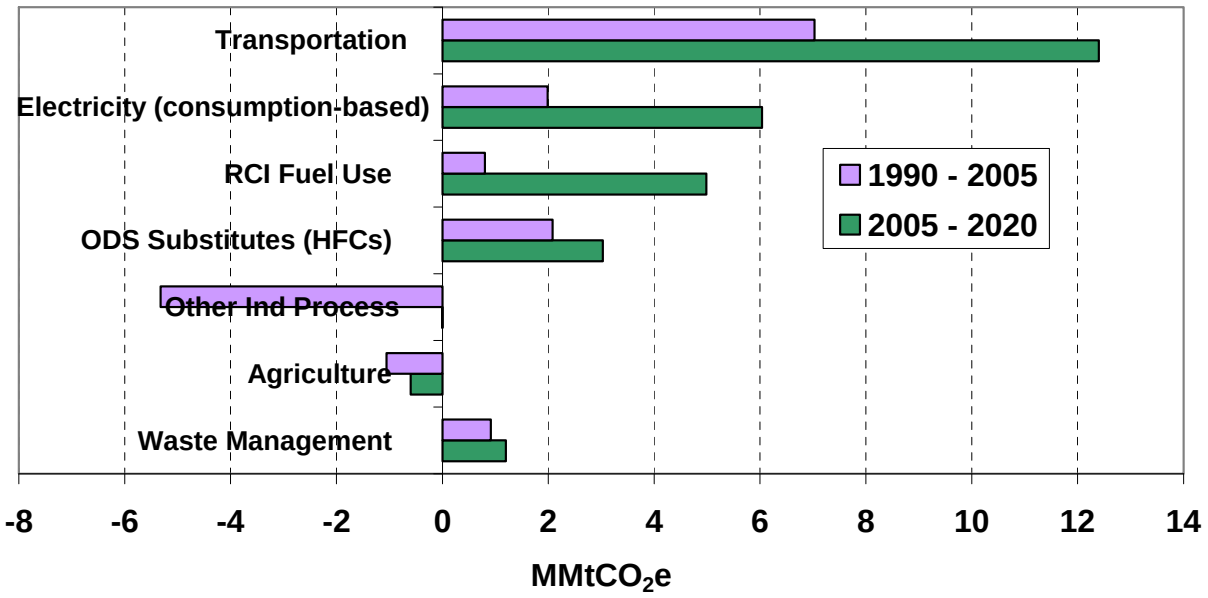


Figure 4. Sector Contributions to Emissions Growth in Washington, 1990-2020: Reference Case Projections



Key Uncertainties and Next Steps

Some data gaps exist in this analysis, particularly for the reference case projections. Key refinements include review and revision of key emissions drivers (such as transportation fuel use growth rates) that will be major determinants of Washington's future GHG emissions. 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. Other refinements include improved estimates of GHG emissions associated with electricity consumption. Finally, uncertainty remains regarding the estimates for historic GHG sinks from forestry, and projections for these emissions will greatly affect the net GHG emissions attributed to Washington. We expect that Washington's ongoing climate change action planning process will shed light on these issues.

Table 3. Key Annual Growth Rates for Washington, Historical and Projected

Key Parameter	1990-2005	2005-2020	Sources
Population	1.7%	1.5%	The State of Washington, Office of Financial Management
Employment Goods Services	 0.8% 2.1%	 1.1% 0.9%	Washington State Employment Security Department
Electricity Sales	-0.6%	1.3%	EIA data for 1990-2005, Projections based on information from Northwest Power and Conservation Council and Utility plans (see Appendix A)
Vehicle Miles Traveled	1.9%	2.0%	Washington State Department of Transportation

* Population and employment projections for Washington were used together with US DOE's Annual Energy Outlook 2006 projections of changes in fuel use on a per capita and per employee, as relevant for each sector. For instance, growth in Washington's residential natural gas use is calculated as the Washington population growth times the change in per capita natural gas use for the Mountain region.

Approach

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

General Methodology

CCS prepared this analysis in close consultation with Washington agencies, in particular, with the CTED and Ecology 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 forecasts are lacking, we use straightforward spreadsheet analysis and linear 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 U.S. EPA in its national GHG emissions inventory[13] and its guidelines for States.[14] These inventory guidelines were developed based on the guidelines from the Intergovernmental Panel on Climate Change, the international organization responsible for developing coordinated methods for national GHG inventories.[15] The inventory methods provide flexibility to account for local conditions. The key sources of activity and projection data are shown in Table 4.

Table 4 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 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[16], 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 Washington. It covers all six GHGs covered by U.S. and other national inventories:

[13] U.S. EPA, Feb 2005. *Draft Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2003.* http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2005.html.
[14] http://yosemite.epa.gov/oar/globalwarming.nsf/content/EmissionsStateInventoryGuidance.html.
[15] http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.
[16] "Reference case" refers to a projection of the current or "base year" inventory to one or more future years under business-as-usual forecast conditions (for example, existing control programs and economic growth).

Source	Information provided	Use of Information in this Analysis
Washington's Greenhouse Gas Emissions: Sources and Trends[17]	GHG emissions from energy consumption (including electric sector) and industrial processes for 1990-2004.	GHG emissions from the Washington state inventory were used directly in this analysis
Washington Fuel Mix Disclosure Data	Mix of resources used to provide electricity for Washington consumers http://www.cted.wa.gov/site/539/default.aspx	Estimates of GHG emissions from electricity consumption for 2000, 2001, 2002 and 2006.
U.S. 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 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.
U.S. DOE Energy Information Administration (EIA) State Energy Data (SED)	EIA SED source provides energy use data in each State, annually to 2004 or in some cases 2005).	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 the EIA website for years after 2001. Emission factors from US EPA SGIT are used to calculate energy-related emissions.
U.S. DOE Energy Information Administration Annual Energy Outlook 2006 (AEO2006)	EIA AEO2006 projects energy supply and demand for the U.S. from 2005 to 2030. Energy consumption is estimated on a regional basis. Washington is included in the Pacific Census region (AK, CA, HI, OR, WA)	EIA AEO2006 is used to project changes in per capita (residential) and per employee (commercial/industrial) energy consumption
Office of Pipeline Security (OPS), Distribution and Transmission Annuals	Natural gas transmission and distribution pipeline mileage.	Pipeline mileage from OPS used with SGIT to estimate natural gas transmission and distribution emissions.
U.S. 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).
U.S. Forest Service	Data on forest carbon stocks for multiple years.	Data are used to calculate carbon dioxide 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

[17] Waterman-Hoey and Nothstein, Department of Community, Trade and Economic Development. December 2006

- CO_2, CH_4, N_2O, SF_6, HFCs, and PFCs and black carbon. 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 Significant Emissions Sources:** In general, activities with relatively small emissions levels may not be reported with the same level of detail as other activities.

- **Priority of Existing State and Local Data Sources:** In gathering data and in cases where data sources 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.

- **Use of Consumption-Based Emissions Estimates:** To the extent possible, we estimated emissions that are caused by activities that occur in Washington. For example, we reported emissions associated with the electricity consumed in Washington. 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, as well as the emissions due to fuels combusted at electricity plants in the State, the emissions related to electricity *consumed* in Washington. This entails accounting for the electricity sources used by Washington utilities to meet consumer demands. CTED has collected fuel mix data from the utilities for 2002 to 2005 and a simplified approach was used to estimate historic and future consumption-based emissions.

If further refinement of this analysis could include estimating other sectors emissions on a consumption basis, such as accounting for emissions from combustion of transportation fuel used in Washington, but purchased out-of-state. In some cases this can require venturing into the relatively complex terrain of life-cycle analysis. In general, a consumption-based approach is recommended 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) Fossil Fuel Combustion;
- Appendix C. Transportation Energy Use;
- Appendix D. Industrial Processes;
- Appendix E. Fugitive Emissions from Fossil Fuel Industries;
- Appendix F. Agriculture;
- Appendix G. Waste Management; and
- Appendix H. Forestry.
- Appendix I. Black carbon emissions
- Appendix J. Additional background information from the U.S. EPA on greenhouse gases and global warming potential values.

Appendix A. Electricity Use and Supply

Washington's electricity load is met through facilities both in-state and out-of-state. Hydro-electric generation meets the majority of the load, accounting for over 65% of the electricity provided for the state. Coal, natural gas, and oil provide another 25% to 27% with nuclear accounting for approximately 5%. Renewable generation – biomass, wind, landfill gas, and geothermal – provide the remainder of Washington's electricity needs and their contribution is expected to grow in the future.

The mix of electricity generated in Washington is similar to the mix of electricity supplied to the State's customers. Hydro-electric generation dominates even more, accounting for over 70% of electricity generation. The Centralia coal plant accounts for another 10% of generation, and about 80% of the state's GHG emissions from power production. Most of the remaining generation, and the primary source of recent growth in capacity in the State, is natural gas and wind power. Hydropower has largely reached its maximum potential in Washington; no large new projects are expected to be built in the future, though increased generation from existing facilities is possible.

While the operation of hydro facilities releases no GHG emissions, seasonal and annual variations in hydro availability can indirectly affect the operation and thus emissions from other, fossil-fueled generation. The historical variation in hydro-electricity production largely explains the wide swings in emissions from the electric sector (see charts below), and future availability of hydro-electricity could thus have a considerable effect on emissions as well.

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 Washington to meet electricity needs in other states, and vice-versa (GHG emissions from electricity generated in other states to meet Washington electricity demand). 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 many discussions on Washington's climate change strategies emphasize the consumption (load-based) approach, and because the state's inventory and emissions goals are based on this perspective, this section first examines GHG emissions from this perspective. It then considers GHG emission estimates from the production-basis perspective, which is how national inventories are compiled and is germane to some climate policy options, such as a generation-based cap-and-trade system. .

This appendix assesses Washington's electricity sector in terms of consumption and production emissions, and describes the assumptions used to develop the reference case projections. As noted previously, the Reference Case should be viewed as a "no recent policy" baseline, against which the benefits of policies, both those recently enacted and those to be recommended by the CAT can be assessed. In particular, the reference case excludes the renewable energy and energy efficiency requirements under the 2006 Energy Independence Act (Initiative 937). The appendix concludes with a summary of key assumptions and results.

Electricity Trade and Allocation of GHG Emissions

Washington 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.

In 2006, 66 entities were involved in providing electricity to Washington customers. The State's three investor-owned utilities serve approximately 45% of the customers, and provide 36% of the electricity sales. The State's 18 electric cooperatives serve 5% of the customers and account for 4% of sales. One federal and 40 public utilities account for the remaining 50% of customers and almost 60% of sales. The top 5 providers of retail electricity in the State are reported in Table A1.

Table A1. Retail Electricity Providers in Washington (2006)

Entity	Ownership Type	2006 GWh
Puget Sound Energy Inc	Investor-Owned	21,092
Seattle City of	Public	9,455
PUD No 1 of Snohomish County	Public	6,483
Avista Corporation	Investor-Owned	5,411
Tacoma City of	Public	4,732
Total Sales, Top Five Providers		47,173
Total, All Washington		**85,033**

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 Washington 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 Washington and other Western states, such as California and

Oregon.[18] 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. To address this issue, Washington House Bill 2565 (Fuel Mix Disclosure Law) requires retail electricity suppliers in Washington to provide a disclosure label to their retail customers, at least semi-annually. This information has been collected and reported by the Department of Community, Trade, and Economic Development (CTED).

The report, *Washington's Greenhouse Gas Emissions: Sources and Trends*, (CTED December 2006)[19] provides the following analysis:

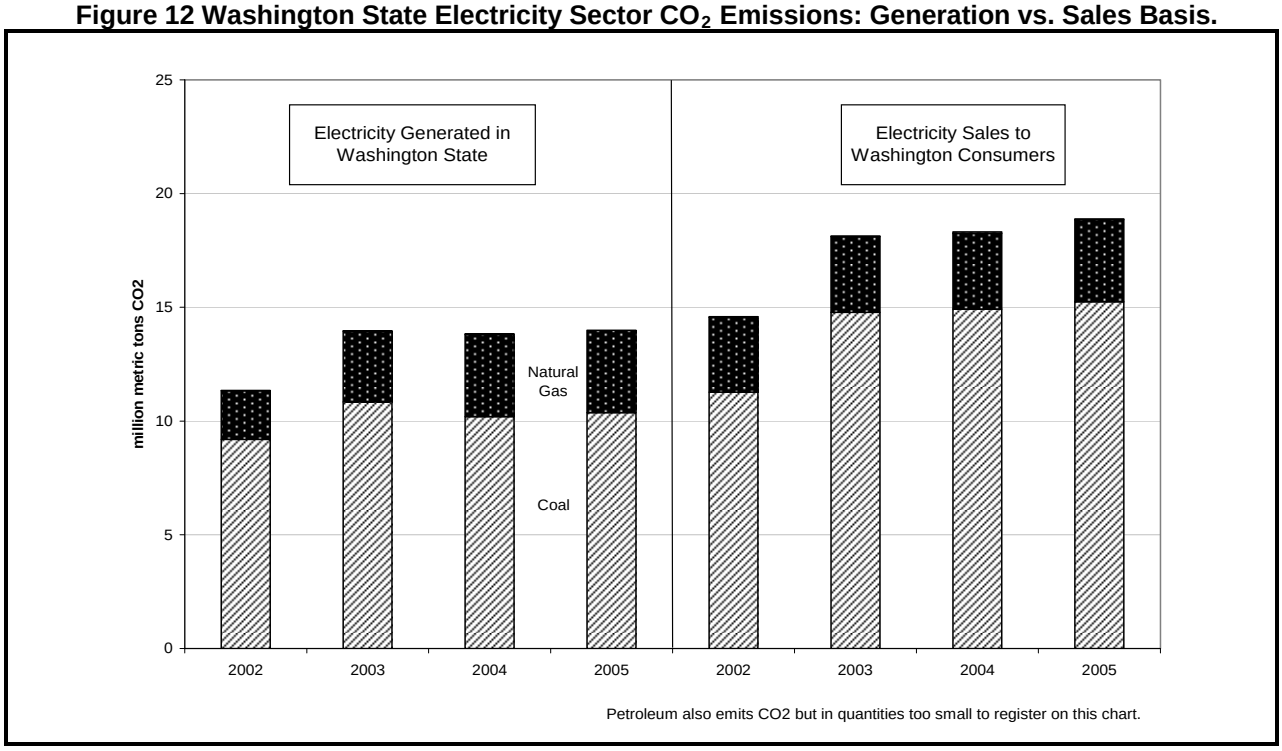
Utilities can purchase or generate electricity from sources outside the state to serve their customers. Much of this out-of-state power is from fossil-based power plants, which impacts the emissions for Washington State associated with electricity consumption. Additionally, our hydro system is highly seasonal with much of the power being generated in the spring and early summer when the snow melts. Annually, Washington State is a net exporter of electricity but during the winter season, we rely on imports to meet our needs. Our excess electricity in the spring and summer is traded out of state in exchange for electricity that arrives when we need it most. However, this imported power is generally fossil and nuclear-based.

Beginning in 2000, Washington State began tracking the electricity sold to Washington consumers as a result the Fuel Mix Disclosure law. As shown in Figure 12 below, the data collected through this process allows us to compare the emissions from our electricity generation in Washington to the electricity generation that serves Washington consumers. It is apparent that some utilities in our state rely heavily on out-of-state fossil-based electricity generation to serve their customers and to balance seasonal electricity needs. Figure 12 reveals that CO_2 emissions associated with electric consumption are actually 30 percent higher than estimated using generation based data. Other states that have developed GHG inventories are also beginning to differentiate between CO_2 associated with in-state electricity generation and load based electricity sales.

[18] 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).

[19] Waterman-Hoey and Nothstein, Department of Community, Trade and Economic Development. December 2006

Figure 12 Washington State Electricity Sector CO_2 Emissions: Generation vs. Sales Basis.



The challenge for this analysis is extending the approach using the Fuel Mix Disclosure data to historic and future years, since the GHG emissions data are currently only available for 2002 through 2006. We applied the following simple approach:

- For 1990, CTED and Ecology recognized the need to estimate load-based GHG emissions for Washington electricity consumption. Staff reviewed public data on electricity sales and power plant ownership shares for each utility in the state. This information was combined with data on electricity generation and GHG emissions from power plants in the Northwest Power Pool to approximate the emissions associated with Washington's electricity consumption.[20] The value estimated by CTED/Ecology is used here.
- For historic years, 1991 – 1999, we interpolated the change in GHG emissions using total change between the estimated values for 1990 and 2000, with annual growth based on changes in production-based GHG emissions.
- For 2000-2002, GHG emissions were estimated based on electricity purchases from the Fuel Mix Disclosure data for these years and emission rates from the 2003 data.
- For future years, we assumed that the mix of resources supplying new electricity demand to Washington consumers would be similar to new electricity production in the entire Northwest Power Council region, as projected by the Northwest Power and

[20] http://www.ecy.wa.gov/climatechange/docs/Updated1990GHGreport20071119.pdf

Conservation Council.[21] Based on this approach, new electricity demand in Washington for the period 2007-2020 is assumed to be supplied by a mix of electricity that is 22% coal, 46% natural gas, 26% wind and 6% biomass/geothermal/hydro. We do not estimate that location of this electricity generation; new coal could be provided by plants located outside of Washington.

The results section for this appendix reports both production-based and consumption-based GHG emissions for Washington for 1990 to 2020.

Electricity Generation – Washington's Power Plants

The following section provides information on GHG emissions and other activity associated with power plants located in Washington. In other words, these are production-based emissions. While Washington is using a consumption-basis as the primary accounting approach for developing GHG emission targets and other key policies, the State and other states in the region are also tracking production-based emissions.

As displayed in Figure A1, hydro electric plants were used to generate the majority (over 70%) of Washington's electricity in 2004, with natural gas, coal, biomass, and wind accounting for the remainder. Since hydro, biomass and wind generate no or very low GHG emissions and coal generation yields higher GHG emissions per MWh generated than natural gas, coal accounts for 74% of the GHG emissions from power plants in Washington.

We considered two sources of data in developing the historic inventory of GHG emissions from Washington power plants:

- EIA State Energy Data (SED), which must be multiplied by GHG emission factors for each type of fuel consumed.
- EPA data on CO_2 emissions by power plant.

To calculate total GHG emissions from electricity production in Washington, 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.[22] The GHG emissions from plants not listed individually in Table A2 is

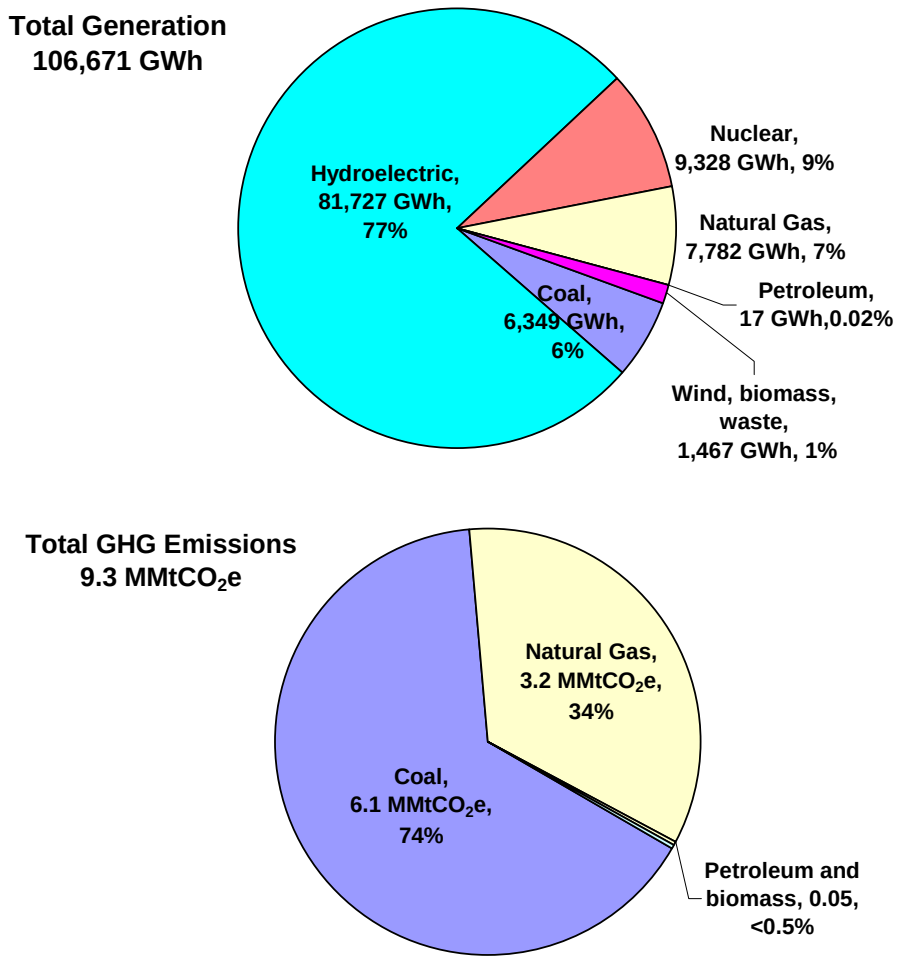
[21] The reference case projections in this report are based on the 'Utility Plans' scenario of the report, Carbon Dioxide Footprint of the Northwest Power System (November 2007). http://www.nwcouncil.org/library/2007/2007-15.htm

[22] 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). In addition, the EPA data currently excludes several key plants in Washington State, such as Encogen (160 MW), March Point (167 MW) and Tenaska (245 MW), capacity values from Northwest Power and Conservation Council. October 2006. *Power Plants in the Pacific Northwest* Excel spreadsheet downloaded from www.nwcouncil.org.). 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 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.

calculated as the difference between the total State CO_2 emissions based on EIA data and the reported CO_2 emissions for individual plants.

Table A2 reports the emissions from the five plants in Washington with the highest emissions from 2000 to 2005. The plant with the highest GHG emissions, Centralia, accounted for over 80% of Washington's GHG electricity-related emissions. TransAlta Corporation purchased Centralia in 2000 and added a 248 MW combined cycle gas turbine in 2002 to the existing 1340 MW of coal fired capacity.[23] The values reported in Table A2 for Centralia combine both coal and natural gas emissions. Electricity trade and GHG allocation are discussed in a following section.

Figure A1. Electricity Generation and CO_2 Emissions from Washington Power Plants, 2006



Note: Petroleum and biomass generation emitted 0.022 MMtCO2e (0.16%) and 0.034 (0.25%) MMtCO2e in 2004, respectively

[23] http://www.power-technology.com/projects/centralia/.

Table A2. CO_2 Emissions from Individual Washington Power Plants, 2000-2006

(Million metric tons CO2)	2000	2001	2002	2003	2004	2005	2006
Centralia	*9.4*	*9.2*	*9.5*	*12.1*	*11.1*	*11.5*	*7.2*
Chehalis Generation Facility	*0.0*	*0.0*	*0.0*	*0.3*	*1.0*	*0.9*	*0.5*
Frederickson Power LP	*n/a*	*n/a*	*0.1*	*0.3*	*0.3*	*0.3*	*0.3*
Goldendale Energy Project	*0.0*	*0.0*	*0.0*	*0.0*	*0.1*	*0.4*	*0.4*
River Road	*0.7*	*0.7*	*0.6*	*0.6*	*0.7*	*0.6*	*0.5*
Other Plants	*3.8*	*3.8*	*1.1*	*0.5*	*0.4*	*0.2*	*0.3*
Total CO2 emissions	**13.9**	**13.8**	**11.2**	**13.8**	**13.6**	**13.8**	**9.2**

Source: U.S. EPA Clean Air Markets database for named plants (http://camddataandmaps.epa.gov/gdm/index.cfm). Total emissions calculated from fuel use data provided by SED (US DOE Energy Information Administration). Emissions from Other Plants is calculated as the difference between the Total Emissions and emissions reported from individual plants.

Table A3 shows the growth in generation by fuel type between 1990 and 2005. Overall generation grew by 0.5% over the 15 years. In Washington, natural gas generation has had particularly strong growth, growing from less than 0.1% of total generation to over 8.5% of generation in 2004. Hydro-electric generation is the dominant energy resource in the State. The table masks the year by year variation from hydro-electricity. In the 16 year period, hydro generation ranged from a low of 54,674 GWh in 2001 to a high of 103,875 GWh in 1997. Nuclear, biomass and wind generation all showed strong increases.

Table A3. Growth in Electricity Generation in Washington 1990-2005.

	Generation (GWh)	
	1990	2005
Coal	7,352	10,475
Hydroelectric	87,193	72,648
Natural Gas	24	8,468
Nuclear	5,742	8,242
Wind	0	401
biomass and waste	340	1,043
Petroleum	14	47
Total	100,664	101,325

Source: EIA Electric Power Annual Data, wind and biomass estimated from EIA Renewable Energy Annual

Electricity Consumption

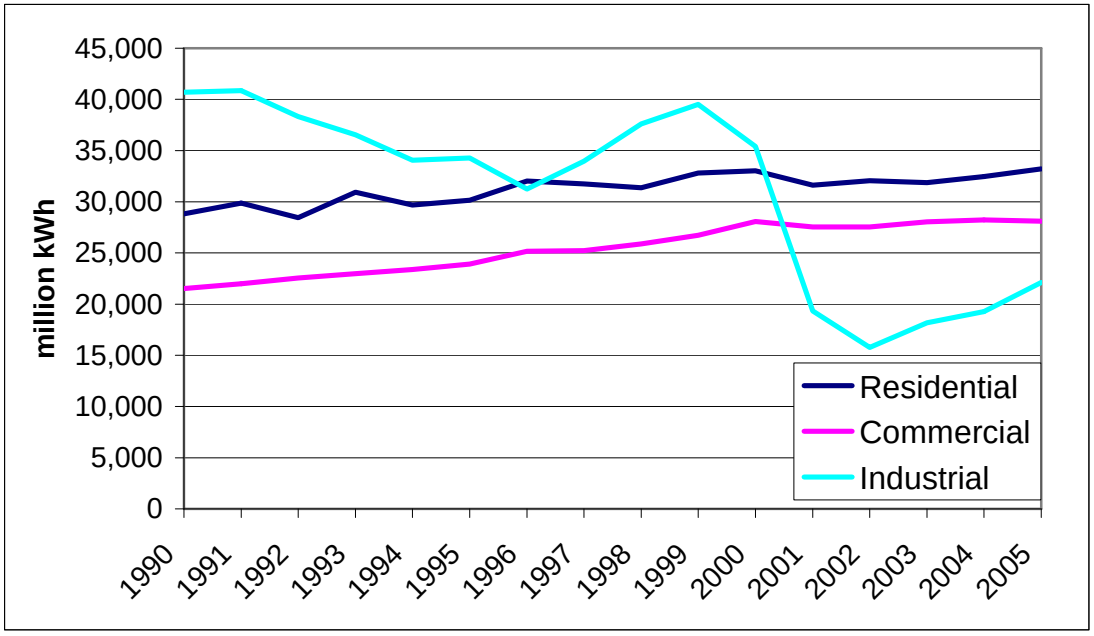
At about 13,000 kWh/capita (2004 data), Washington's electricity use per person is higher than the US average of 12,000 kWh per year.[24] Many components influence a state's per capita electricity consumption including weather (and subsequent demand for heating and cooling), the size and type of industries in the State, and the type and efficiency of equipment in the residential, commercial and industrial sectors.

As shown in Figure A2, electricity sales in the residential and commercial sectors grew moderately from 1990 to 2000 and have generally flattened since then. Industrial electricity sales in Washington fluctuated with decreases from 1990 through 1997 followed by increases to 2000.

[24] Census Bureau for U.S. population, Energy Information Administration for electricity sales.

Industrial sales experienced a large decrease in 2001, when during the electricity crunch, high electricity prices led to the closure of a number of aluminum plants.

Figure A2. Electricity Consumption by Sector in Washington, 1990-2005



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

Future Electricity Consumption

Projections of electricity sales from 2006 through 2020 are based an approximate average of projections by the 4 largest utilities in the State (Puget Sound Energy, City of Seattle, Snohomish County PUD, and Avista Corporation).[25] Although it would be preferable to combine projected growth rates from all utilities in the State, resources were not available to collect and integrate this information. The four largest utilities accounted for just over 50% of total sales in Washington in 2004. Table A4 reports both historic and projected annual average growth rates.

[25] Avista: http://www.wutc.wa.gov/rms2.nsf/0/FF5F2D308EE7BB5488257149007B0CA3/$file/Avista+2005+electric+LCP+acknowledgement+letter+FINAL.doc, Puget Sound Energy: http://www.pse.com/energyEnvironment/electricSupplyResPlanning.aspx, City of Seattle: http://www.seattle.gov/light/news/issues/irp/ Snohomish: http://www.snopud.com/Content/External/Documents/customerpubs/IRP04final.pdf

Table A4. Electricity Growth Rates, historic and projected

	Historic		Projections	
	1990-2000	2000-2005	2005-2010	2010-2020
Residential	1.4%	0.1%	0.9%	0.9%
Commercial	2.7%	0.0%	2.3%	2.3%
Industrial	-1.4%	-9.0%	0.9%	0.9%
Total	**0.6%**	**-2.9%**	**1.4%**	**1.3%**

Source: Historic from EIA data, overall (total) projections from Integrated Resource Plans from (Puget Sound Energy, City of Seattle, Snohomish County PUD, and Avista Corporation). Sector breakdowns based on Puget Sound Energy projections.

Future Electricity Generation

Estimating future generation and GHG emissions from Washington power plants requires estimation of 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 different types of power plants that will operate in the future in Washington remains uncertain as the trends are influenced by many factors. Since 2000, new power plants in Washington have been mainly natural gas-fired with some wind and biomass. Most plants that are currently under construction or *planned*[26] are natural gas and wind. Several large natural gas plants have been proposed and Washington is also considering tidal energy. Table A5 presents data on new and proposed plants in Washington.

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

[26] Planned refers to plants with a firm date for start of construction or for completion published; construction not underway

Table A5. New and Proposed Power Plants in Washington

	Plant Name	Fuel	Status or On-line date	Capacity MW	Illustrative Annual generation GWh	Emissions $MMtCO_2e$
Recent Plants	Big Hanaford	Natural gas	Aug-02	248.0	257	0.1
	Chehalis Generating Facility	Natural gas	Nov-03	520.0	1617	0.9
	Sierra Pacific Industries Aberdeen	Biomass	2003	18.0	132	0.0
	Frederickson Power 1	Natural gas	Aug-02	249.0	630	0.3
	Goldendale Energy Center	Natural gas	Sep-04	237.0	696	0.4
	Hopkins Ridge	Wind	Dec-05	150.0	460	0.0
	Nine Canyon Phase I & II	Wind	Sep-02 / Dec-03	63.7	147	0.0
	Pasco	Natural gas	Jul-02	43.0	57	0.0
	Big Horn	Wind	Dec-06	200	559	0.0
	Marengo I	Wind	Aug-07	140	394	0.0
	Wild Horse	Wind	Dec-06	229	701	0.0
Under Construction and Planned Plants	Mint Farm	Natural gas	Oct-07	286	2,255	0.8
	Goodnoe Hills East	Wind	Nov-07	94	267	0.0
	Nine Canyon Phase III	Wind	2007	32	91	0.0
	White Creek	Wind	2007	205	581	0.0
	Marengo II	Wind	Jun-08	70	199	0.0
	Wild Horse Solar	Solar	Dec-07	0.5	1.0	0.0
	Grays Harbor Energy Facility (Satsop) (Phase II)	Natural gas	2008	650.0	4,840	1.8
Permitted and Proposed plants	Agate Passage	Tidal current	Proposed	52.0	146	0.0
	BP Cherry Point Cogeneration Project	Natural gas	Proposed	720.0	5,361	2.0
	Kittitas Valley	Wind	Proposed	150.0	460	0.0
	Longview Power Station	Natural gas	Proposed	290.0	2,159	0.8
	Pacific Mountain Energy Center	Petroleum	Proposed	600.0	4,468	3.6
	Reardan Twin Buttes	Wind	Proposed	50.0	140	0.0
	Saddleback Mountain	Wind	Proposed	70.0	196	0.0
	San Juan Channel	Tidal current	Proposed	5.3	33	0.0
	Windy Point I & II	Wind	Permitted	242.5	744	0.0

Sources: Northwest Power and Conservation Council. October 2007. *Power Plant Development in the Pacific Northwest* Excel spreadsheet downloaded from www.nwcouncil.org. Illustrative Generation and emission estimates for new plants are based on 0.15 capacity factor for peaking plants, 0.85 for baseload, 0.35 for wind and 0.24 for solar. Generation estimates for *Recent Plants* are based on EIA data where available (all plants except Sierra Pacific biomass, Hopkins wind and Pasco natural gas – generation for these plants is estimated based on capacity factors listed for new plants).

Given the many factors impacting 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 Washington'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 Washington grows at 2.1% per year from 2006-2009, based on generation estimates from plants that are currently under construction (see table A5).
- Generation from power plants in Washington grows at 0.7% per year from 2010 to 2020. Overall average growth rate from 2006 to 2020 is 1.1% per year, just slightly lower than the rate assumed for electricity consumption in Washington.
- Generation from existing natural gas plants is based on holding generation at 2006 levels. Generation from existing hydro-electric plants is assumed to be 81,051 GWh per year, the average generation from the last ten years. Generation from existing coal plants is assumed to be 9,378 GWh, reflecting average generation over the period 2002 through 2006.
- New power plants built between now and 2009 are assumed to be the mix of resources indicated in Table A5, for 'Under-construction and planned plants.' Those plants built between 2010 and 2020 will be a mix of 68% natural gas, 27% wind, and 5% biomass / landfill gas or geothermal. This mix of proposed plants is based on regional projections from the Northwest Power Council, reflecting updated modeling of the 5th power plan.[27]

As noted above, this reference case does not include the impact of recent policies and actions such as Initiative 937 (I-937) renewable and efficiency requirements.[28]

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:

- 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.

[27] Information provided by Jeff King (NWPCC) to Alison Bailie (CCS consultant) on July 20, 2007.

[28] In 2006, Washington voters approved Initiative 937 (I-937), a renewable energy standard. I-937 requires each utility with more that 25,000 customers to undertake cost-effective energy conservation and to obtain 3% of its load from new renewable resources by 2012. The required fraction of new renewable generation increases to 9% in 2016, and 15% in 2020, and every year thereafter.

- The response to changing fuel prices.
- The fuel/technology mix of new generation plants.

The key assumptions described above are summarized in Tables A6 and A7.

Table A6. Key Assumptions and Methods for Consumption (Load) Based Electricity Emissions Estimates

Electricity sales	Average annual growth of 1.4% from 2007 to 2010 and 1.3% from 2010 to 2020, based on growth rates reported by the 4 largest utilities.
Projected fuel mix	The mix of resources supplying new electricity demand to Washington consumers would be similar to new electricity production in the entire Northwest Power Council region, as projected by the Northwest Power and Conservation Council. Based on this approach, new electricity demand in Washington for the period 2007-2020 is assumed to be supplied by a mix of electricity that is 22% coal, 46% natural gas, 26% wind and 6% biomass/geothermal/hydro.
Transmission and Distribution losses	7% losses are assumed, based on regional losses projected by the AEO2006.

Table A7. Key Assumptions and Methods for Production Electricity Emissions Estimates (In-state generation)

Transmission and Distribution losses	Per above
In-state electricity generation	Average growth of 2.8% per year from 2005-2009 (based on plants under construction); 1.3% per year from 2010 to 2020, based on growth in electricity sales.
New Generation Sources (2006-2009)	The mix of new generation is based on plants under construction for this period (table A3).
New Generation Sources (2010-2020)	The mix of new non-renewable generation in this period is assumed to be 5% biomass, landfill gas or geothermal 27% wind 68% natural gas
Heat Rates	The assumed heat rate for new natural gas generation is 7000 Btu/kWh, based on estimates used in similar analyses.[29]
Operation of Existing Facilities	Existing natural gas facilities are assumed to continue to operate as at 2006 levels. Existing hydro facilities are assumed to generate 81,051 GWh per year, the average generation over the period 1996-2005. Generation from existing coal plants is assumed to be 9,378 GWh, reflecting average generation over the period 2002 through 2006.

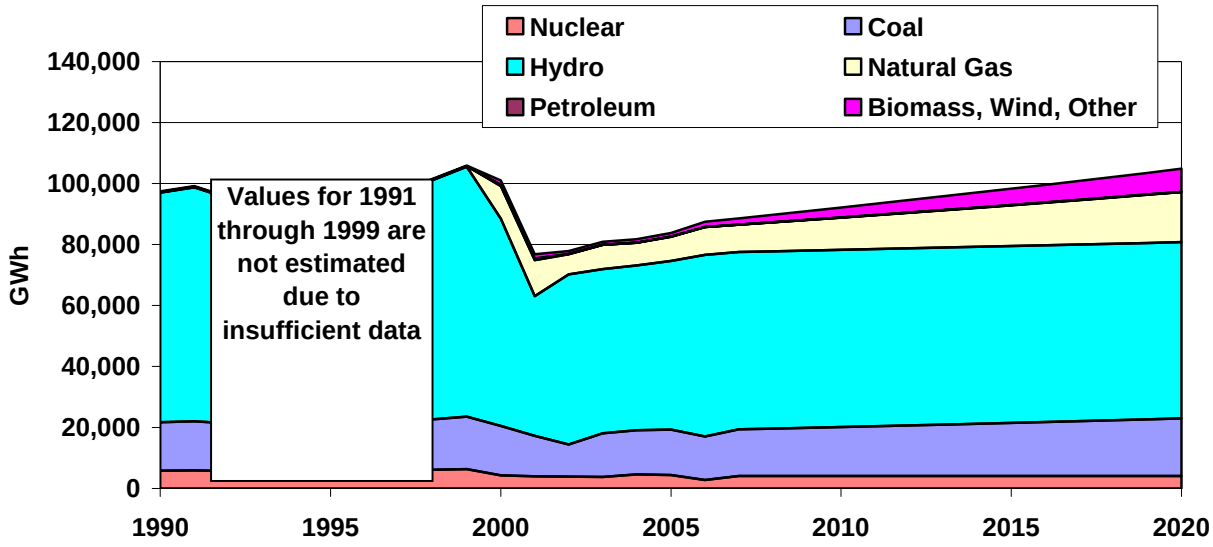
[29] See, for instance, the Oregon Governor's Advisory Group on Global Warming, http://egov.oregon.gov/ENERGY/GBLWRM/Strategy.shtml.

Results

Consumption (Load) -based results

Figure A3 shows the estimated sources of electricity generated to supply Washington's electricity load by fuel source, along with projections to the year 2020 based on the assumptions described above. The estimated generation for 1990 and 2000 – 2006 has been calculated by CTED. Estimates for electricity generation on a load-basis for 1991 through 1999 are not currently available. For future years, overall electricity demand is projected to grow at an average of 1.3% per year from 2006 to 2020. As described above, we estimate that this demand will be met by a mix of fossil and renewable resources. Non-hydro renewable generation shows strong growth, from approximately 1,600 GWh in 2006 to over 7,500 GWh in 2020, with almost 5,500 GWh from wind. Natural gas generation is projected to increase by 80% from 2006 to 2020.

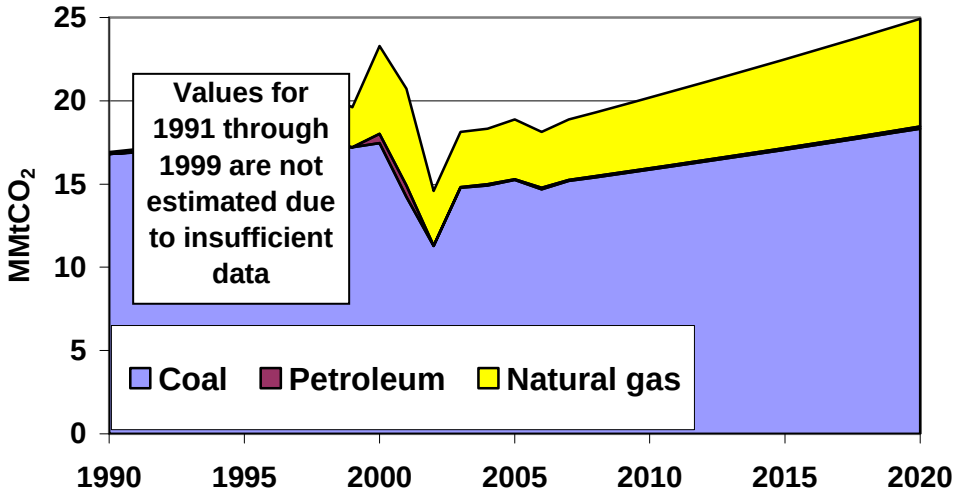
Figure A3. Electricity Generated to meet Washington's Electricity Demand 1990-2020



Source: 1990 & 2000-2006 CTED estimates, 2007-2020 calculations based on assumptions described above, generation from petroleum resources is too small to be visible in the chart

Figure A4 shows GHG emissions associated with Washington's electricity demand, using the consumption basis derived from the Fuel Mix Disclosure data as described above. This reflects the data indicating imports of coal-based electricity and assumptions that Washington will continue to import some of its electricity from coal or other fossil fuel-based resources, while exporting electricity from hydro or other low GHG emitting resources. The large increase in emissions in 2000 and 2001 reflect high levels of electricity imports from coal and other fossil fuel-based sources. In 2002, emissions dropped due to both greater in-state hydro generation and lower in-state electricity sales. Consumption-based emissions for the State increase by 1.9% per year from 2005 to 2020.

Figure A4. Washington GHG Emissions Associated with Electricity Use (Consumption-Basis)

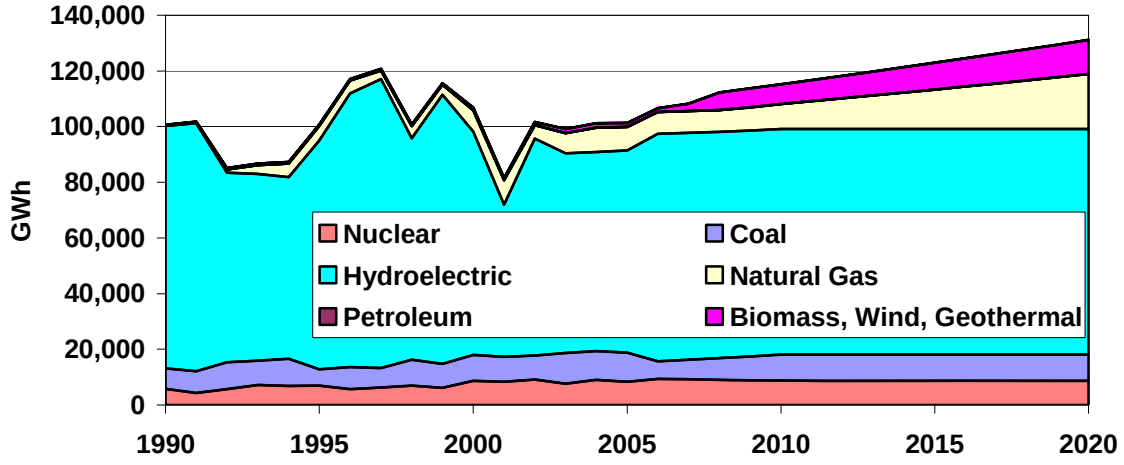


Source: 1990 & 2000-2006 CTED estimates, 2007-2020 calculations based on assumptions described above

Production-based results

Figure A5 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. Overall electricity generation grows at 1.1% per year from 2006 to 2020. Renewables (biomass and wind) and natural gas generation show strong growth, relative to 2005 levels. Wind generation is projected to grow from approximately 500 GWh per year currently to just over 5,500 GWh in 2020, with much of the growth occurring in the next three years as Big Horn, Wild Horse, Marengo and other plants already under construction come on-line. Natural gas generation in Washington state is projected to double from 2006 to 2020.

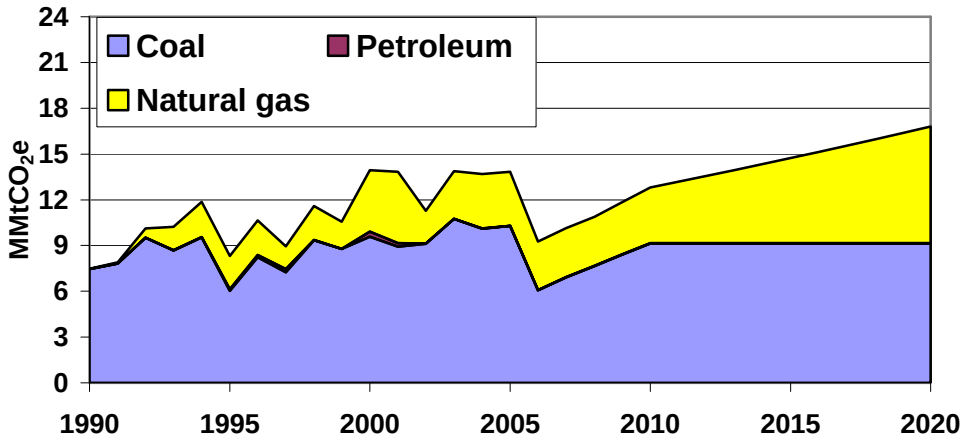
Figure A5. Electricity Generated by Washington Power Plants 1990-2020



Source: 1990-2005 EIA data, 2006-2020 Calculations based on assumptions described above, generation from petroleum resources is too small to be visible in the chart

Figure A6 illustrates the GHG emissions associated with the mix of electricity generation shown in Figure A5 (production-based emissions). From 2005 to 2020, the emissions from Washington electricity generation are projected to grow at 1.3% per year with most of the projected growth occurring after 2010. Prior to 2010, the mix of new plants is dominated by the wind plants currently under construction. The GHG emission intensity (emissions per MWh) of Washington electricity generation is projected to decrease from 0.14 $MtCO_2$/MWh in 2005 to 0.11 in 2010 then increasing to 0.13 $MtCO_2$/MWh in 2020.

Figure A6. Washington GHG Emissions Associated with Electricity Production (Production-Basis)



Source: Calculations based on approach described in text.

Summary of Results

Table A8 summarizes the GHG emissions for Washington's electric sector from 1990 to 2020. During this time period, emissions are projected to increase by almost 50% on a consumption-basis and more than double on a production-basis.

Table A8. Washington GHG Emissions from Electric Sector, Production and Consumption-based estimates, 1990-2020.

(Million Metric Tons CO_2e)	1990	2000	2005	2010	2020
Electricity, Consumption-based	**16.9**	**23.3**	**18.9**	**20.2**	**24.9**
Coal	16.8	17.4	15.2	15.9	18.3
Natural Gas	0.0	0.6	0.0	0.1	0.1
Petroleum	0.1	5.3	3.6	4.3	6.5
Biomass and Waste (CH_4 and N_2O)	0.0	0.0	0.0	0.0	0.0
Electricity, Production-based	**7.5**	**13.9**	**13.8**	**13.7**	**15.9**
Coal	7.4	9.6	10.3	9.1	9.1
Natural Gas	0.0	4.0	3.6	4.6	6.8
Petroleum	0.0	0.3	0.0	0.0	0.0
Biomass and Waste (CH_4 and N_2O)	0.0	0.0	0.0	0.0	0.0

Note: Values that are less than 0.005 MMTCO2e are listed as 0.0 in table A8.

Key Uncertainties

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

- Future projections for electricity consumption and mix of new generation. In particular, coal plants that could be built in Washington State to meet out-of-state electricity needs are not included in this analysis and could lead to large increases in GHG emissions.
- Future generation from existing hydro-electric plants. Generation levels have fluctuated significantly in the last 15 years and future generation is dependent on uncertain weather-related factors.

We have also identified the following uncertainties with the FMD data used to estimate consumption-based emissions for 2000-2006:

- Utility Fuel mix reporting is not reviewed or verified and reporting requirements are less rigorous than the Energy Information Administration standards.
- GHG emission estimates for electricity generated outside the North West Power Pool could be refined further.

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

Overview

Activities in the RCI[30] 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 applications. Carbon dioxide accounts for over 98% of these emissions in Washington on a million metric tons (MMt) of CO_2 equivalent (CO_2e) basis. In addition, since these sectors consume electricity, one can also attribute emissions associated with electricity generation to these sectors in proportion to their electricity use.[31] If emissions from the generation of the electricity they consume are not included, the RCI sectors are between them the second largest source of gross greenhouse gas (GHG) emissions in Washington. Direct use of oil, natural gas, coal, and wood in the RCI sectors accounted for an estimated 19.4 $MMtCO_2e$ (20%) of gross GHG emissions in 2005.[32]

Data Sources and Approach

Emissions for direct fuel use were estimated, in this inventory and forecast prepared for the Washington Climate Advisory Team (CAT), 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.[33] The default data used in SGIT for Washington are from the United States Department of Energy (US DOE) Energy Information Administration's (EIA) *State Energy Data* (SED). The SGIT default data for Washington were revised using the most recent data available, which includes: (1) 2002 SED information for all fuel types;[34] (2) 2003 SED information for coal, and wood and wood waste;[35] (3) 2003 and 2004 SED information for natural gas and petroleum (distillate oil, kerosene and liquefied petroleum gas) consumption (same data source as previous citation); (4) 2004 electricity consumption data from the EIA's

[30] The industrial sector includes emissions associated with agricultural energy use and fuel used by the fossil fuel production industry.

[31] 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.

[32] 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 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.

[33] 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.

[34] 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=WASHINGTON).

[35] 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).

State Electricity Profiles;[36] and (5) 2005 natural gas consumption data from the EIA's *Natural Gas Navigator*.[37] The inventory described in this appendix reflects estimated 2004 coal consumption for all three of the RCI sectors as prepared by the Washington Department of CTED (see reference below). The Washington Department of CTED also accounted for a significant portion of industrial petroleum coke consumption by primary aluminum manufacturing under the industrial processes non-fuel use category (see Appendix D), therefore, the petroleum coke consumption data for the industrial fuel use sector described in this Appendix B were adjusted to eliminate double counting of emissions associated with petroleum coke consumption in Washington.

The Washington Department of Community, Trade, and Economic Development (CTED) prepared a GHG inventory for the RCI sectors using the default SED information[38]. For the inventory described in this Appendix B, the SED information used is essentially the same as that used by CTED, with the exception that the Center for Climate Strategies (CCS) updated SED information for 2004 and 2005 published by the EIA after CTED completed its inventory. In addition, CTED inventory for residential wood consumption contained SED data through 2001; since SED information was available through 2003, SED residential wood consumption values for 2001 through 2003 were included in the inventory described in this appendix.

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 fuel feedstocks not used to provide energy. For example, the methods account for carbon stored in petrochemical feedstocks, and 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.[39] 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,[40] 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),[41] with adjustments for

[36] EIA *Electric Power Annual 2005 - State Data Tables*, (http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html).
[37] EIA *Natural Gas Navigator* (http://tonto.eia.doe.gov/dnav/ng/ng_cons_sum_dcu_SWA_a.htm).
[38] *Washington's Greenhouse Gas Emissions: Sources and Trends*, by Stacey Waterman-Hoey and Greg Nothstein, WA State Dept. of Community, Trade & Economic Development, Energy Policy Division, dated December 2006 (Revised 2/12/07), and available from http://www.cted.wa.gov/portal/alias__CTED/lang__en/tabID__853/DesktopDefault.aspx.
[39] EIIP, Volume VIII: Chapter 1 "Methods for Estimating Carbon Dioxide Emissions from Combustion of Fossil Fuels", August 2004.
[40] A mixture of hydrocarbons, mostly pentanes and heavier fractions, extracted from natural gas.
[41] EIA AEO2006 with Projections to 2030, (http://www.eia.doe.gov/oiaf/aeo/index.html).

Washington's projected population[42] and employment growth. Washington employment data for the manufacturing (goods producing) and non-manufacturing (commercial or services providing) sectors were obtained from the Washington State Employment Security Department.[43] Regional employment data for the same sectors were obtained from EIA for the EIA's Pacific region.[44] 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 average about 1.5% annually between 2004 and 2020; this demographic trend is reflected in the growth rates for residential fuel consumption. Based on the Washington State Employment Security Development's forecast (2004 to 2014), commercial and industrial employment are projected to increase at compound annual rates of 0.93% and 1.07%, respectively, and these growth rates are reflected in the growth rates in energy use shown in Table B2 for the two sectors. These estimates of growth relative to population and employment reflect expected responses of the economy — as simulated by the EIA's National Energy Modeling System — to changing fuel and electricity prices and changing technologies, as well as to structural changes within each sector (such as shifts in subsectoral shares and in energy use patterns).

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

Sector	1990-2004*	2005-2010**	2010-2020**
Residential	0.9%	0.9%	0.9%
Commercial	2.0%	2.3%	2.3%
Industrial	-5.2%	0.9%	0.9%
Total	**-0.9%**	**1.4%**	**1.3%**

* 1990-2004 compound annual growth rates calculated from Washington 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 2005-2010 and 2010-2020 for total consumption and for each of the three sectors were taken from the forecast for the energy supply sector (see Appendix A).

Results

Figures B1, B2, and B3 show historical and projected emissions for the RCI sectors in Washington 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. The residential sector's share of total RCI emissions from direct fuel use and electricity use was 23% in 1990, increased to a high of 33% in 2005, and is projected to decline to 30% by 2020. The commercial sector's share of total RCI emissions from direct fuel use and electricity use was 19% in 1990, increased to 24% in 2005, and is projected to increase slightly more to 25% by 2020. The industrial sector's share of total RCI emissions from direct fuel use and electricity use was 58% in 1990, declined to a low of 43% in 2005, and is projected to increase slightly to 45% by 2020.

[42] Population data from the State of Washington, Office of Financial Management, Forecast of the State Population, November 2006 Release (http://www.ofm.wa.gov/pop/stfc/default.asp).
[43] Washington State Employment Security Department, Labor Market and Economic Analysis, Workforce Employer, Publications and Reports, Located under "Projections / Long-term Employment Projections," Excel File Name = 5004_indlongp.xls, Excel file title = Annual Average Nonagricultural Wage and Salary Employment, Estimated 2004 and Projected 2009 and 2014, Washington State (in thousands), June 2006 (http://www.workforceexplorer.com/cgi/dataanalysis/?PAGEID=94&SUBID=149).
[44] AEO2006 employment projections for EIA's Pacific region obtained through special request from EIA (dated September 27, 2006).

Emissions associated with the generation of electricity to meet RCI demand from 1990 through 2020 accounts for about, on average, 48% of the emissions for the residential sector, 56% of the emissions for the commercial sector, and 23% of the emissions for the industrial sector. Natural gas consumption is the next-highest source of emissions for all three sectors, accounting for about 38% of total emissions in the residential sector, 35% for the commercial sector, and 27% for the industrial sector when averaged over the 1990 to 2020 period.

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

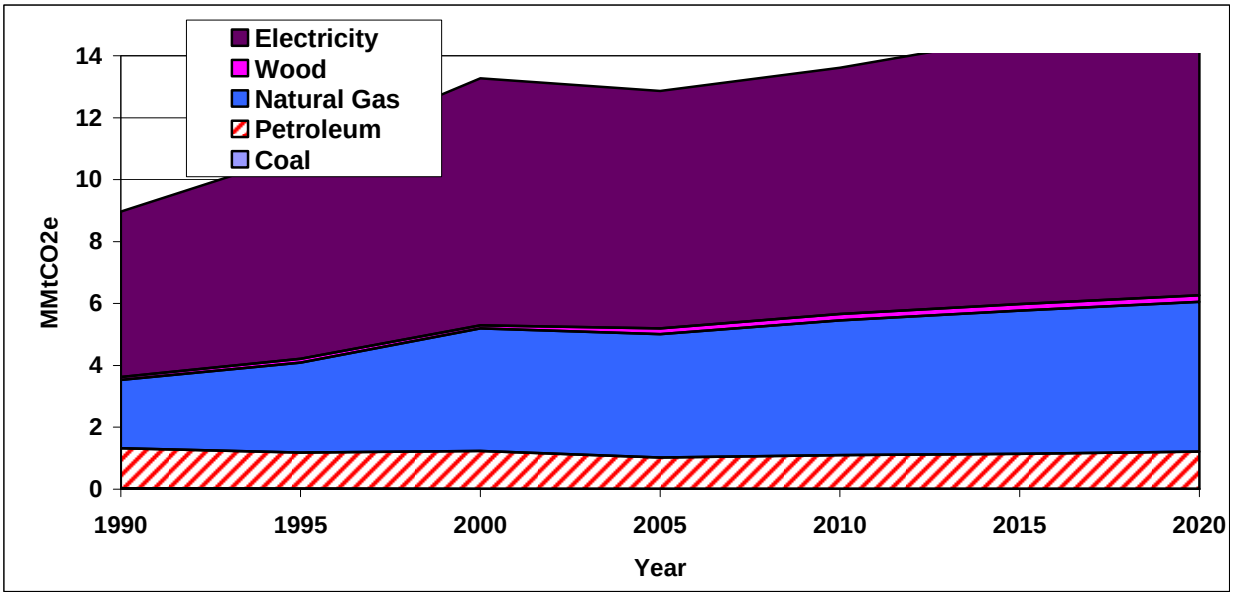
	1990-2004*	2005-2010**	2010-2015**	2015-2020**
Residential				
natural gas	4.0%	1.9%	1.3%	1.0%
petroleum	-1.5%	1.7%	0.3%	2.0%
wood	5.1%	1.8%	0.5%	0.6%
coal	-9.6%	1.7%	-0.3%	-0.5%
Commercial				
natural gas	1.7%	-0.4%	1.7%	1.0%
petroleum	-5.1%	-1.0%	0.5%	0.0%
wood	9.0%	-0.6%	-0.1%	-0.5%
coal	-6.2%	-0.7%	-0.1%	-0.5%
Industrial				
natural gas	-1.1%	1.5%	2.1%	2.4%
petroleum	-6.2%	3.4%	1.8%	1.2%
wood	-2.6%	3.6%	2.8%	2.7%
coal	-6.5%	2.5%	0.5%	1.1%

* Compound annual growth rates calculated from EIA SED historical consumption by sector and fuel type for Washington. 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. The Washington Department of CTED, in its GHG inventory, estimated 2004 coal consumption for all three sectors, and accounted for a significant portion of industrial petroleum coke consumption by primary aluminum manufacturing under the industrial processes non-fuel use category (see Appendix D).

** Figures for growth periods starting after 2004 are calculated from AEO2006 projections for EIA's Pacific region, adjusted for Washington's projected population for the residential sector, non-manufacturing employment for the commercial sector, and manufacturing employment for the industrial sector.

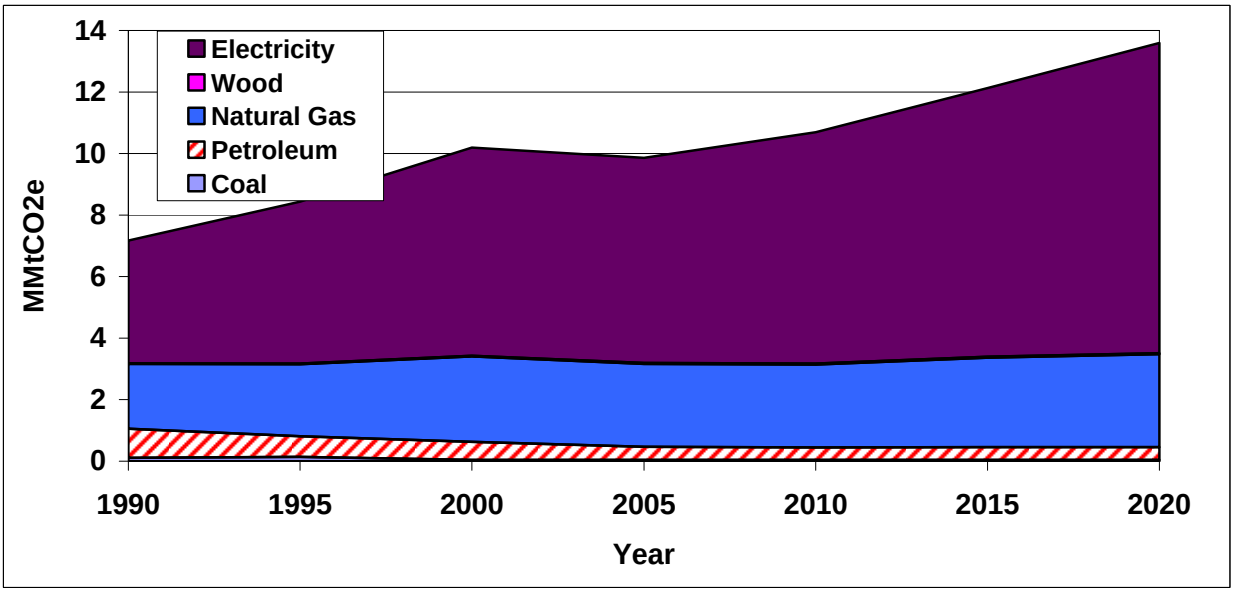
For the residential sector, emissions from electricity and direct fossil fuel use in 1990 were about 9.0 $MMtCO_2e$, and are estimated to increase to about 15.6 $MMtCO_2e$ by 2020. Emissions associated with the generation of electricity to meet residential energy consumption demand account for about 60% of total residential emissions. In 1990, natural gas consumption accounted for about 25% of total residential emissions and is estimated to account for about 31% of total residential emissions by 2020. Residential-sector emissions associated with the use of petroleum accounted for about 14% of total residential emissions in 1990 and are estimated to decline to 8% of total residential emissions by 2020. Residential-sector emissions associated with the use of coal and wood in 1990 were about 0.12 $MMtCO_2e$ combined, and accounted for about 1% of total residential emissions. By 2020, emissions associated with the consumption of these two fuels are estimated to be 0.22 $MMtCO_2e$ and to account for 1% of total residential sector emissions by that time.

Figure B1. Residential Sector GHG Emissions from Fuel Consumption



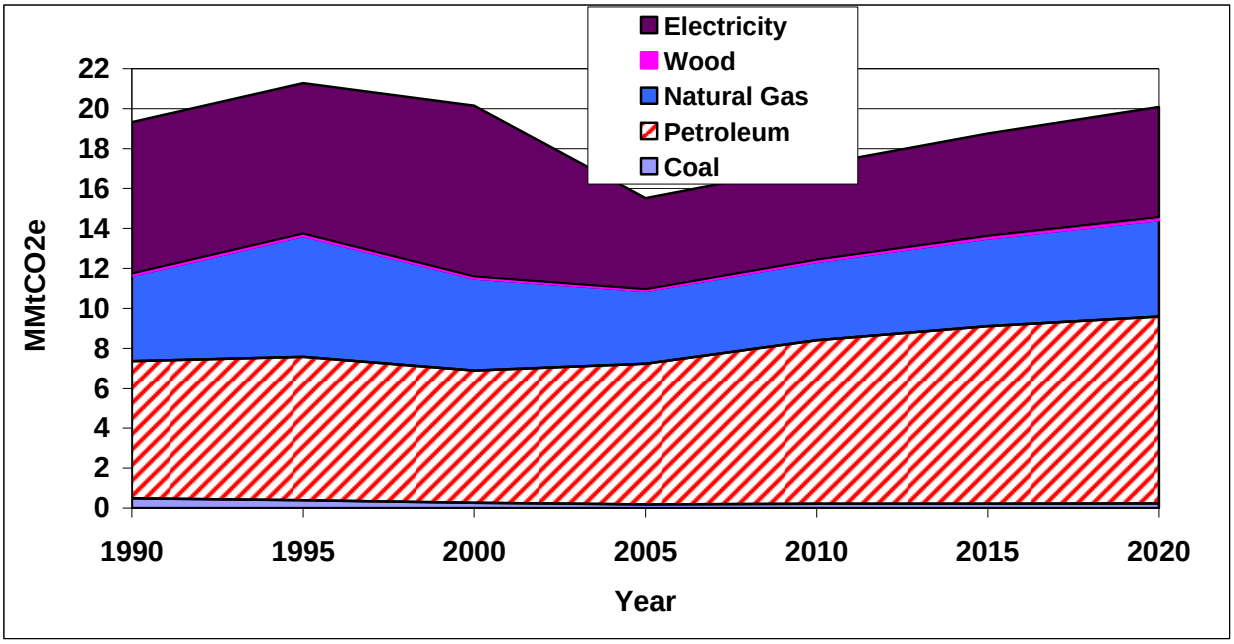
Source: Calculations based on approach described in text.
Note: Emissions associated with coal combustion are too small to be seen on this graph.

Figure B2. Commercial Sector GHG Emissions from Fuel Consumption



Source: CCS calculations based on approach described in text.
Note: Emissions associated with coal 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.

For the 15-year period 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 1.3%, 1.3%, and 1.2%, respectively. Emissions associated with the use of coal and wood are expected to increase annually by about 0.2% and 0.9%, respectively. Total GHG emissions for this sector increase by an average of about 1.3% annually over the 15-year period.

Residential wood consumption increased by over 58% from between 2000 and 2001, and increased by about 68% from 2000 through 2003. According to a contact with the Washington Department of CTED, this increase is most likely associated with households switching to using wood for home heating due to increases in electricity prices during this time period.

For the commercial sector, emissions from electricity and direct fuel use in 1990 were about 7.2 $MMtCO_2e$ and are estimated to increase to about 13.6 $MMtCO_2e$ by 2020. Emissions associated with the generation of electricity to meet commercial demand accounted for about 56% of total commercial emissions in 1990, and are estimated to increase to about 74% of total commercial emissions by 2020, as use of electricity in this sector grows much more rapidly than use of other fuels. In 1990, natural gas consumption accounted for about 29% of total commercial emissions, and is estimated to account for about 22% of total commercial emissions by 2020. Commercial-sector emissions associated with the use of petroleum accounted for about 13% of total commercial emissions in 1990, and are projected to decline to about 3% of total commercial emissions by 2020. Commercial-sector emissions associated with the use of coal accounted for about 1.5% of total commercial emissions in 1990, and are estimated to decline to about 0.3% of total commercial emissions by 2020. Commercial-sector emissions associated with the use of wood accounted for about 0.15% of total commercial emissions in 1990, and are projected to increase slightly to account for 0.22% of total commercial emissions by 2020.

For the 15-year period 2005 to 2020, commercial-sector GHG emissions associated with the use of electricity and natural gas are expected to increase at average annual rates of about 2.8% and 0.8%, respectively. Emissions associated with the use of petroleum, coal, and wood are expected to decline at average annual rates of about 0.2%, 0.5%, and 0.4%, respectively. Total GHG emissions for this sector increase at an average of about 2.2% 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 20 $MMtCO_2e$ by 2020. Emissions associated with the generation of electricity to meet industrial demand accounted for about 39% of total industrial emissions in 1990 and are estimated to decline to about 27% of total industrial emissions by 2020. In 1990, natural gas consumption accounted for about 22% of total industrial emissions, and this fraction is estimated to increase slightly, to about 24% of total industrial emissions by 2020. Industrial-sector emissions associated with the use of petroleum accounted for about 36% of total industrial emissions in 1990, and are projected increase to about 47% of total industrial emissions by 2020. Industrial-sector emissions associated with the use of coal accounted for about 2.5% of total industrial emissions in 1990, and are estimated to decline to about 1.1% of total industrial emissions by 2020. Industrial-sector emissions associated with the use of wood accounted for about 1% of total industrial emissions in 1990, and are projected to continue to account for about 1% of total industrial emissions through 2020.

For the 15-year period 2005 to 2020, industrial sector GHG emissions associated with the use of electricity, natural gas, and petroleum are expected to increase at average annual rates of about 1.2%, 1.9%, and 1.9%, respectively. Emissions associated with the use of coal and wood are expected to increase annually by about 1.2% and 2.9%, respectively. Total GHG emissions for this sector increase by an average of about 1.7% annually over the 15-year period.

Figures B1 and B2 show substantial increases from 1990 through 2000 in GHG emissions associated with the generation of electricity for the residential and commercial sectors, respectively. These increases are associated with an increase in the use of coal and natural gas (as opposed to hydro power, which has historically supplied much of the Northwest's power) for generation to meet the residential and commercial sectors' increased demand for electricity over this period. As a consequence, the increases in residential and industrial emissions associated with electricity use are a composite of growth in electricity use by those sectors, and an increase in the average emission factor for GHG emissions per unit of electricity generated (and consumed). Figure B3 shows a decline in GHG emissions for the industrial sector from 2000 to 2005, corresponding to a large decrease in industrial electricity consumption beginning in 2001, when during a period of rapidly rising rates for electricity, high electricity prices led to the closure of a number of aluminum plants.

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 Pacific modeling region scaled for Washington 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 Washington to the extent that such data become available.

- The AEO2006 projections that underlie much of the reference case projection presented here 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.
- For CH_4 and N_2O, to convert tons of gas emitted to CO_2-equivalents, the Washington Department of CTED used the 100-year global warming potentials published by the Intergovernmental Panel on Climate Change (IPCC) in their Third Assessment Report (TAR, IPCC 2001).[45] For the inventory described in this appendix, the US EPA SGIT was used to calculate CH_4 and N_2O for the RCI sectors. The SGIT tool uses the global warming potential values that the IPCC published in their Second Assessment Report (SAR)[46] in order to be consistent with the US EPA National GHG inventory. Thus, the emissions for CH_4 and N_2O on a CO_2-equivalent basis will differ slightly from the emissions calculated by the Washington Department of CTED. The following compares the global warming potential factors in the IPCC SAR and TAR:

Gas	SAR	TAR
CO_2	1	1
CH_4	21	23
N_2O	310	296

[45] IPCC (2001) *Climate Change 2001: A Scientific Basis*, Intergovernmental Panel on Climate Change; J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell, eds.; Cambridge University Press. Cambridge, U.K.

[46] IPCC (1996) *Climate Change 1995: The Science of Climate Change*. Intergovernmental Panel on Climate Change; J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds.; Cambridge University Press. Cambridge, U.K.

Appendix C. Transportation Energy Use

Overview

Transportation is one the largest GHG source sectors in Washington. The transportation sector includes light and heavy-duty (on-road) vehicles, aircraft, rail engines, and marine engines. Carbon dioxide accounts for about 98 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.

Inclusion of Maritime Transportation

Several options exist for estimating transportation GHG emissions in Washington State. One fundamental question is whether to include GHG emissions from marine transportation. The analysis here includes an estimate of marine fuel consumption, and resulting emissions, based on analyses by local air agencies. The CTED report, *Washington's Greenhouse Gas Emissions: Sources and Trends* (2006) excludes emissions from residual fuel consumption in the transportation sector following an inventory agreement between the West Coast States. The Puget Sound Maritime Air Forum has recently completed a study on emissions from maritime-related diesel equipment operating within the greater Puget Sound region, and this data has been incorporated into the inventory.[47] .

Data Sources and Approach

GHG emissions for 1990 through 2005 come from a combination of the report, *Washington's Greenhouse Gas Emissions: Sources and Trends*, (CTED December 2006)[48] and using SGIT and the methods provided in the EIIP guidance document for the sector.[49,50] For on-road 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 fuel consumption data within SGIT were used to estimate emissions, with the most recently available fuel consumption data (2005) from EIA SED added.[51] The one exception is motor gasoline consumption from 1996 to 2005. For this data, the analysis follows the approach taken by *Washington's Greenhouse Gas Emissions: Sources and Trends* guidelines and uses Washington Department of Licensing Fuel Tax Receipts data. The default annual VMT data for in SGIT was the same as that provided by WSDOT.[52] The state-level VMT was allocated to vehicle types using vehicle mix data from FHWA.[53]

---

[47] http://maritimeairforum.org/emissions.shtml

[48] Waterman-Hoey and Nothstein, Department of Community, Trade and Economic Development. December 2006

[49] 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.

[50] 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.

[51] Energy Information Administration, State Energy Consumption, Price, and Expenditure Estimates (SED), http://www.eia.doe.gov/emeu/states/_seds.html

[52] Pat Whittaker, Highway Performance Monitoring System Functional Classification Manager, Transportation Data Office, Washington Department of Transportation

[53] Highway Statistics, Federal Highway Administration, http://www.fhwa.dot.gov/policy/ohpi/hss/index.htm.

On-road Vehicles

On-road vehicle gasoline and diesel emissions were projected based on VMT forecasts provided by WSDOT[54] 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., 28 percent growth between 2005 and 2020 in heavy-duty gasoline vehicle VMT versus 149 percent growth in light-duty diesel truck VMT over this period). The procedure first applied the AEO2006 vehicle type-based national growth rates to 2005 Washington 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 WSDOT estimates for total VMT in the State for each year to yield the vehicle type VMT estimates and compound annual average growth rates are displayed in Tables C2 and C3, respectively.

[54] VMT forecasts provided by Brian Lagerberg, WSDOT.

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 – 2005)** EPA SGIT and fuel consumption from EIA SED and Washington Fuel Tax Receipts **Reference Case Projections (2006 – 2020)** Gasoline and diesel fuel projected using VMT projections provided by WSDOT adjusted by fuel efficiency improvement projections from AEO2006. Other onroad fuels projected using Pacific 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 – 2005)** 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 U.S. EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003.* State total VMT replaced with VMT provided by WSDOT, VMT allocated to vehicle types using default data in SGIT. **Reference Case Projections (2006 – 2020)** VMT projections from WSDOT allocated to vehicle types using vehicle specific growth rates from AEO2006.
Non-highway fuel consumption (jet aircraft, gasoline-fueled piston aircraft, boats, locomotives) – CO_2, CH_4 and N_2O	**Inventory (1990 – 2005)** EPA SGIT and fuel consumption from EIA SED, except for commercial marine, which was taken from Puget Sound Maritime Air Forum and Corbett inventories and allocation of national fuel consumption data using port freight tonnage data. **Reference Case Projections (2006 – 2020)** Aircraft projected using aircraft operations projections from FAA. No growth assumed for rail diesel. Marine fuels projected based on historical data.

Table C2. Washington Vehicle Miles Traveled Estimates (millions)

Vehicle Type	2002	2005	2010	2015	2020
Heavy Duty Diesel Vehicle	3,603	3,969	4,578	5,410	6,182
Heavy Duty Gasoline Vehicle	524	556	595	685	766
Light Duty Diesel Truck	538	619	845	1,200	1,668
Light Duty Diesel Vehicle	170	195	267	378	526
Light Duty Gasoline Truck	17,901	18,221	19,594	21,882	23,631
Light Duty Gasoline Vehicle	31,858	32,428	34,872	38,943	42,055
Motorcycle	182	185	199	223	240
Total	54,776	56,174	60,951	68,721	75,067

Table C3. Washington Vehicle Miles Traveled Compound Annual Growth Rates

Vehicle Type	2002-2005	2005-2010	2010-2015	2015-2020
Heavy Duty Diesel Vehicle	3.28%	2.90%	3.39%	2.70%
Heavy Duty Gasoline Vehicle	1.99%	1.38%	2.84%	2.27%
Light Duty Diesel Truck	4.76%	6.43%	7.26%	6.80%
Light Duty Diesel Vehicle	4.76%	6.43%	7.26%	6.80%
Light Duty Gasoline Truck	0.59%	1.46%	2.23%	1.55%
Light Duty Gasoline Vehicle	0.59%	1.46%	2.23%	1.55%
Motorcycle	0.59%	1.46%	2.23%	1.55%
Total	0.84%	1.65%	2.43%	1.78%

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

Gasoline consumption projections were also adjusted to account for ethanol. According to fuel consumption data from EIA, motor gasoline consumed in Washington contained 2.7% ethanol in 2002. For the reference case projections, ethanol consumption was assumed to remain at 2.7% of gasoline consumption through 2020. For this inventory and reference case projection, ethanol is assumed to be carbon neutral, consistent with U.S. EPA GHG inventory procedures.

The on-road gasoline and diesel projections adjusted for fuel efficiency improvements and ethanol consumption suggest average on-road fuel consumption growth rates of 1.05% per year for gasoline and 3.16% per year for diesel between 2005 and 2020.

Washington recently adopted California's vehicle emission standards, which include greenhouse gas emission standards. Currently, these standards are being challenged in the courts by the automobile industry; therefore, the effects of these controls were not included in the baseline inventory.

Aviation

For the aircraft sector, emission estimates for 1990 to 2002 are based on SGIT methods and fuel consumption from EIA. Emissions for jet fuel were projected from 2002 to 2005 using historical jet fuel prime supplier sales volumes in Washington for 2002-2005 from EIA[55]. Emissions for jet fuel were projected from 2005 to 2020 using commercial aircraft operations and emissions for aviation gasoline were projected from 2002-2020 using general aviation operations from the Federal Aviation Administration's Terminal Area Forecast System[56] 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-2005 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 Washington, which was obtained from the FAA source noted above. The resulting compound annual average growth rates are displayed in Table C4.

Table C4. Washington Aviation Fuels Compound Annual Growth Rates

Fuel	2002-2005	2005-2010	2010-2015	2015-2020
Aviation Gasoline	-0.59%	1.46%	1.43%	1.17%
Jet Fuel	0.64%	0.85%	0.52%	0.41%

Rail

For the railroad sector, 1990 – 2004 estimates are based on SGIT methods and fuel consumption from EIA. The historic data for rail shows no significant positive or negative trend; therefore, no growth was assumed for this sector.

Marine

Estimates of commercial marine emissions and fuel consumption were taken from different sources for four areas: Puget Sound, the Columbia and Snake Rivers, other coastal ports, and offshore. Table C5 summarizes the methodology for estimating commercial marine emissions. For the Puget Sound area (Island, Skagit, Whatcom, King, Kitsap, Pierce, Snohomish, Clallam, Jefferson, Mason, and Thurston Counties) base year (2005) emissions were taken from the recent Puget Sound Martime Forum inventory. For the Columbia and Snake Rivers, total 1999 fuel consumption by commercial marine vessels was taken from an inventory developed by Corbett for WA Ecology.[57] Base year (2002) off-shore emissions within state territorial waters (200 nautical miles from shore) were estimated based on a study by Corbett.[58] Other Washington

[55] Washington Prime Supplier Sales Volumes of Petroleum Products, Energy Information Administration, http://tonto.eia.doe.gov/dnav/pet/pet_cons_prim_dcu_SWA_a.htm.
[56] Terminal Area Forecast, Federal Aviation Administration, http://www.apo.data.faa.gov/main/taf.asp.
[57] Corbett, J., "Commercial Marine Vessel Inventory Review and Preparation for the Northwest U.S.", Prepared for the Washington Department of Ecology, May, 2001.
[58] Estimate, Validation, and Forecasts of Regional Commercial Marine Vessel Inventories, submitted by J. Corbett, prepared for the California Air Resources Board, California Environmental Protection Agency, and Commission for Environmental Cooperation in North America, http://coast.cms.udel.edu/NorthAmericanSTEEM/.

coastal port historic emissions were estimated by allocating national EIA marine fuel consumption data in proportion to port tonnage. For Columbia/Snake River, coastal, and off-shore estimates, fuel consumption was allocated to residual and diesel fuel in order to calculate emissions. More detail on each of these estimates are described below.

Table C5. Summary of Methodology for Commercial Marine Fuel Emissions

	Source of Historic Emissions	**Source of Current Year Emissions**	**Source of Forecasts**
Off-shore	Backcast based on ratio of Seattle+ Tacoma tonnage (from ACE)	2002 emissions from Corbett study	RTI forecast of North Pacific commercial marine fuel use (developed for EPA by RTI); CAGR=2.95%
Columbia/Snake Rivers	Backcast based on Columbia River System tonnage	Based on 1999 marine fuel use from Corbett inventory for ECY	Linear trend of 1992-2005 Columbia River System tonnage (from ACE); CAGR=-0.71
Coastal	EIA fuel use allocated based on port tonnage	EIA fuel use allocated based on port tonnage	Linear trend of 1992-2005 WA coastal tonnage (from ACE); CAGR=-1.15%
Puget Sound – Containership	Backcast based on ratio of Seattle+ Tacoma TEUs	2005 emissions from PS Maritime Air Forum	Seattle+Tacoma TEU growth 1990-2005; CAGR=4.17%
Puget Sound – Other OGV	Backcast based on ratio of Seattle+ Tacoma tonnage (from ACE)	2005 emissions from PS Maritime Air Forum	Linear trend of 1992-2005 Seattle+ Tacoma tonnage (from ACE); CAGR=1.05%
Puget Sound – Ferries	Assume constant	2005 emissions from PS Maritime Air Forum	WSDOT Ferries Draft Strategic Plan, hours of operation; CAGR=1.5% (2005-15); CAGR=1.7% (2015-20)
Puget Sound – Tugs and Other Harbor Craft	Backcast based on ratio of total OGV emissions	2005 emissions from PS Maritime Air Forum	Proportional to total OGV forecast emissions; CAGR=2.67%

To estimate historic and future emissions from Puget Sound commercial marine activity, four types of vessels were considered, on the assumption that growth rates would differ by these vessel types: containerships, other ocean-going vessels (OGVs), ferries, other harbor craft (primarily tugs). These methods are summarized as follows:

- Containership emissions for 1990-2004 were estimated by scaling 2005 emissions based on the combined volume of twenty-foot equivalent units (TEUs) at the Port of Tacoma and Port of Seattle. Future year containership emissions were estimated using a growth factor that reflects the 1990-2006 compound annual growth in TEUs at the two ports (4.17%).

- Other OGV emissions for 1990-2004 were estimated by scaling 2005 emissions based on the combined tonnage at the Port of Tacoma and Port of Seattle, as reported the Corps of Engineers “Waterborne Commerce of the United States”. Future year emissions from

other OGVs were estimated to grow in proportion to a projected linear regression of 1990-2005 tonnage at the Port of Tacoma and Seattle (or 1.05% compounded annually).

- 1990-2004 emissions from Puget Sound ferries were assumed to be equal to 2005 emissions. Future year ferry emissions were estimated using growth rates for ferry hours of operation presented in the Washington State Ferries draft *Long-Range Strategic Plan*.[59] These compound annual growth rates are 1.5% for the period 2005-2015 and 1.7% for 2015-2020.

- To estimate 1990-2004 emissions from other Puget Sound harbor craft, we scaled the 2005 emissions based on the ratio of emissions from Puget Sound OGVs. Future year emissions from other harbor craft were assumed to grow in proportion to total Puget Sound OGV emission (2.67% compounded annually).

Table C6 shows the fuel consumption estimates for the Columbia and Snake Rivers and the amount of fuel included in this inventory. For sections of river along the border between Washington and Oregon, half of the fuel consumption is assumed to occur in Washington. Future year emissions for the Columbia and Snake Rivers were estimated based on a linear projection of marine tonnage on this system, as reported the Corps of Engineers "Waterborne Commerce of the United States" (compound annual growth of -1.15%).

Table C6. 1999 Fuel Use by Commercial Marine Vessels in Columbia and Snake Rivers

River Name	Total Fuel Use (1,000 gallons)	Total in WA (1,000 gallons)
Snake River	2,133	2,133
Columbia River Entrance	1,298	649
Willamette above Portland and Yamhill	79	0
Columbia at Bakers Bay	0.5	0.5
Lower Willamette	2,176	0
Columbia & Lower Willamette below Vancouver	24,046	12,023
Columbia between Vancouver and the Dalles	3,687	1,844
Columbia above the Dalles Dam to McNary Lock & Dam	3,459	1,730
Columbia above McNary Lock & Dam to Kennewick	1,236	618
Columbia between Wenatchee & Kettle Falls	7	7
Total	38,119	19,002

Fuel consumption estimates for Washington coastal ports (not covered by the Puget Sound inventory), and for the Columbia/Snake Rivers for the purpose of allocating total fuel consumption, were developed by allocating 1990-2004 national diesel and residual oil vessel bunkering fuel consumption estimates obtained from EIA.[60] Marine vessel fuel consumption was allocated to using the marine vessel activity allocation methods/data compiled to support the

[59] See http://www.wsdot.wa.gov/ferries/planning
[60] U.S. Department of Energy, Energy Information Administration, "Petroleum Navigator" (diesel data obtained from http://tonto.eia.doe.gov/dnav/pet/hist/kd0vabnus1a.htm; residual data obtained from http://tonto.eia.doe.gov/dnav/pet/hist/kprvatnus1a.htm).

development of EPA's National Emissions Inventory (NEI).[61] In keeping with the NEI, 75 percent of each year's distillate fuel and 25 percent of each year's residual fuel were assumed to be consumed within the port area (remaining consumption is assumed to occur while ships are underway). National port area fuel consumption was allocated to this area based on year-specific freight tonnage data for the top 150 ports in the nation as reported in "Waterborne Commerce of the United States, Part 5 – Waterways and Harbors National Summaries."[62] Emissions were then estimated from fuel consumption estimates using SGIT emissions factors for marine diesel and residual fuels.

Offshore estimates of CO_2 and hydrocarbon (HC) emissions for marine vessels in Washington's exclusive economic zone (EEZ) was taken from a study by Corbett for the Commission for Environmental Cooperation in North America (CEC).[63] Offshore CH_4 emissions were estimated by estimating the HC emissions using the CARB TOG profile (#818).[64] Offshore N_2O emissions were estimated by applying the ratio of N_2O to CH_4 emission factors to the CH_4 emission estimate. The 2002 offshore emissions from the CEC inventory were scaled to other historic years based on the combined tonnage handled at the ports of Seattle and Tacoma, as reported in the Corps of Engineers "Waterborne Commerce of the United States, Part 5 – Waterways and Harbors National Summaries." Future year off-shore emissions were estimated using a growth factor (2.95% compound annual growth) for North Pacific commercial marine fuel developed by Research Triangle Institute for the U.S. EPA.

Nonroad Engines

It should be noted that fuel consumption data from EIA includes nonroad gasoline and diesel fuel consumption in the commercial and industrial sectors. Emissions from these nonroad engines are included in the RCI emissions in this inventory (see Appendix B). Table C7 shows how EIA divides gasoline and diesel fuel consumption between the transportation, commercial, and industrial sectors.

Table C7. 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

[61] See methods described in ftp://ftp.epa.gov/EmisInventory/2002finalnei/documentation/mobile/2002nei_mobile_nonroad_methods.pdf

[62] Note that it was necessary to estimate 1990-1992 values by interpolating between by forecasting back from 1993-2004 data.

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

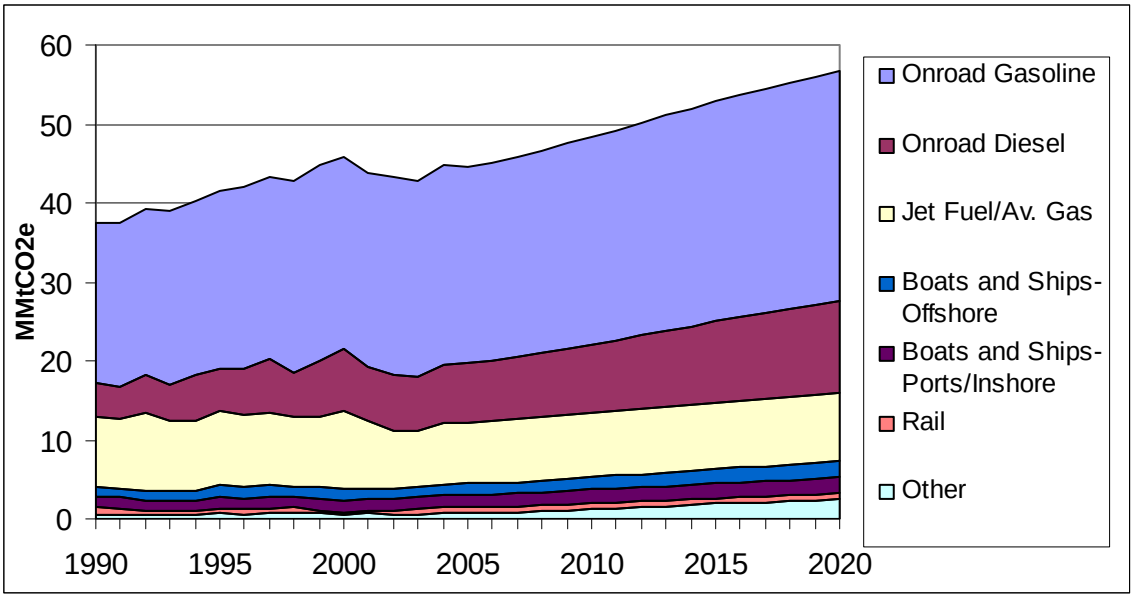
[64] California Air Resources Board, Speciation Profiles, http://www.arb.ca.gov/ei/speciate/speciate.htm.

Results

As shown in Figure C1, on-road gasoline consumption accounts for the largest share of transportation GHG emissions. Emissions from on-road gasoline vehicles increased by 21% from 1990-2005 to account for 56% of total transportation emissions in 2005. GHG emissions from on-road diesel fuel consumption increased by 85% from 1990 to 2005, and by 2005 accounted for 17% of GHG emissions from the transportation sector. The historical data shows a decrease in aviation and diesel fuel consumption between 2000 and 2005, due in part to the economic downturn during that period. Washington's gross state product (GSP) grew at an average rate of 7.1% per year between 1990 and 1999, however, the rate of growth slowed to 2.6% per year between 2000 and 2002. Due to the large decrease in aviation fuel consumption during the first half of this decade, emissions from aviation decreased by 14% between 1990 and 2005. In 2005 jet fuel and marine fuels accounted for 17% and 7% of total transportation emissions, respectively. Emissions from all other categories combined (locomotives, natural gas and LPG, and oxidation of lubricants) contributed approximately 3% of total transportation emissions in 2005.

GHG emissions from all on-road vehicles combined are projected to increase by 27% between 2005 and 2020, due to a 34% increase in VMT during this period and projected fuel efficiency improvements. Historical growth for diesel fuel was much stronger than for gasoline. This trend is expected to continue for the 2005-2020 period, with gasoline and diesel fuel consumption projected to increase by 18% and 57%, respectively. Jet fuel and aviation gasoline consumption is projected to increase by 9% between 2005 and 2020.

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



Key Uncertainties

<u>Projections of Vehicle Miles of Travel (VMT) and Biofuels Consumption</u>

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, on-road 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 consumption of international bunker fuels included in jet fuel consumption from EIA is another uncertainty. This fuel consumption associated with international air flights should not be included in the state inventory (as much of it is actually consumed out of state); 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 Washington, and for which emissions are estimated in this inventory and reference case projection prepared for the Washington Climate Advisory Team (CAT), include the following:

- Carbon Dioxide (CO_2) from:
  - Production of cement;
  - Consumption of limestone, dolomite, and soda ash;
- Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) from semiconductor manufacture;
- CO_2, tetrafluoromethane (CF_4), and Hexafluoroethane (C_2F_6) from aluminum production;
- SF_6 from transformers used in electric power transmission and distribution (T&D) systems; and
- HFCs and PFCs from consumption of substitutes for ozone-depleting substances (ODS) used in cooling and refrigeration equipment.

Washington produces small amounts of lime and nitric acid. These processes emit GHGs but the low levels of production in Washington are expected to generate relatively low GHG emissions. This version of the GHG inventory and projections excludes estimates for these processes, but they may be included in future revisions pending data availability.

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

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

Data Sources and Approach

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.[65] 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

[65] GHG emissions were calculated using SGIT, with reference to EIIP, Volume VIII: Chapter. 6. "Methods for Estimating Non-Energy Greenhouse Gas Emissions from Industrial Processes", August 2004. Referred to as "EIIP" below.

the historical years for which emissions were calculated based on the availability of data. The Washington Department of Ecology's GHG inventory for 1990 through 2004 (recently updated in 2006[66]) for all of the categories shown in Table D1 (except for the consumption of limestone, dolomite, and soda ash) was used in preparing the inventory described in this appendix. The Center for Climate Strategies included emission estimates for the consumption of limestone, dolomite, and soda ash in this inventory to maintain consistency with US EPA methods.

Table D1. Approach to Estimating Historical Emissions

Source Category	Time Period	Required Data for SGIT	Data Source
Cement Manufacturing - Clinker Production	1990 - 2004	Metric tons (Mt) of clinker produced each year.	Washington Department of Ecology provided annual emission estimates for 1990 through 2004 based on actual production data for each year.
Aluminum Production	1990 - 2004	Mt of aluminum produced each year.	Washington Department of Ecology provided annual emission estimates for 1990 through 2004 based on actual production data for each year.
Limestone and Dolomite Consumption	1990 - 2002	Mt of limestone and dolomite consumed.	Used default consumption data available in SGIT for 1994 through 2002. Default data for 1990 through 1993 were not available in SGIT. For default data, the state's total limestone consumption (as reported by USGS[67]) 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 (see footnote 1 for reference to EIIP guidance document).
Soda Ash Consumption	1990 - 2002	Mt of soda ash consumed.	*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 - 2004	Based on state's population and estimates of emissions per capita from the US EPA national GHG inventory.	Washington Department of Ecology provided annual emission estimates based on the SGIT methodology for 1990 through 2004.
Semiconductor Manufacturing	1990 - 2004	State and national value of semiconductor shipments for NAICS code 334413 (Semiconductor and Related Device Manufacturing). Method uses ratio of state-to-national value of semiconductor shipments to estimate state's proportion of national emissions for 1990 - 2002.	Washington Department of Ecology provided annual emission estimates based on the SGIT methodology for 1990 through 2004.
Electric Power T&D Systems	1990 - 2004	Emissions from 1990 to 2004 based on the national emissions per kWh and state's electricity use provided in SGIT.	Washington Department of Ecology provided annual emission estimates based on the SGIT methodology for 1990 through 2004.

[66] *Washington's Greenhouse Gas Emissions: Sources and Trends*, by Stacey Waterman-Hoey and Greg Nothstein, WA State Dept. of Community, Trade & Economic Development, Energy Policy Division, dated December 2006 (Revised 2/12/07), and available from http://www.cted.wa.gov/portal/alias__CTED/lang__en/tabID__853/DesktopDefault.aspx.

[67] United States Geological Survey.

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.

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 Production	2005 - 2020	Compound annual growth rate in employment for Washington's nonmetallic mineral products sector.	Washington State Employment Security Department, Labor Market and Economic Analysis, Workforce Employer, Publications and Reports, Located under "Projections / Long-term Employment Projections."	None*	1.14	1.14	1.14
Limestone and Dolomite Consumption	2003 - 2020	Ditto	Ditto	1.14	1.14	1.14	1.14
Aluminum Production	2005 - 2020	Compound annual growth rate in employment for Washington's primary metals sector.	Ditto	None*	-0.42	-0.42	-0.42
Soda Ash 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	2005 - 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).	None*	7.9	5.8	5.3
Semiconductor Manufacturing	2005 - 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).	None*	-6.2	-9.0	-2.8
Electric Power T&/D Systems	2005 - 2020	Ditto	Ditto	None*	-6.2	-9.0	-2.8

* Actual data used for 2000 – 2004.

Results

Figures D1 and D2 show historic and projected emissions for the industrial processes sector from 1990 to 2020. Total gross Washington GHG emissions from industrial processes were about 7.0 $MMTCO_2e$ in 1990, declined to about 3.3 $MMTCO_2e$ in 2005, but are projected to increase to about 6.2 $MMTCO_2e$ in 2020. The fluctuation in historical emissions (see Figures D1 and D2) is associated with the interaction between declining production activity in the aluminum industry,

and the growth in emissions associated with the use of ODS substitutes that offset the decline in aluminum production emissions. Future emissions are expected to grow rapidly, 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.

Substitutes for Ozone-Depleting Substances (ODS)

HFCs and PFCs are used as substitutes for ODS, most notably CFCs (CFCs are also potent warming gases, with global warming potentials on the order of thousands of times that of CO_2 per unit of emissions) in compliance with the *Montreal Protocol* and the *Clean Air Act Amendments of 1990*.[68] 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. GHG-equivalent emissions from the use of ODS substitutes in Washington were calculated using the default methods in SGIT (see dark green line in Figure D2). Emissions have increased from 0.007 $MMtCO_2e$ in 1990 to about 1.6 $MMtCO_2e$ in 2000, and are expected to increase at an average rate of 6.1% 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.

Aluminum Production

The Washington Department of CTED prepared annual emission estimates for primary aluminum production for 1990 through 2004 based on actual production data for each year. The aluminum production industry is thought to be the largest source of two perfluorocarbons (PFCs) – tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6). Emissions of these two potent GHGs occur during the reduction of alumina in the primary smelting process (see footnote 1 for reference to EIIP guidance document). The employment growth rate for Washington's primary metals sector was used to project emissions to 2020. As shown in Figure D2 (see dark blue line), emissions in 1990 were 5.89 $MMtCO_2e$, declined by about one-third to 3.91 $MMtCO_2e$ in 1995, increased slightly to about 3.94 $MMtCO_2e$ in 2000, and then declined sharply to about 0.36 $MMtCO_2e$ in 2005. From 2005 forward, emissions are projected to decline to about 0.34 $MMtCO_2e$ in 2020, reflecting an overall average annual decrease of about 0.42% over that time period.

[68] 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.

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

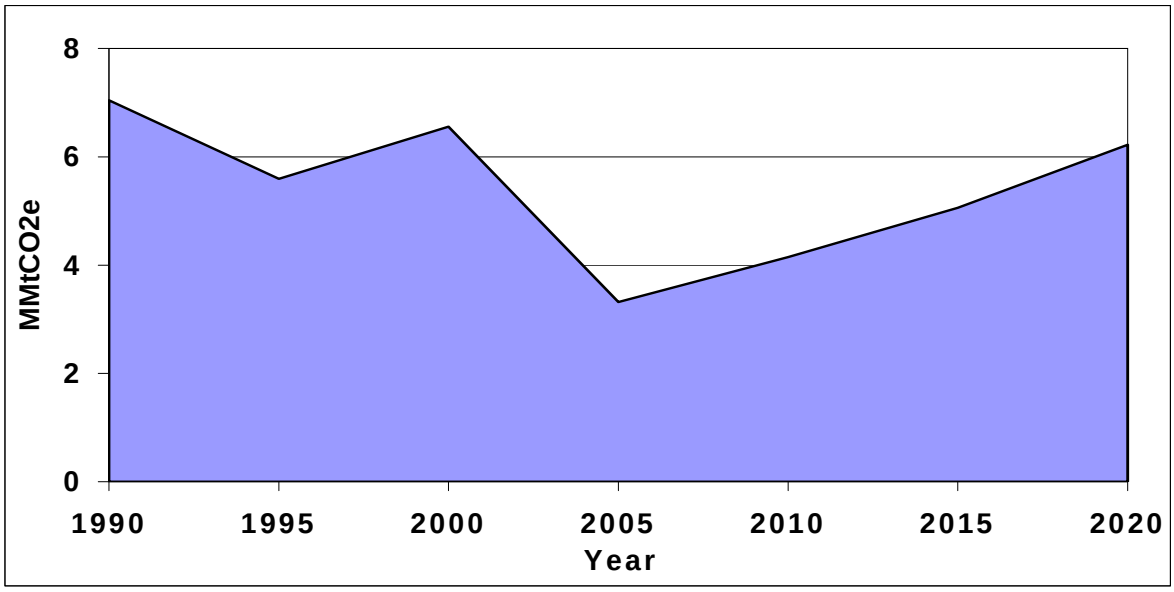
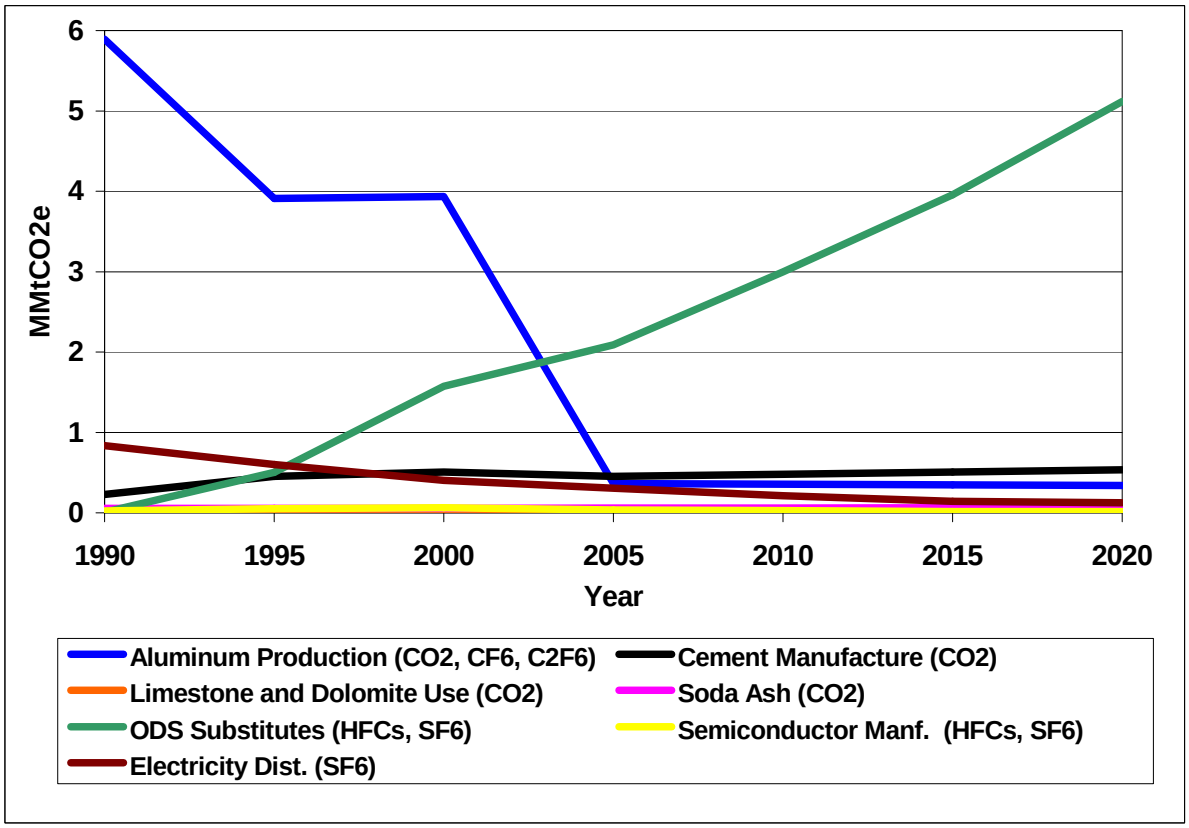


Figure D2. GHG Emissions from Industrial Processes, 1990-2020, by Source



Electricity Distribution

Emissions of SF_6 from electrical equipment 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 electricity T&D systems. Emissions for Washington from 1990 to 2002 were estimated based on the estimates of emissions per kWh from the US EPA GHG inventory and Washington'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 Washington. 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 0.84 $MMtCO_2e$ in 1990 and 0.12 $MMtCO_2e$ in 2020), and therefore appear at the bottom of the graph because of scaling effects in Figure D2.

Semiconductor Manufacture

Emissions of SF_6 and HFCs from the manufacture of semiconductors have experienced declines since 2000 (see yellow line in Figure D2). Emissions for Washington from 1990 to 2004 were estimated based on the default estimates provided in SGIT, which uses the ratio of the state-to-national value of semiconductor shipments to estimate the state's proportion of national emissions from the US EPA GHG inventory (US EPA 2005 *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2003*). 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 Washington. The decline in emissions in the future reflects expectations of future actions by the semiconductor industry to reduce these emissions. Relative to total industrial non-combustion process emissions, emissions associated with semiconductor manufacturing are low (about 0.024 $MMtCO_2e$ in 1990 and 0.015 $MMtCO_2e$ in 2020), and therefore appear at the bottom of the graph because of scaling effects in Figure D2.

Clinker Production for Cement Manufacture

Washington Department of Ecology prepared annual emission estimates for clinker production for 1990 through 2004 based on actual production data for each year. Clinker is an intermediate product from which finished Portland and masonry cement are made. 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 footnote 1 for reference to 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 masonry cement production was not available. The employment growth rate for Washington's nonmetallic mineral products sector was used to project emissions to 2020. As shown in Figure D2 (see black line), emissions in 1990 were 0.23 $MMtCO_2e$, increased to about 0.51 $MMtCO_2e$ in 2000, and declined to about 0.45 $MMtCO_2e$ by 2005. From 2005 forward, emissions are projected to increase to about 0.54 $MMtCO_2e$ in 2020, reflecting an overall average annual increase of about 1.14% 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, chemicals, glass manufacturing, and environmental pollution

control industries, as well as in metallurgical industries such as magnesium production.[69] Recent historical data for Washington were not available from the USGS; consequently, the default data provided in SGIT were used to calculate emissions for Washington from the use of these materials (see orange line in Figure D2). The employment growth rate for Washington's nonmetallic mineral products 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 0.023 $MMtCO_2e$ in 1995 and 0.027 $MMtCO_2e$ 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 Washington for 1990 through 1993, and therefore emissions were not estimated for these years.

Soda Ash Consumption

Commercial soda ash (sodium carbonate) is used in the manufacture of many consumer products such as glass, soap and detergents, paper, textiles, and food. CO_2 is also released when soda ash is consumed (see footnote 1 for reference to 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 0.053 $MMtCO_2e$ in 1990 and 0.061 $MMtCO_2e$ 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:

- Since emissions from industrial processes are determined by the level of production and the production processes of a few key industries, and in some cases, a few key plants, there is relatively high uncertainty regarding future emissions from the industrial processes category as a whole. Future emissions depend on the competitiveness of Washington manufacturers in these industries, and on the specific nature of the production processes used in Washington.
- The projected largest source of future industrial emissions, HFCs and PFCs used in cooling applications, is subject to several uncertainties as well. First, historical emissions are based on national estimates; Washington-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.

[69] 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).

- State-specific industrial consumption data were not available for use of limestone or of dolomite and soda ash. For this initial inventory, the default activity in SGIT was used to estimate emissions. The inventory for these categories can be improved upon in the future by obtaining actual production and consumption data for these industries by contacting the companies that sell limestone and dolomite and soda ash to industries in Washington.
- 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 CO_2 sources above (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. Fugitive Emissions from Fossil Fuel Industries

This appendix reports the additional GHG emissions that are released during the production, processing, transmission, and distribution of fossil fuels. Known as fugitive emissions, these are methane emissions released via leakage and venting at coal mines, oil and gas fields, processing facilities, and pipelines. In 2004, fugitive emissions from natural gas systems, petroleum systems, and coal mines accounted for 2.8% of total US greenhouse gas emissions.[70] Emissions associated with energy consumed by these processes are included in Appendix B, Residential, Commercial and Industrial Sectors.

Oil and Gas Production

Washington does not have any indigenous oil or natural gas production. Washington's five oil refineries import crude oil from the Alaska North Slope, Canada, and other locations, and have a combined capacity of 624 thousand barrels per day, supplying markets throughout the Northwest region.

There is no active oil or gas production in Washington; a few exploratory wells are drilled each year or two but no commercial production is occurring. Thus, emissions of methane (CH_4) occur only from processing, transmission and distribution systems. Washington has five oil refineries, one natural gas geologic storage reservoir, two LNG storage compressor stations and over 2,000 miles of gas pipelines.[71] Uncertainties associated with estimates of Washington's GHG emissions from the oil and gas sector are compounded by the fact that there are no regulatory requirements to track CO_2 or methane emissions. Therefore, estimates based on actual emissions measurements in Washington are not possible at this time.

Data Sources and Approach

The State Greenhouse Gas Inventory Tool (SGIT), developed by the US EPA, facilitates estimation of state-level greenhouse gas emissions.[72] Methane emission estimates are calculated by multiplying emissions-related activity levels (e.g. miles of pipeline, number of compressor stations) by aggregate industry-average emission factors. Key information sources for the activity data are the US DOE EIA[73] and Office of Pipeline Security Distribution and Transmission Annuals 1990- 2005.[74] Methane emissions were estimated using SGIT, with reference to the EIIP guidance document.

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

- Consumption – See Appendix A, Electricity, and Appendix B, Residential, Commercial and Industrial Sector for assumptions used in projecting natural gas consumption in Washington.

[70] "The US Inventory of Greenhouse Gas Emissions and Sinks", US EPA, 2005.
[71] Data from EIA and Gas Facts.
[72] 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.
[73] "Petroleum Navigator" and "Natural Gas Navigator", US DOE Energy Information Administration website, November 2006, Accessed at http://www.eia.doe.gov
[74] http://ops.dot.gov/stats/stats.htm#additional.

Based on those assumptions, Washington's natural gas consumption is projected to grow at an annual rate of about 1.5% until 2020.

- Processing – Refining and transportation rates are forecast to follow recent trends in the State through 2020. Any additional transmission lines in the State may significantly increase actual emission levels, input from reviewers in this regard is welcomed.

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

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 Transmission	Miles of transmission pipeline	Office of Pipeline Security	Emissions are held flat at 2004 levels.[75]
	Number of gas transmission compressor stations	EIIP[76]	
	Number of gas storage compressor stations	EIIP[77]	
	Number of LNG storage compressor stations	Federal Energy Regulatory Commission[78]	
Natural Gas Distribution	Miles of distribution pipeline	Office of Pipeline Security	Distribution emissions follow State gas consumption trend - annual average growth rate of 1.5% between 2006 and 2020.[79]
	Total number of services		
	Number of unprotected steel services	Ratio estimated from 2002 data[80]	
	Number of protected steel services	Ratio estimated from 2002 data[80]	
Oil Refining	Annual amount refined	EIA[81]	Emissions projected to follow trend of 1.6% annual growth in state oil refining.[82]
Oil Transport	Annual oil transported	Unavailable, assumed oil refined = oil transported	Emissions follow trend of state oil refining, as above.

[75] Any new transmission lines proposed for Washington could significantly increase projected emission levels. Review of the Washington State Energy Facility Site Evaluation Council (EFSEC) website did not reveal any proposed transmission lines that have entered the permitting process.
[76] Number of gas transmission compressor stations = miles of transmission pipeline x 0.006 EIIP. Volume VIII: Chapt. 5. March 2005.
[77] Number of gas storage compressor stations = miles of transmission pipeline x 0.0015 EIIP. Volume VIII: Chapt. 5. March 2005.
[78] Northwest Pipeline Corporation Filing with Federal Energy Regulatory Committee Issued July 31, 2006 Accessed at http://www.ferc.gov/eventcalendar/Files/20060731183500-RP06-416-000.pdf
[79] Based on US DOE regional projections and electric sector growth assumptions (see Appendix A and B).
[80] Gas Facts reported unprotected and protected steel services for 2002, but only total services for other years. Therefore the ratio of unprotected and protected steel services in 2002 was assumed to be the ratio for all other years (0.4891 for protected services and 0.0045 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.
[81] Refining assumed to be equal to the total input of crude oil into PADD V times the ratio of Washington's refining capacity to PADD V's total refining capacity. No data for 1995 and 1997, so linear relationship assumed from previous and subsequent years.
[82] Based on EIA data, average growth in crude refined annually was 1.6% between 2000 and 2004.

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

Coal Production Emissions

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

As reported by the EIA, Washington's only operating coal mine was TransAlta's Centralia open pit mine, which produced 5.3 million short tons in 2005.[83] In late 2006, TransAlta stopped mining operations at the Centralia mine, citing that out-of-state coal had become a more economic source of coal for the Centralia power plants.[84] However, Trans Alta is applying for permits to open new coal field in the near future.[85]

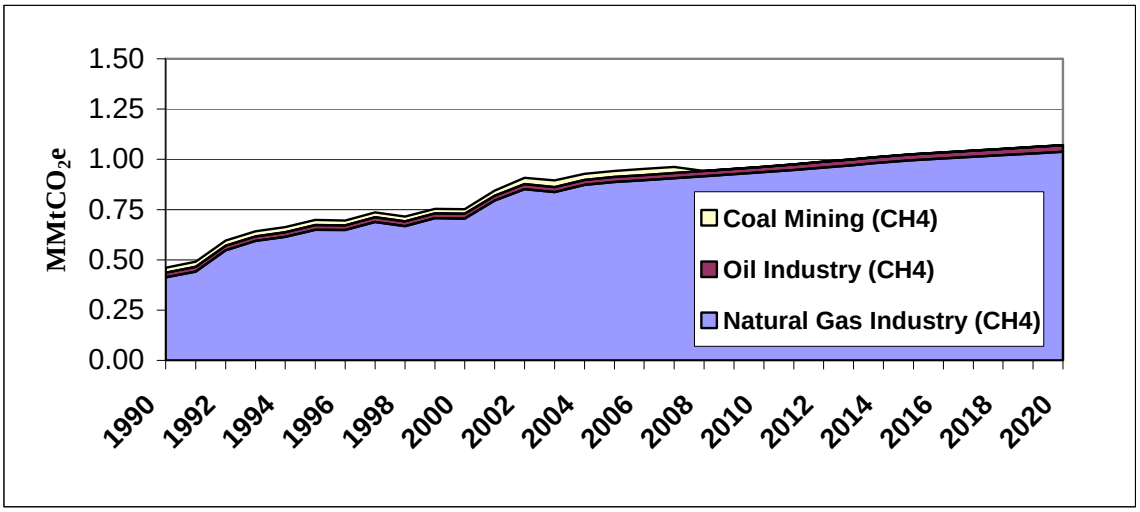
In this inventory, methane emissions from coal mines are as reported by the EPA, and include emissions from the surface mine and post-mining activities.[86] As a result of the Centralia mine closure and current lack of permits for new coal developments, future emissions of coal mine methane were estimated to decrease to zero in 2007 and remain at that level through 2020. Note that any methane emissions from abandoned coal mines are not included in this inventory, as the EPA's emission inventory for abandoned coal mines does not include surface mines and does not report any methane emissions from abandoned Washington coal mines.[87] Any input from TWG members is welcomed.

Results

Figure E1 displays the methane emissions from coal mining and natural gas and oil systems, on a CO_2 equivalent basis. Emissions from this sector doubled from 1990 to 2005 and are projected to increase by a further 13% from 2005 to 2020. Natural gas transmission and distribution systems are the major contributors to historic fugitive GHG emissions, with natural gas distribution driving future emissions growth for this sector. While the Centralia mine closure reduced projected coal mine methane emissions, historically, total emissions from coal mining have been small compared with the natural gas industry.

[83] EIA Annual Coal Report 2005 Accessed at http://www.eia.doe.gov/cneaf/coal/page/acr/acr_sum.html#fes1
[84] TransAlta press release, "TransAlta stops mine operations at Centralia, switches to Powder River Basin coal, and announces intention to write-down Centralia gas-fired plant", November 27, 2006, accessed at www.transalta.com.
[85] Personal Communication. Al Newman, WA Air Quality Program, Department of Ecology. April 2007.
[86] Emissions from EPA *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2004* (April 2006) http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2006.html
[87] US EPA, "Methane Emissions from Abandoned Coal Mines in the United States: Emission inventory methodology and 1990-2002 emissions estimates", April 2004. Note that this inventory does not include emissions data for abandoned surface mines.

Figure E1. Fossil Fuel Industry Emission Trends (Million metric tons CO2e)



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 processing, or any production, of fossil fuels in the State. These industries are difficult to forecast with the mix of drivers: economics, resource supply, demand, and regulatory procedures. The assumptions used for the projections 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 processing and the associated GHG emissions. New government policy could also lead to changes in production, such as future coal-bed methane production as part of geologic sequestration of CO_2 by point sources.
- Other uncertainties include any methane emissions from abandoned coal mines in Washington and potential emission reduction improvements to processing, transportation, and pipeline technologies.

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 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 because of digestive activity in the large fore-stomach. Methane and N_2O emissions from the storage and treatment of livestock manure (e.g., in compost piles or anaerobic treatment lagoons) occur as a result of manure decomposition. The environmental conditions of decomposition drive the relative magnitude of emissions. In general, the more anaerobic the conditions are, the more CH_4 is produced because decomposition is aided by CH_4 producing bacteria that thrive in oxygen-limited aerobic conditions. Under aerobic conditions, N_2O emissions are dominant. Emissions estimates from manure management are based on manure that is stored and treated on livestock operations. Emissions from manure that is applied to agricultural soils as an amendment or deposited directly to pasture and grazing land by grazing animals are accounted for in the agricultural soils emissions.

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

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

Data Sources and Approach

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.[88] 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.[89]

Data on crop production in Washington from 1990 to 2005 and 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.[90] 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 Washington 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 Washington 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 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). As discussed in the following section for soil carbon, the Natural Resources Ecology Laboratory at Colorado State University estimated 0.22 $MMtCO_2$ of emissions from cultivated high organic content soils in Washington for 1997. Therefore, future work should attempt to obtain data to estimate N_2O emissions from cultivated histosol soils in Washington to improve the emission estimates for this category.

Agricultural residue burning is conducted in Washington. The SGIT methodology calculates emissions by multiplying the amount (e.g., bushels or tons) of each crop produced by a series of

[88] 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.

[89] 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/).

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

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 Washington, the default SGIT activity data were used to calculate emissions because state-specific 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 for the 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 Washington 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	-1.3%	Historical emissions for 1990-2002.
Manure Management	1.7%	Historical emissions for 1990-2002.
Agricultural Burning	0.0%	Assumed no growth.
Agricultural Soils – Direct Emissions		
Fertilizers	-3.1%	Historical emissions for 1990-2002.
Crop Residues	0.3%	Historical emissions for 1990-2005.
Nitrogen-Fixing Crops	1.5%	Historical emissions for 1990-2005.
Histosols	0.0%	No historical data available.
Livestock	-2.2%	Historical emissions for 1990-2002.
Agricultural Soils – Indirect Emissions		
Fertilizers	-3.1%	Historical emissions for 1990-2002.
Livestock	-1.2%	Historical emissions for 1990-2002.
Leaching/Runoff	-2.4%	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.

Soil Carbon

Net carbon fluxes from agricultural soils have been estimated by researchers at the Natural Resources Ecology Laboratory at Colorado State University and are reported in the US Inventory of Greenhouse Gas Emissions and Sinks[91] and the US 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 US Agriculture and Forestry Greenhouse Gas Inventory.[7] 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 Washington, Table F2 shows a

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

summary of the latest estimates available from the USDA, which are for 1997.[92] These data show that changes in agricultural practices are estimated to result in a net sink of 1.4 $MMtCO_2e$/yr in Washington. Since data are not yet available from USDA to make a determination of whether the emissions are increasing or decreasing, the net sink of 1.4 $MMtCO_2e$/yr is assumed to remain constant.

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	(0.15)	(0.11)	(0.51)	(0.04)	(0.18)	(0.07)	(0.81)	(0.27)	0.22	(1.4)

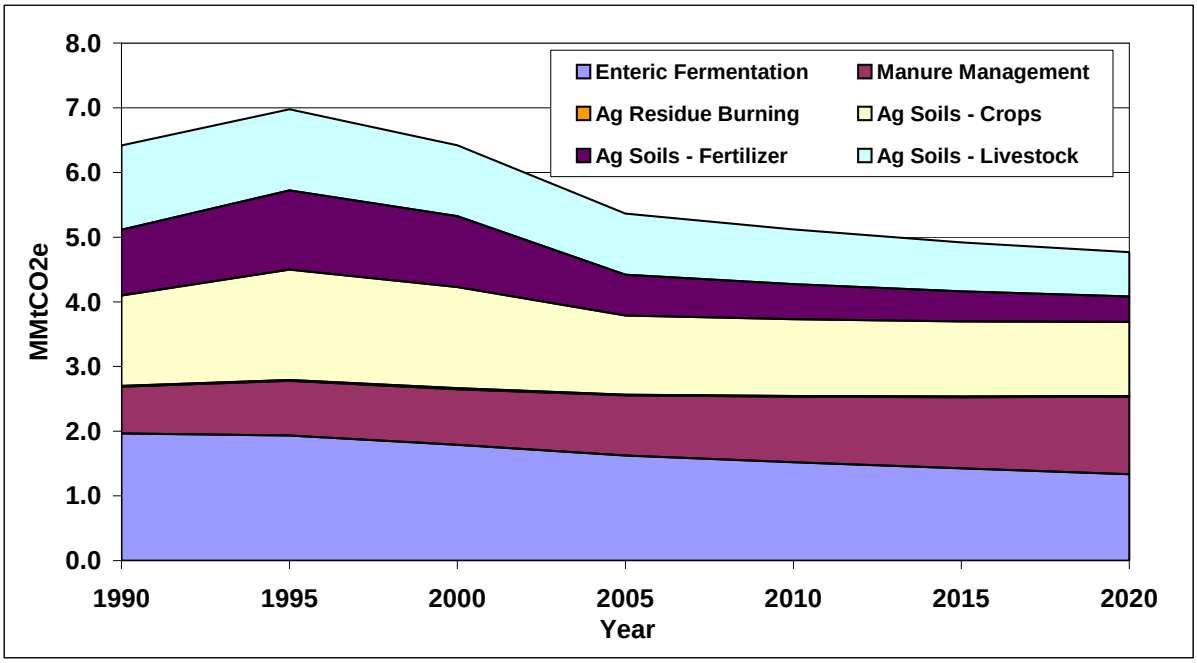
Based on USDA 1997 estimates. Parentheses indicate net sequestration.
[1] Losses from annual cropping systems due to plow-out of pastures, rangeland, hayland, set-aside lands, and perennial/horticultural cropland (annual cropping systems on mineral soils, e.g., corn, soybean, cotton, and wheat).
[2] 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.

Results

As shown in Figure F1, gross GHG emissions from agricultural sources range between about 6.4 and 4.8 $MMtCO_2e$ from 1990 through 2020, respectively. In 1990, enteric fermentation accounted for about 31% (1.96 $MMtCO_2e$) of total agricultural emissions and is estimated to decline to about 28% (1.33 $MMtCO_2e$) of total agricultural emissions in 2020. The manure management category, which shows the highest rate of growth relative to the other categories, accounted for 11% (0.72 $MMtCO_2e$) of total agricultural emissions in 1990 and is estimated to account for about 25% (1.2 $MMtCO_2e$) of total agricultural emissions in 2020. The agricultural soils category shows declining growth, with 1990 emissions accounting for 58% (3.72 $MMtCO_2e$) of total agricultural emissions and 2020 emissions estimated to be about 47% (2.22 $MMtCO_2e$) of total agricultural emissions. Including the CO_2 sequestration from soil carbon, the historic and projected emissions for the agriculture sector would range between about 5.0 and 3.4 $MMtCO_2e$/yr from 1990 through 2020, respectively. Livestock populations for beef and dairy cattle and swine in Washington have declined from 1995 through 2002 (the latest year for which SGIT data were available) resulting in the decline in historical emissions associated with the enteric fermentation, manure management, and agricultural soils livestock categories (see in Figure F1).

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

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); emissions for agricultural residue burning are too small to be seen in this chart. Soil carbon sequestration is not shown (see Table F2).

For the manure management category, historical emission trends increase by an average annual rate of 1.7% while animal populations have declined (see Table F1). The increase in emissions associated with manure management is related to the default assumptions (that change from 1990 through 2002) used in EPA's SGIT on the types of manure management systems primarily for dairy cattle operations. For dairy cattle and heifers, the proportion of manure managed in systems that yield higher GHG emissions (e.g., anaerobic lagoons and liquid slurry) than other systems (e.g., pasture) increased from 68% for dairy cattle and 71% for dairy heifers in 1990, to 76% for dairy cattle and 77% for dairy heifers for 1997 through 2002. For swine operations, from 1990 through 2002, the default SGIT assumptions include a 2% change toward the use of manure management systems that yield higher GHG emissions relative to other systems. Note that for beef cattle, the SGIT uses the same distribution of manure management systems for 1990 through 2002.

Agricultural burning emissions were estimated to be relatively large for Washington based on the SGIT activity data (about 0.01 $MMtCO_2e$/yr from 1990 to 2002). For Washington, this category accounts for about 0.2% of total gross GHG emissions associated with the agricultural sector. Emissions for this category account for about one-half of the national emissions included in the USDA Inventory, which relative to other agricultural categories, reports a low level of residue burning emissions (0.02 $MMtCO_2e$). Even though these initial emission estimates using the SGIT are low relative to emissions associated with the other agricultural categories in Washington, the emission estimates for agricultural burning in Washington are highly uncertain using the SGIT methodology and should be refined using actual activity data for Washington, if available.

The only standard IPCC source categories missing from this report are CO_2 emissions from limestone and dolomite application, and N_2O emissions from the cultivation of histosol soils (discussed above). Estimates for CO2 emissions from limestone and dolomite for Washington were not available; however, the USDA's national estimate is about 9 $MMtCO_2e/yr$.[93]

Key Uncertainties

Emissions from enteric fermentation and manure management are dependent on the estimates of animal populations and the various factors used to estimate emissions for each animal type and manure management system (i.e., emission factors which are derived from several variables including manure production levels, volatile solids content, and CH_4 formation potential). Each of these factors has some level of uncertainty. Also, 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 Washington.

An additional issue related to changes in terrestrial carbon potentially resulting in CO_2 emissions is that of land conversion from agricultural cover to urbanized use. Agricultural cover includes pasturelands, rangelands, croplands, and CRP lands. Data that would yield sufficient information to examine the carbon impact of the conversion of these lands to urbanized development are available (e.g. soil carbon losses due to different types of land development. Therefore, CCS did not develop estimates of GHG emissions related to changes in land cover, in particular agricultural land conversion to urbanized use.

Another contributor to the 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 show a decline in the use of fertilizers; however, there may be a leveling-off in fertilizer use trends due to recent efficiency gains that my be close to reaching their full technical potential.

Although the agricultural burning emissions estimated using the SGIT method are low relative to emissions associated with the other agricultural categories covered by this sector, the emissions account for about one-half of the US total estimated for this category. Future work on the agricultural sector should include efforts to improve the estimates for agricultural burning.

[93] US 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 – 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, CO_2, and N_2O emissions from the controlled combustion of solid waste in incinerators or waste to energy plants; also uncontrolled combustion, also referred to as open burning of waste (e.g. in residential burn barrels) ; and
- Wastewater management – CH_4 and N_2O from municipal wastewater and CH_4 from industrial wastewater (WW) treatment facilities.

Municipal solid waste (MSW), a category of solid waste generated by households and commercial businesses, consists primarily of durable and non-durable goods, packaging, food waste and yard trimmings. The greenhouse gas impact of MSW is dependent on the composition and quantity of waste generated; the waste management strategy such as combustion, recycling or disposing in landfills; landfill characteristics; and the existence of methane flaring or energy conversion technology.[94]

In the MSW sector, this inventory and forecast captures emissions for landfill activities that occur within the State. It is important to note that this does not capture some waste that is imported from other States. For example, some waste is imported from other States and put in the landfill at the Roosevelt landfill in eastern WA. Ecology estimates that about 200,000 to 275,000 tons of waste from out-of-State sources are placed in WA landfills annually with more than half of this going into the Roosevelt landfill.[95] This represents about 5% of the total 2005 landfill waste in the State.

This inventory and forecast does not capture waste that is exported for disposal in other States. For example, the City of Seattle has exported waste to a disposal site in Arlington, Oregon since 1991. Data were not identified to capture the GHG emissions associated with exported waste.

Inventory and Reference Case Projections

Solid Waste Management

Landfills. For municipal solid waste landfills, we used the U.S. EPA SGIT and data on waste emplacement at WA landfills from Ecology[96] as starting points to estimate emissions. The Ecology data served as input data to estimate annual waste emplacement needed by SGIT. SGIT

[94] *Solid Waste Management and Greenhouse Gases, A Life Cycle Assessment of Emissions and Sinks*, US EPA, pg ES-6; http://www.epa.gov/climatechange/wycd/waste/SWMGHGreport.html, September 2006.
[95] Washington State, Department of Ecology, *Solid Waste in Washington State, Fifteenth Annual Status Report*, 2006, p. 96.
[96] Washington State, Department of Ecology, *Solid Waste in Washington State, Fifteenth Annual Status Report*, 2006.

then estimates CH_4 generation for each landfill site using a commonly-employed first order waste decomposition model (e.g. as in EPA's AP-42 document).[97] Additional post-processing outside of SGIT to account for controls was then performed to estimate CH_4 emissions.

The data provided by Ecology contained annual waste emplacement data from 1992 to 2005 for three categories of landfills: controlled landfills with a landfill gas to energy (LFGTE) plant; controlled landfills with a flare; and uncontrolled landfills. Since SGIT requires emplacement data back to at least 1990, the missing years of data for each site were filled in using the average annual emplacement from 1992-1994.

There were a total of 29 sites in the Ecology database plus another 20 miscellaneous landfills that were small uncontrolled sites that were closed in the early 1990s or earlier. Eight of the sites collect landfill gas for use in an LFGTE plant. Another seven sites collect and flare landfill gas. These 15 sites are listed in the table below. The remaining 14 sites are uncontrolled.

Site Name	Control
Roosevelt Regional LF	LFGTE
Cedar Hills LF	LFGTE
Hidden Valley LF	LFGTE
Olympic View LF	LFGTE
Northside LF	LFGTE[a]
Tacoma LF	LFGTE
Cowlitz County LF	LFGTE
Centralia LF	LFGTE
Cathcart LF	Flare
Greater Wenatchee LF	Flare
Thurston Co.	Flare
Terrace Heights	Flare
Cheyne	Flare
Leichner	Flare
Fort Lewis	Flare

[a] Closed in 2005.

CCS performed three different runs of SGIT to estimate methane emissions from MSW landfills: (1) uncontrolled landfills; (2) landfills with a landfill gas collection system and LFGTE plant; and (3) landfills with landfill gas collection and a flare. SGIT produced annual estimates through 2005 for each of these landfill categories. CCS then performed some post-processing of the landfill emissions to account for landfill gas controls (at LFGTE and flared sites) and to project the emissions through 2020. For the controlled landfills, CCS assumed that the overall methane collection and control efficiency is 75%.[98] Of the methane not captured by a landfill gas collection system, it is further assumed that 10% is oxidized before being emitted to the atmosphere (consistent with the SGIT default assumption).

[97] EPA's AP-42 Section covering Municipal Solid Waste Landfills can be found at: http://www.epa.gov/ttn/chief/ap42/ch02/final/c02s04.pdf.
[98] As per EPA's AP-42 Section on Municipal Solid Waste Landfills: http://www.epa.gov/ttn/chief/ap42/ch02/final/c02s04.pdf.

Growth rates were estimated by using the historic (1995-2005) growth rates of emissions in both the controlled and uncontrolled landfill categories. The period from 1995 to 2005 was used since there were a large number of landfill closures prior to 1995 (which could have affected waste management practices). Hence, the post-1995 period is thought to be most representative of waste emplacement rates and subsequent emissions. The annual growth rates are: 3.5% for uncontrolled sites; 1.1% for flared sites; and 3.2% for LFGTE landfills.

CCS used the SGIT default for industrial landfills. Based on estimates of the quantity of waste in place at industrial landfills and on the estimated organic content of industrial landfills compared to MSW landfills, U.S. EPA (1993) estimated that CH_4 generation from industrial landfills in the United States is approximately 7 percent of CH_4 generation from MSW landfills in the United States, prior to adjusting for flaring and recovery or oxidation.[99] We assumed that this additional industrial waste emplacement occurs beyond that already addressed in the emplacement rates for MSW sites. Due to a lack of data, no controls were assumed for industrial landfill waste. For industrial landfills, the overall growth rate in MSW emissions from 1995 to 2005 was 2.9%/yr, which was used to project emissions to 2010 and 2020.

Solid Waste Combustion. Ecology provided throughput data for the only municipal waste combustion facility currently operating in WA (Spokane).[100] SGIT defaults (emission factors, waste characteristics) were used to estimate emissions using these data. Data on other waste combustion facilities that previously operated in WA were not available. No information was identified on plans for additional plants in the future or expanded capacity at the existing plant, so emissions were held constant in the forecast years.

Open burning of MSW at residential or municipal sites can also contribute GHG emissions. If data are available, future inventory work should attempt to capture this source of emissions.

Wastewater Management

Municipal Wastewater Management. 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 G1 below. The growth rate for municipal wastewater treatment used to forecast emissions from 2005 to 2020 is 2.1%/yr. This is based on the historical emissions growth between 1990 and 2005.

[99] EIIP Volume VIII, Chapter 13 – Municipal Solid Waste, August 2004.
[100] Gail Sandlin, Ecology, personal communication with S. Roe, CCS, May 2007.

Table G1. SGIT Key Default Values for Municipal Wastewater Treatment

Variable	Value
BOD	0.065 kg /day-person
Amount of BOD anaerobically treated	16.25%
CH_4 emission factor	0.6 kg/kg BOD
WA residents not on septic	75%
Water treatment N_2O emission factor	4.0 g N_20/person-yr
Biosolids emission Factor	0.01 kg N_2O-N/kg sewage-N
Source: U.S. EPA State Inventory Tool – Wastewater Module; methodology and factors taken from U.S. EPA, Emission Inventory Improvement Program, Volume 8, Chapter 12, October 1999: www.epa.gov/ttn/chief/eiip/techreport/volume08/.	

Industrial Wastewater Management. For industrial wastewater emissions, SGIT provides default assumptions and emission factors for three industrial sectors: Fruits & Vegetables, Red Meat & Poultry, and Pulp & Paper. Ecology was able to provide information on flows and chemical oxygen demand (COD) for fruit and vegetable processing, but only COD for the other two categories.[101] Therefore, only emissions from fruit and vegetable processing were estimated. The data on annual wastewater flows from Ecology were used to back-calculate an annual production value using SGIT data (3.8 cubic meters of wastewater for every ton processed). Due to incomplete data for all years, the calculated production value was used for each year of the inventory and forecast.

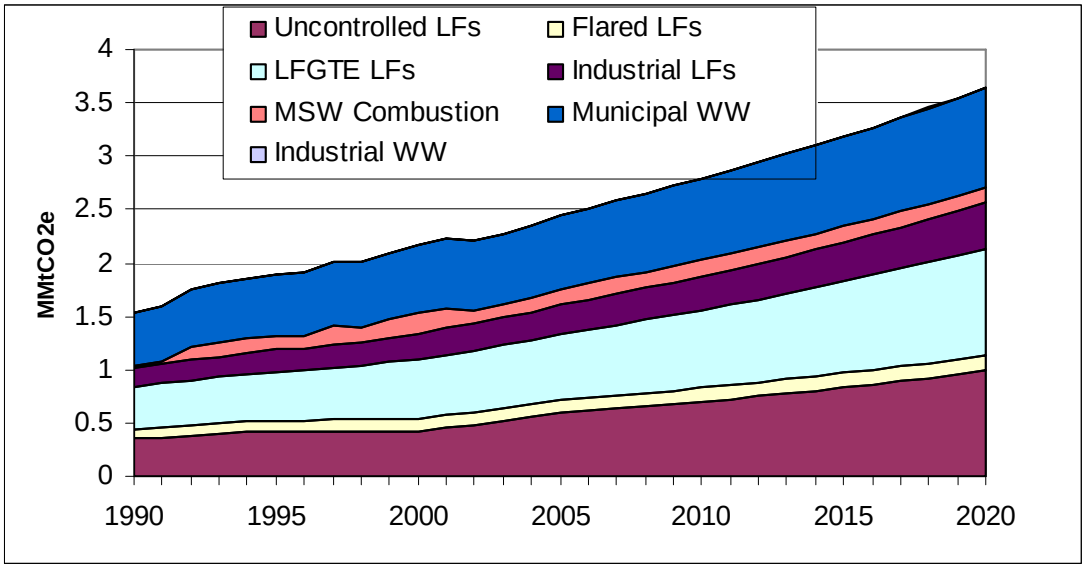
Results

Figure G1 shows the emission estimates for the waste management sector. Overall, the sector accounts for 2.4 $MMtCO_2e$ in 2005. By 2020, emissions are expected to increase to 3.6 $MMtCO_2e$/yr. For solid waste management sector, emissions are expected to increase as a result of more waste being emplaced in each of the landfill categories. In 1990, about 23% of the waste management sector emissions were contributed by the uncontrolled landfills; and about 25% by LFGTE landfills. By 2020, the contributions from these landfill categories are expected to rise slightly 27% and 28%, respectively.

As mentioned above, due to data availability, we modeled only emissions from fruit and vegetable processors in the industrial wastewater treatment sector (and these emissions were held constant at 2005 levels throughout the inventory and forecast). Less than 0.1% of the emissions were contributed by the industrial wastewater treatment sector. In 2005, 28% of the waste management sector emissions were contributed from municipal wastewater treatment systems. Note that these estimates are based on the default parameters listed in Table G1 above and might not adequately account for existing controls (e.g. anaerobic digesters served by a flare or other combustion device). By 2020, municipal wastewater treatment is expected to contribute about 26% of the waste management sector emissions.

[101] Carrol Johnston, Ecology, personal communication with S. Roe, CCS, December 2006. The average COD for fruit and vegetable processors at the monitoring point listed as "process wastewater" was 3.8 grams/liter compared to the SGIT default of 5.6 grams/liter. This value was used within SGIT to estimate methane emissions. Process wastewater flow data were available for 1995, 2000, and 2005; however, the 2005 data appeared to be most complete. For seven fruit and vegetable processing facilities, an annual flow of 369 million gallons was estimated and used as input for all years.

Figure G1. Washington GHG Emissions from Waste Management



Notes: LF – landfill; WW – wastewater; LFGTE – landfill gas to energy. Industrial WW is too small to show on this chart.

Key Uncertainties

The methods used to model landfill gas emissions do not adequately account for the points in time when controls were applied at individual sites. Hence, for landfills, the historical emissions are less certain than current emissions and future emissions for this reason (since each site that is currently controlled was modeled as always being controlled, the historic emissions are low as a result). The modeling also does not account for uncontrolled sites that will need to apply controls during the period of analysis due to triggering requirements of the federal New Source Performance Standards/Emission Guidelines. Similarly, the modeling does not account for sites that are currently flared, but may opt to incorporate LFGTE during the period of analysis.

As mentioned above, these estimates for MSW landfills do not capture emissions associated with waste that is generated in the State but exported for disposal elsewhere. Also, some importing of waste for landfilling occurs, and these emissions are also not captured in this analysis. Future work should include gathering information on the amounts of waste imported/exported and the methods of disposal, so that emissions can be estimated.

For industrial landfills, these were estimated using national defaults (7% of the rate of MSW methane generation). Hence, the industrial landfill inventory and forecast has a significant level of uncertainty and should be investigated further. For example, the existence of active industrial landfills should be determined, available emissions data assessed, or modeling performed based on waste characteristics (based on the biodegradable fraction of the waste). As with overall MSW landfill emissions, industrial landfill emissions are projected to increase slightly between 2005 and 2020.

For the wastewater sector, the key uncertainties are associated with the application of SGIT default values for the parameters listed in Table G1 above (e.g. fraction of the WA population on septic; fraction of BOD which is anaerobically decomposed). The SGIT defaults were derived from national data. Also, data were not available to estimate emissions from the meat & poultry and pulp & paper industry sectors. Based on the rough estimates prepared for fruit and vegetables, CCS anticipates that the contributions from the industrial wastewater treatment sector would be fairly low.

Appendix H. Forestry

Overview

Forestland emissions refer to the net CO_2 flux[102] from forested lands in Washington, which account for about 48% of the state's land area.[103] The dominant forest types in WA are Douglas fir forests, which make up about 38% of forested lands and Hemlock-Sitka spruce forests which make up another 23%. Other important forest types are Ponderosa pine, Fir-Spruce, and hardwood forests.

Forestlands are net sinks of CO_2 in Washington. 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. CO_2 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 States Department of Agriculture Forest Service (USDA-FS) has been developing and refining a forest carbon modeling system for the purposes of estimating forest carbon inventories. The methodology is used to develop national forest CO_2 fluxes for the official US Inventory of Greenhouse Gas Emissions and Sinks.[104] The national estimates are compiled from state-level data. The Washington forest CO_2 flux data in this report come from the national analysis and are provided by USDA-FS.

The forest CO_2 flux methodology relies on input data in the form of plot level forest area and 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 tree measurements to give estimates of C density (Mg per hectare) for the tree carbon pool. The carbon content of other pools is estimated using relationships between tree carbon and those pools. Soil carbon is estimated as a function of forest cover type. Detailed descriptions of the FORCARB2 modeling system can be found in current versions of the U.S. Inventory of Greenhouse Gas Emissions and Sinks.

CO_2 flux is estimated as the change in carbon stock for each carbon pool over a specified time frame. Forest carbon stock data from at least two points in time are required to calculate flux. The change in carbon stocks between time intervals is estimated for specific carbon pools (Live Tree, Standing Dead Wood, Understory, Down & Dead Wood, Forest Floor, and Soil Organic

[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 21.9 million acres. Acreage by forest type available from the USFS at: http://www.fs.fed.us/ne/global/pubs/books/epa/states/WA.htm. The total land area in WA is 45.6 million acres (http://www.50states.com/Washington.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.

Carbon) and divided by the number of years between inventory measurements. Annual increases in carbon stocks reflect carbon sequestration in a specific pool; decreases in carbon stocks 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 sum of carbon stock changes for all forest carbon pools yields a total net CO_2 flux for forest ecosystems. Personal communication with USDA-FS experts indicates a high degree of uncertainty in the soil carbon pool estimates; therefore this pool is not included in the total for Washington.

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 Table H1, nearly 12 $MMtCO_2$/yr is estimated as sequestered annually in wood products from WA forests.[105] The USDA-FS models the amount of carbon moving into and remaining stored in the HWP products pool over time using the WOODCARB model. Additional details on the HWP model and other aspects of the forest carbon inventory methods can be found in Annex 3 to EPA's 2006 GHG inventory for the U.S.[106]

Forest carbon stocks at any point in time are the product of forest carbon density and forest area. Thus, the combined impact of changes in both of these factors over a specified time period influences the total estimated net carbon flux. These factors vary to some degree by different ownership classes and major climatic regions. For this reason, the USDA-FS provided forest carbon estimates separately for the East- and West-sides of Washington and for National and non-National Forests (Tables H1, H2, and H3).

The data shown below are based on the most recent estimates from the USDA-FS and will be included in the upcoming 2005 estimates in EPA's national GHG inventory.

[105] Jim Smith, USFS, personal communication with S. Roe, CCS, October 2006.
[106] 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.

Table H1. Forest Carbon Flux Estimates for Washington (MMtCO2e)

	Westside			Eastside			
	National Forest	Non-National Forest	Westside Total	National Forest	Non-National Forest	Eastside Total	**WA State Total**
Live Tree	-6.10	-5.98	-12.08	-5.29	5.31	0.01	-12.06
Standing dead	0.88	-0.38	0.50	-0.48	0.00	-0.48	0.02
Understory	-0.10	0.05	-0.05	-0.21	-0.14	-0.36	-0.41
Down dead	-0.79	-0.89	-1.68	-0.61	0.56	-0.04	-1.72
Forest floor	-0.07	-2.30	-2.37	-0.01	-0.35	-0.36	-2.73
Soil organic C	-3.02	-1.10	-4.12	-2.27	-1.39	-3.66	-7.79
HWP	na	na	na	na	na	na	-11.73
Total Forest C Flux (not including soil carbon)							**-28.63**

Negative values indicate sequestration; positive values indicate emissions
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 and with K. Bickel June 2007.

Discussion

Forest Area Trends

As noted above, changes in forest area influence total forest carbon flux in Washington State. Therefore, reliable estimates of forest area over time are an important input to any forest carbon methodology. The USDA-FS methodology relies on FIA data for forest areas, as shown in Table H2[107]. FIA data indicate a net increase in forest area for Washington from 1991 to 2005.

Table H2. Forest Area Data (hectares) for 1991 and 2005 used to estimate Forest Carbon Stocks

	Westside			Eastside			
	National Forest	Non-National Forest	Westside Total	National Forest	Non-National Forest	Eastside Total	**WA State Total**
1991	1,371,667	3,588,209	4,959,876	1,831,120	2,025,402	3,856,522	8,816,398
2005	1,412,367	3,536,270	4,948,637	1,933,292	2,069,372	4,002,664	8,951,301
Change in Area	40,700	-51,939	-11,239	102,172	43,970	146,142	134,903

A look at finer temporal periods can reveal trends in forest land use change during this time frame that are not evident in the above data. For example, CCS queried the FIA database for total forest area in 2003, resulting in an estimated area of 8,742,746 hectares of forestland in

[107] National Forest lands are not included in the 1991 FIA database. The USFS used a data from the 1987 Resource Planning Assessment to estimate forest area and carbon flux on National Forests in 1991.

2003. Thus, according to FIA, forest areas declined in Washington from 1991 to 2003, and increased from 2003 to 2005, eventually surpassing 1991 levels. While finer scale land area change data are available, the total forest carbon estimates are only available for 1991 and 2005, thus the net flux calculated for this report reflects the average trends for this time period. Key uncertainties in the FIA forest sampling system are discussed in the Key Uncertainties section below.

Given the important role of forest area change in determining net carbon flux, relevant data from a recent study conducted by the University of Washington are reported here as well.[108] The UW study analyzed trends in forest area change using both FIA data from 1978-2001 and remote sensing data from 1988-2004. The study used FIA data to look at trends in non-National Forest timberlands (i.e., forests capable of growing more than 20 cubic feet of timber per year) from 1978-2001 across all of Washington, and concluded that land area in timberlands declined at a rate of 0.37% per year during this time. The report also used FIA data to analyze ownership trends for timberland classes and showed an overall trend of shifting ownership from traditional forest industry companies to private ownership classes, followed by the subsequent conversion of timberland in private ownership to non-forest uses. The remote sensing analysis covered western Washington only and revealed trends of net forest loss on the order of 1.04% per year from 1988-2004.

Forest Carbon Density Trends

Important differences in carbon density exist between Eastside and Westside forests, and also between National Forest and non-National Forest ownerships. The USDA-FS methodology accounts for this by separating the analysis of area change and carbon density change into four different categories (Table H3).

Table H3. Differences in 2005 forest C density between Eastside and Westside and across ownerships for Washington.

	C density (t C per ha)	
	in forest	trees only
Eastside		
National Forest	220.8	100.7
nonNational Forest	188.6	77.3
Westside		
National Forest	380.2	229.2
nonNational Forest	302.1	159.2
total	**270.6**	**138.7**

This analysis shows that average Westside forests of all ownerships have more than double the C density of average Eastside forests of all ownerships, and National Forest ownerships tend to have higher C density values than non-National Forest ownerships.

[108] Future of Washington's Forest and Forest Industries Study July 2007, Study 4: Forest Land Conversion in Washington State

Interannual Variability

The annual carbon flux for Washington forests calculated from inventory measurements reflects average annual trends over fourteen years. Of course, annual fluxes will vary from year to year. However, current available data and methodologies do not allow for analysis of inter-annual variability. Moreover, information is not currently available on the near term effects of climate change and their impacts on forest productivity, or on future rates of forest area change. Hence, there is no change in the estimated future sinks for 2010 and 2020.

Wildfire and Non-CO2 Losses

The USDA-FS forest carbon methodology captures carbon stock losses from fires, but it does not address non-CO_2 emissions. In order to provide a more comprehensive understanding of GHG sources/sinks from the forestry sector, CCS also developed some rough estimates of state-wide emissions for methane and nitrous oxide from wildfires and prescribed burns. A study published earlier this year in *Science* indicated an increasing frequency of wildfire activity in the western U.S. driven by a longer fire season and higher temperatures.[109]

CCS used 2002 emissions data developed by the Western Regional Air Partnership (WRAP) to estimate CO_2e emissions for wildfires and prescribed burns.[110] The CO_2e from methane emissions from this study were added to an estimate of CO_2e for nitrous oxide to estimate a total CO_2e for fires. The nitrous oxide 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 fires contributed about 0.28 MMtCO_2e of methane and nitrous oxide. Most of this was contributed by wildfires (0.14 MMtCO_2e) and agricultural burning (0.11 MMtCO_2e). In 2002, there were about 90,000 acres burned by wildfires and about 660,000 acres of agricultural burning. About 90% of the CO_2e was contributed by CH_4. Note that the 2002 level of wildfire activity compares to about 132,000 acres burned in Washington in 1996.[111] Also, in 2002, about two-thirds of the total fuel consumed came from agricultural burning.

A comparison estimate was made using emission factors from a 2001 global biomass burning study[112] and the total tons of biomass burned from the 2002 WRAP fires emissions inventory. This estimate is 0.63 MMtCO_2e with about equal contributions from methane and nitrous oxide on a CO_2e basis. Given the large swings in fire activity from year to year and the current lack of

[109] Westerling, A.L. et al, "Warming and Earlier Spring Increases Western U.S. Forest Wildfire Activity", *Sciencexpress*, July 6, 2006.
[110] *2002 Fire Emission Inventory for the WRAP Region Phase II*, prepared by Air Sciences, Inc. for the Western Regional Air Partnership, July 22, 2005. Ecology also provided activity data for agricultural and silvicultural burning to CCS. A review of the WRAP's report shows that data are included for WA covering the prescribed fire, agricultural burning, and prescribed rangeland burning categories. Therefore, the WA were not used to prepare any additional emission estimates.
[111] *1996 Fire Emission Inventory*, Draft Final Report, prepared by Air Sciences, Inc. for the Western Regional Air Partnership, December 2002.
[112] 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.

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 0.1 – 0.5 $MMtCO_2e$ annually in WA from methane and nitrous oxide emissions.

Key Uncertainties

A key uncertainty in the forest carbon flux estimates is the comparability over time of the underlying forest area data. The FIA forest sampling program is developed to provide an unbiased representation of forest land area. FIA chooses an unbiased set of plots for field sampling in each inventory cycle, with the goal of representing the variety of forest conditions occurring on the ground at that time. It is widely believed to be the best available long-term data set on forest resources in the nation. However, conversations with national experts and local FIA personnel revealed that aspects of the FIA program and its evolution over time have resulted in potential sampling errors that can challenge long-term comparisons made from FIA data. These are described below to give an indication of the potential sources of error.

Nationwide, in the late 1990's and early 2000's FIA moved from a periodic to an annual sampling protocol; the annual sampling protocol was first implemented in Washington in 2001. The annualized protocol involves sampling a fraction of the total number of FIA plots in a state each year, so that 100% of the plots are inventoried every ten years. In Washington, this means that 400 plots are sampled each year for a total of 4,000+ plots in WA over the full inventory cycle. Each year, the inventory results are adjusted to incorporate new data that are collected that year.

After a full ten-year cycle is completed, the FIA will have sampled approximately one in 6,000 forested acres in Washington. In the initial years of the inventory cycle, relatively few plots have been sampled so the potential error in summarized results calculated from these data is relatively large. As new data are added to the database each year, the potential error in inventory-based results will decrease.

In this report, the 1991 FIA data are derived from the periodic sampling protocol, while the 2005 data are based on four years of sampling under the more recent annualized design (i.e., includes 40% of the total FIA plots). Therefore, the range of error around these forest carbon estimates is likely to be relatively wide. While a quantitative assessment of the error range for the forest carbon estimates reported here is not available, as with most inventory-based estimates of forest C stock change in North America, it is possible that the true value lies somewhere within 50% above or 50% below the estimate reported here.[113] If these estimates were recalculated

[113] Birdsey, R.A., J.C. Jenkins, M. Johnston, E. Huber-Sannwald, B. Amerio, B. de Jong, J.D.E. Barra, N. French, F. Garcia-Olivia, M. Harmon, L.S. Heath, V. Jaramillo, K. Johnsen, B.E. Law, O. Masera, R. Neilson, Y. Pan, K.S. Pregitzer, E.M. Spiotta, 2007: North American forests, in *The First State of the Carbon Cycle Report (SOCCR): The North American Carbon Budget and Implications for the Global Carbon Cycle.* A.W. King, L. Dilling, G.P. Zimmerman, D.M. Fairman, R.A. Houghton, G. Marland, A.Z. Rose, T.J. Wilbanks, editors. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

annually, the range of error would likely decrease until 2011 when the sampling of all FIA plots in Washington will be completed.

When sampling switched from the periodic to the annual inventory system, in WA as in other states, attempts were made to retain and re-sample plots that had been sampled previously in order to maintain a record that would allow for trend estimation. Attempts were also made to retain the unbiased nature of the sample, so there is no indication that a sampling bias has occurred in any forest type in the transition from periodic to annual inventory.

There have been modifications to the definition of forests for some specific forest classes. For example, FIA modified the definition of forest cover for the woodlands class of forestland. Earlier FIA cycles defined woodlands as having a tree cover of at least 10%, while the newer sampling methods used a woodlands definition of tree cover of at least 5% (leading to more area being defined as woodland). In woodland areas, the earlier FIA surveys might not have inventoried trees of certain species or with certain tree form characteristics (leading to differences in both carbon density and forested acreage). Given that woodlands do not make up much of Washington's forests, these methodological differences are not thought to have a substantial effect on the flux estimates.

For the specific case of newly established riparian areas (an area of potential interest in Washington), FIA's definition of "forest" includes contiguous land that is at least 1 acre in size and at least 50 feet wide. Therefore, if a narrow riparian buffer has been established in an area that was previously pasture or cropland, the FIA forest area sample will not reflect that increase in tree cover. If management activities have changed in existing riparian buffers, the effects of those changes will be reflected in the overall inventory, just as changes in any other management trends would be reflected in the overall inventory sample.

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 7% of the total 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 USDA-FS. In general, Western National Forests show a relatively large rate of carbon sequestration concurrent with an increase in forest area. It is possible that changes in FIA sampling resulted in more forest area coming into the inventory sample in the second time period.

Appendix I. Inventory and Forecast for Black Carbon

This appendix summarizes the methods, data sources, and results of the development of an inventory and forecast for black carbon (BC) emissions in Washington. 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 and other sources.[114] 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.[115] 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

[114] Tom Moore, Western Regional Air Partnership, data files provided to Steve Roe, CCS, December 2006; Corbett, J., et al, *Estimation, Validation, and Forecasts of Regional Commercial Marine Vessel Emissions, Tasks 1 and 2: Baseline Inventory and Ports Comparison, Final Report,* May 3, 2006.
[115] Version 4.0 of the SPECIATE database and report: http://www.epa.gov/ttn/chief/software/speciate/index.html#related.

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.

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.[116] These methods are based on the modeling of Jacobson (2002)[117] and his updates to this work (Jacobson, 2005a).[118] 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).

[116] 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.

[117] 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.

[118] 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.

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 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 and Discussion

We estimate that BC mass emissions in Washington total about 9.5 MMtCO_2e in 2002. This is the mid-point of the estimated range of emissions. The estimated range is 6.1 – 12.9 MMtCO_2e (see Table I1). The primary contributing sectors in 2002 were nonroad diesel (48%), onroad diesel (25%), nonroad gasoline (7%), commercial marine vessels (6%), and rail (6%). The commercial marine vessels (CMV) sector includes emissions for both in-port operations as well as underway emissions within 200 miles of Washington's coastline.[119]

The nonroad diesel sector includes exhaust emissions from construction/mining, industrial and agricultural engines, as well as recreational marine vessels. Agricultural engines contributed about 45% of the nonroad diesel total, while construction and mining engines contributed another 35%. For nonroad gasoline engines, primary contributors included pleasure craft (47%), lawn and garden equipment (20%), and recreational equipment (16%).

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 4.5 MMtCO_2e in 2002 drops to 1.2 MMtCO_2e in 2018. For the onroad diesel sector, 2.4 MMtCO_2e was estimated for 2002 dropping to 0.4 MMtCO_2e in 2018. 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.

Data for underway commercial marine vessels were not available. However, we would expect these to be the dominant source of BC emissions in the future, since the new federal standards mentioned above are not expected to have any significant effect on this sector.

[119] Particulate matter emissions, from the Corbett et al (2006) study referenced in the footnote above, were used as the starting point for estimating CMV emissions. These include in-port as well as underway emissions within 200 miles from shore (the Exclusive Economic Zone). The BC and OM fractions from the same speciation profiles used in the WRAP inventory (also referenced above) were applied to estimate BC and OM mass emissions, which were then transformed into their CO_2 equivalents.

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).[120] 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. 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.

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

Table I1. 2002 BC Emission Estimates

Sector	Subsector	Mass Emissions			CO_2e		Contribution to CO_2e
		BC	OM	BC + OM	Low	High	
		Metric Tons			Metric Tons		
Electric Generating Units (EGUs)							
	Coal	50	72	122	49,717	105,009	0.8%
	Oil	1	1	3	1,093	2,309	0.0%
	Gas	0	27	27	0	0	0.0%
	Other	3	5	9	3,125	6,600	0.1%
Non-EGU Fuel Combustion (Residential, Commercial, and Industrial)							
	Coal	24	35	59	24,050	50,796	0.4%
	Oil	37	33	70	36,713	77,543	0.6%
	Gas	0	1,094	1,094	0	0	0.0%
	Other[a]	3,071	14,785	17,856	191,902	405,320	3.1%
Onroad Gasoline (Exhaust, Brake Wear, & Tire Wear)		226	907	1,133	78,312	165,404	1.3%
Onroad Diesel (Exhaust, Brake Wear, & Tire Wear)		1,733	729	2,462	1,543,126	3,259,268	25.3%
Aircraft		96	195	291	94,590	199,787	1.5%
Railroad[b]		371	122	492	366,903	774,944	6.0%
Commercial Marine Vessels		389	126	515	385,110	813,399	6.3%
Other Energy Use							
	Nonroad Gasoline	405	1,140	1,545	400,605	846,127	6.6%
	Nonroad Diesel	3,115	1,022	4,137	3,083,740	6,513,232	47.6%
	Other Combustion[c]	4	38	42	0	0	0.0%
Industrial Processes		67	743	810	13,334	28,164	0.2%
Agriculture[d]		349	7,486	7,834	0	0	0.0%
Waste Management							
	Landfills	0	3	3	0	0	0.0%
	Incineration	10	18	28	9,568	20,208	0.2%
	Open Burning	772	9,917	10,689	0	0	0.0%
	Other	4	6	10	4,144	8,752	0.1%
Wildfires/Prescribed Burns		830	8,124	8,954	0	0	0.0%
Miscellaneous[e]		808	13,162	13,970	0	0	0.0%
	Totals	**12,184**	**59,513**	**71,697**	**6,108,760**	**12,902,442**	**100%**

[a] Large stationary diesel engines and 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[121] were developed prior to the publication of the TAR. Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. This excerpt of the U.S. *Inventory* addresses in detail the differences between emission estimates using these two sets of GWPs. Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends.

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

What is Climate Change?

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

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

Under the UNFCCC, the definition of climate change is "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in

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

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 (CO2)

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 (CH4)

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 (N2O)

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
Gg = Gigagrams (equivalent to a thousand metric tons)
GWP = Global Warming Potential
Tg = Teragrams

GWP values allow policy makers to compare the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of roughly ±35 percent, though some GWPs have larger uncertainty than others, especially those in which lifetimes have not yet been ascertained. In the following decision, the parties to the UNFCCC have agreed to use consistent GWPs from the IPCC Second Assessment Report (SAR), based upon a 100 year time horizon, although other time horizon values are available (see Table 11).

> *In addition to communicating emissions in units of mass, Parties may choose also to use global warming potentials (GWPs) to reflect their inventories and projections in carbon dioxide-equivalent terms, using information provided by the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report. Any use of GWPs should be based on the effects of the greenhouse gases over a 100-year time horizon. In addition, Parties may also use other time horizons. (FCCC/CP/1996/15/Add.1)*

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, other ambient air pollutants (e.g., NO_x, and NMVOCs), and tropospheric aerosols (e.g., SO_2 products and black carbon), however, vary spatially, and consequently it is difficult to quantify their global radiative forcing impacts. GWP values are generally not attributed to these gases that are short-lived and spatially inhomogeneous in the atmosphere.

Table 11. Global Warming Potentials (GWP) and Atmospheric Lifetimes (Years) Used in the Inventory

Gas	Atmospheric Lifetime	100-year GWP[a]	20-year GWP	500-year GWP
Carbon dioxide (CO_2)	50-200	1	1	1
Methane (CH_4)[b]	12±3	21	56	6.5
Nitrous oxide (N_2O)	120	310	280	170
HFC-23	264	11,700	9,100	9,800
HFC-125	32.6	2,800	4,600	920
HFC-134a	14.6	1,300	3,400	420
HFC-143a	48.3	3,800	5,000	1,400
HFC-152a	1.5	140	460	42
HFC-227ea	36.5	2,900	4,300	950
HFC-236fa	209	6,300	5,100	4,700
HFC-4310mee	17.1	1,300	3,000	400
CF_4	50,000	6,500	4,400	10,000
C_2F_6	10,000	9,200	6,200	14,000
C_4F_{10}	2,600	7,000	4,800	10,100
C_6F_{14}	3,200	7,400	5,000	10,700
SF_6	3,200	23,900	16,300	34,900

Source: IPCC (1996)
[a] GWPs used here are calculated over 100 year time horizon
[b] The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

Table 12 presents direct and net (i.e., direct and indirect) GWPs for ozone-depleting substances (ODSs). Ozone-depleting substances directly absorb infrared radiation and contribute to positive radiative forcing; however, their effect as ozone-depleters also leads to a negative radiative forcing because ozone itself is a potent greenhouse gas. There is considerable uncertainty regarding this indirect effect; therefore, a range of net GWPs is provided for ozone depleting substances.

Table 12. Net 100-year Global Warming Potentials for Select Ozone Depleting Substances*

Gas	Direct	Net_{min}	Net_{max}
CFC-11	4,600	(600)	3,600
CFC-12	10,600	7,300	9,900
CFC-113	6,000	2,200	5,200
HCFC-22	1,700	1,400	1,700
HCFC-123	120	20	100
HCFC-124	620	480	590
HCFC-141b	700	(5)	570
HCFC-142b	2,400	1,900	2,300
$CHCl_3$	140	(560)	0
CCl_4	1,800	(3,900)	660
CH_3Br	5	(2,600)	(500)
Halon-1211	1,300	(24,000)	(3,600)
Halon-1301	6,900	(76,000)	(9,300)

Source: IPCC (2001)

* Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as ozone depleting substances (ODSs). However, they are also potent greenhouse gases. Recognizing the harmful effects of these compounds on the ozone layer, in 1987 many governments signed the *Montreal Protocol on Substances that Deplete the Ozone Layer* to limit the production and importation of a number of CFCs and other halogenated compounds. The United States furthered its commitment to phase-out ODSs by signing and ratifying the Copenhagen Amendments to the *Montreal Protocol* in 1992. Under these amendments, the United States committed to ending the production and importation of halons by 1994, and CFCs by 1996. The IPCC Guidelines and the UNFCCC do not include reporting instructions for estimating emissions of ODSs because their use is being phased-out under the *Montreal Protocol*. The effects of these compounds on radiative forcing are not addressed here.

The IPCC recently published its Third Assessment Report (TAR), providing the most current and comprehensive scientific assessment of climate change (IPCC 2001). Within that report, the GWPs of several gases were revised relative to the IPCC's Second Assessment Report (SAR) (IPCC 1996), and new GWPs have been calculated for an expanded set of gases. Since the SAR, the IPCC has applied an improved calculation of CO_2 radiative forcing and an improved CO_2 response function (presented in WMO 1999). The GWPs are drawn from WMO (1999) and the SAR, with updates for those cases where new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases have been recalculated. Because the revised radiative forcing of CO_2 is about 12 percent lower than that in the SAR, the GWPs of the other gases relative to CO_2 tend to be larger, taking into account revisions in lifetimes. However, there were some instances in which other variables, such as the radiative efficiency or the chemical lifetime, were altered that resulted in further increases or decreases in particular GWP values. In addition, the values for radiative forcing and lifetimes have been calculated for a variety of halocarbons, which were not presented in the SAR. The changes are described in the TAR as follows:

New categories of gases include fluorinated organic molecules, many of which are ethers that are proposed as halocarbon substitutes. Some of the GWPs have larger uncertainties than that of others, particularly for those gases where detailed laboratory data on lifetimes are not yet available. The direct GWPs have been calculated relative to CO_2 using an improved calculation of the CO_2 radiative forcing, the SAR response function for a CO_2 pulse, and new values for the radiative forcing and lifetimes for a number of halocarbons.

References

FCCC (1996) Framework Convention on Climate Change; FCCC/CP/1996/15/Add.1; 29 October 1996; Report of the Conference of the Parties at its second session. Revised Guidelines for the Preparation of National Communications by Parties Included in Annex I to the Convention, p18. Geneva 1996.

IPCC (2001) *Climate Change 2001: A Scientific Basis*, Intergovernmental Panel on Climate Change; J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, C.A. Johnson, and K. Maskell, eds.; Cambridge University Press. Cambridge, U.K.

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

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

IPCC (1996) *Climate Change 1995: The Science of Climate Change*. Intergovernmental Panel on Climate Change; J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell, eds.; Cambridge University Press. Cambridge, U.K.

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

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

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

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