Washington State
Greenhouse Gas Inventory and Reference Case Projections, 1990-2020

Center for Climate Strategies
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CENTER FOR CLIMATE STRATEGIES

Disclaimer

The Center for Climate Strategies (CCS) prepared this report for Washington State Department of Ecology (Ecology) through an effort of the Western Regional Air Partnership (WRAP). The information in this report in collaboration with The Department of Ecology and of Community, Trade and Economic Development (CTED provides a starting point for revising the initial estimates as improvements to data sources and assumptions are identified. Ecology and CTED will be continuing to improve the GHG inventory and forecast for the State of Washington. Please contact Gail Sandlin of the Department of Ecology to obtain the latest information on the State of Washington's GHG emissions inventory and forecast.

Note that this report is being reviewed by the participants of Washington State's Climate Change Initiative as a part of an effort to develop recommendations for mitigating GHG emissions in State of Washington. This review may result in revisions to data sources and assumptions for some sectors as a result of the technical expertise of members participating in the Climate Change Initiative. Improvements to this preliminary inventory and forecast will be made available to the public through WA Ecology's website at http://www.ecy.wa.gov/climatechange/.

Executive Summary

The Center for Climate Strategies (CCS) prepared this report for Washington State Department of Ecology (WA Ecology) through an effort of the Western Regional Air Partnership (WRAP). The report contains an inventory and forecast of the State's greenhouse gas (GHG) emissions from 1990 to 2020 to provide an initial comprehensive understanding of Washington State's current and possible future GHG emissions. The information presented provides the State with a starting point for revising the initial estimates as improvements to data sources and assumptions are identified. The work was completed between summer 2006 and spring 2007; the data and approaches used for the emissions estimates reflect what was available at that time. Updates to both data and calculation approaches are expected to continuously occur.

Washington's anthropogenic GHG emissions and sinks (carbon storage) were estimated for the period from 1990 to 2020. Historical GHG emission estimates (1990 through 2005, or most recent historical year) were developed using a set of generally-accepted principles and guidelines for state GHG emission estimates, with adjustments by CCS to provide Washington-specific data and inputs when it was possible to do so. The initial reference case emission projections (2006-2020) are based on a compilation of various existing projections of electricity generation, fuel use, and other GHG-emitting activities, along with a set of transparent assumptions. These projections include the expected impacts of policies that have been implemented, or are sufficiently close to implementation (such as the Washington Clean Energy Initiative, I-937) that the impacts can be estimated.

Table ES-1 provides a summary of historical (1990, 2000 and 2005) and reference case projection (2010 and 2020) GHG emissions for Washington. Activities in Washington accounted for approximately 89 million metric tons (MMt) of *gross*[1] carbon dioxide equivalent (CO_2e) emissions in 2005, an amount equal to about 1% of total US gross GHG emissions.

Figure ES-1 illustrates the State's emissions per capita and per unit of economic output. On a per capita basis, Washington residents emit about 14 metric tons (Mt) of CO_2e annually, much lower than the national average of 25 $MtCO_2e$/yr. Per capita emissions in Washington changed relatively little from 1990 through 2000 but have shown a slight decrease in the post-2000 period. On the other hand, economic growth slightly exceeded emissions growth throughout the 1990-2005 period (leading to declining GHG emissions per unit of state product). [2]

The principal source of Washington's GHG emissions is transportation (including marine transportation), accounting for 44% 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 use (14%, when exported electricity is excluded).

[1] Excluding GHG emissions removed due to forestry and other land uses and excluding GHG emissions associated with exported electricity.
[2] Based on gross domestic product by state (millions of current dollars), available from the US Bureau of Economic Analysis (http://www.bea.gov/regional/gsp/). The national emissions used for these comparisons are based on 2004 emissions, http://www.epa.gov/climatechange/emissions/usinventoryreport.html.

As illustrated in Figure ES-2 and shown numerically in Table ES-1, under the reference case projections, Washington's gross GHG emissions continue to grow, and are projected to climb to 107 $MMtCO_2e$ per year by 2020, 32% above 1990 levels. As shown in Figure ES-3, emissions associated with transportation are projected to be the largest contributor to future emissions growth, followed by emissions from fossil fuel combustion in the residential, commercial and industrial sectors. The figure shows that transportation will add more than 9 $MMtCO_2e$ to Washington's emissions by 2020, while the residential, commercial and industrial sectors will add almost 5 $MMtCO_2e$.

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. Other refinements include improved estimates of GHG emissions associated with electricity consumption. We expect that Washington's ongoing climate change action planning process will shed light on these issues.[3]

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.

Emissions of aerosols, particularly "black carbon" (BC) from fossil fuel combustion, could have significant climate impacts through their effects on radiative forcing. Estimates of these aerosol emissions on a CO_2e basis were developed for Washington based on 2002 and 2018 data from the WRAP. Estimated BC emissions for the year 2002 were a total of 9.5 $MMtCO_2e$, which is the mid-point of a range of estimated emissions (3.1 – 6.6 $MMtCO_2e$). Based on an assessment of the primary contributors, it is estimated that BC emissions will decrease substantially by 2018 after new engine and fuel standards take effect in the onroad and nonroad diesel engine sectors. Details of this analysis are presented in Appendix I to this report. These estimates are not incorporated into the totals shown in Table ES-1 below because a global warming potential for BC has not yet been assigned by the Intergovernmental Panel on Climate Change (IPCC).

[3] http://www.ecy.wa.gov/climatechange/cat_overview.htm

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

(Million Metric Tons CO2e)	1990	2000	2005	2010	2020	Explanatory Notes for Projections
Energy	**63.7**	**79.4**	**76.3**	**81.3**	**92.4**	
Electricity, Production-based	7.5	14.0	13.8	14.3	16.2	
Coal	7.4	9.6	10.2	10.2	10.2	See electric sector assumptions
Natural Gas	0.0	4.0	3.5	4.1	5.7	
Petroleum	0.0	0.3	0.0	0.0	0.2	
Biomass & Waste (CH_4 and N_2O)	0.0	0.0	0.0	0.0	0.0	
Net Imported Electricity (negative for exports)	0.1	-0.1	-1.1	-2.0	-2.1	
Electricity, Net Consumption-based	**7.5**	**13.80**	**12.6**	**12.4**	**14.1**	
Residential/Commercial/Industrial (RCI)	**18.6**	**20.3**	**19.4**	**21.3**	**24.4**	
Coal	0.6	0.3	0.2	0.3	0.3	Based on USDOE regional projections
Natural Gas	8.6	11.4	10.3	11.0	12.7	Based on USDOE regional projections
Oil	9.1	8.4	8.5	9.7	11.0	Based on USDOE regional projections
Wood (CH_4 and N_2O)	0.2	0.2	0.3	0.4	0.4	Based on USDOE regional projections
Transportation	**36.9**	**44.3**	**43.1**	**46.5**	**52.7**	
Onroad Gasoline	19.5	22.6	23.5	24.6	26.6	Based on WSDOT VMT projections
Onroad Diesel	3.5	7.1	7.6	9.1	11.8	Based on WSDOT VMT projections
Marine Vessels	3.8	3.7	4.2	4.6	5.6	Based on trend in historical emissions
Jet Fuel and Aviation Gasoline	9.0	10.0	7.1	7.4	7.7	Based on FAA projections
Rail	0.7	0.3	0.5	0.5	0.5	No growth assumed
Natural Gas, LPG, other	0.3	0.2	0.2	0.3	0.4	Based on USDOE regional projections
Fossil Fuel Industry	**0.7**	**1.0**	**1.1**	**1.2**	**1.3**	
Natural Gas Industry (CH_4)	0.68	0.94	1.07	1.12	1.24	
Coal Mining (CH_4)	0.03	0.02	0.03	0.00	0.00	
Industrial Processes	**7.0**	**6.6**	**3.3**	**4.2**	**6.2**	
Cement Manufacture (CO_2)	0.2	0.5	0.5	0.5	0.5	WA nonmetallic mineral employment growth
Aluminum Production (CO_2, PFC)	5.9	3.9	0.4	0.4	0.3	WA primary metals employment growth
Limestone & Dolomite Use (CO_2)	0.0	0.0	0.0	0.0	0.0	WA nonmetallic mineral employment growth
Soda Ash (CO_2)	0.1	0.1	0.1	0.1	0.1	Based on projections for US production
ODS Substitutes (HFC, PFC, SF_6)	0.0	1.6	2.1	3.0	5.1	EPA 2004 ODS cost study report
Semiconductor Manufacturing (HFC, PFC, and SF_6)	0.0	0.1	0.0	0.0	0.0	Based on national projections (USEPA)
Electric Power T & D (SF_6)	0.8	0.4	0.3	0.2	0.1	Based on national projections (USEPA)
Waste Management	**4.1**	**4.8**	**4.2**	**4.0**	**3.6**	
Solid Waste Management	3.6	4.2	3.5	3.3	3.0	Projections primarily based on population.
Wastewater Management	0.5	0.6	0.7	0.7	0.7	Projections based on population.
Agriculture	**6.4**	**6.4**	**5.4**	**5.1**	**4.8**	
Enteric Fermentation	2.0	1.8	1.6	1.5	1.3	Based on trend in historical emissions
Manure Management	0.7	0.9	0.9	1.0	1.2	Based on trend in historical emissions
Agricultural Soils	3.7	3.8	2.8	2.6	2.2	Based on trend in historical emissions
Total Gross Emissions	**81.3**	**97.2**	**89.1**	**94.5**	**107.1**	
increase relative to 1990		*20%*	*10%*	*17%*	*33%*	
Forestry and Land Use	-28.6	-28.6	-28.6	-28.6	-28.6	All years based on current (2005) estimates from the USFS
Agricultural Soils	-1.4	-1.4	-1.4	-1.4	-1.4	
Net Emissions (incl. forestry*)	**51.3**	**67.2**	**59.1**	**64.5**	**77.1**	

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

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

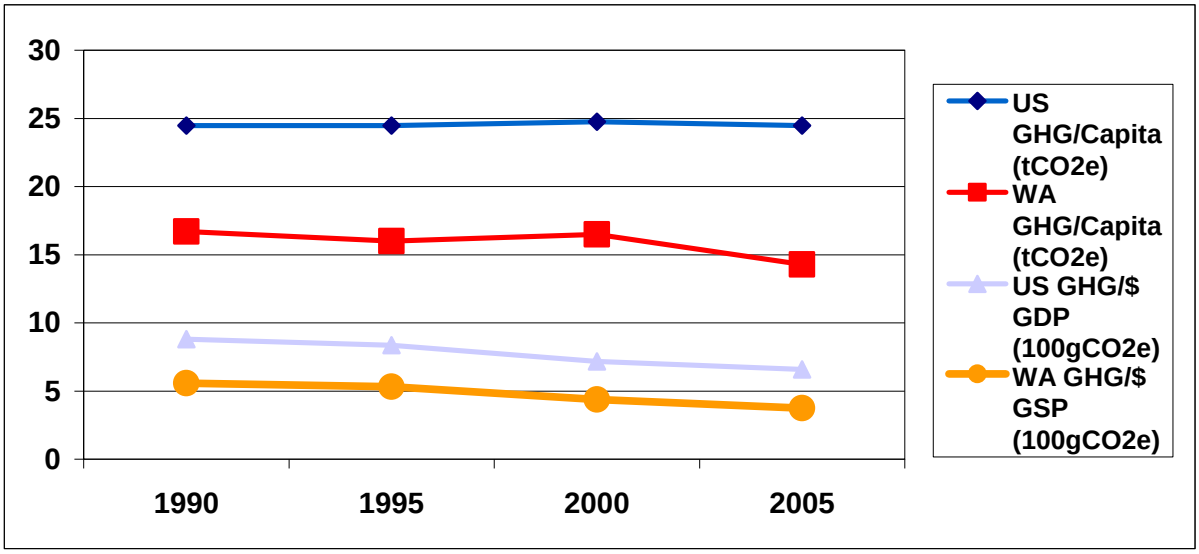
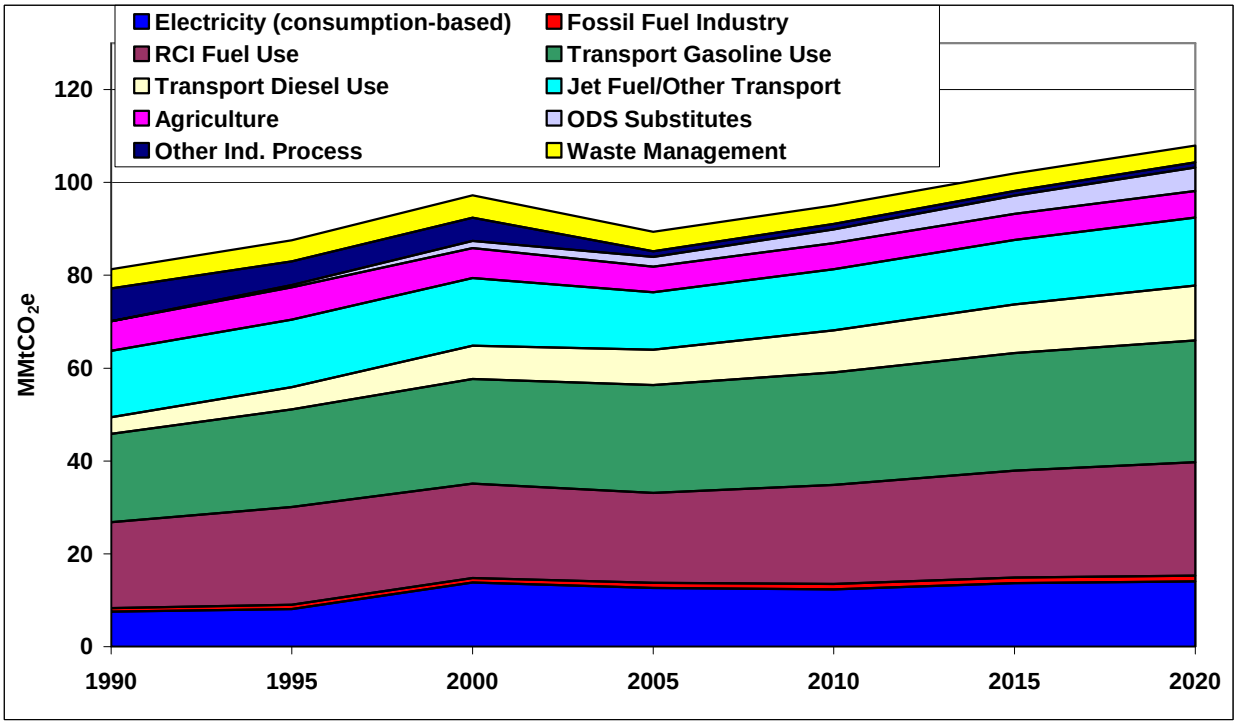
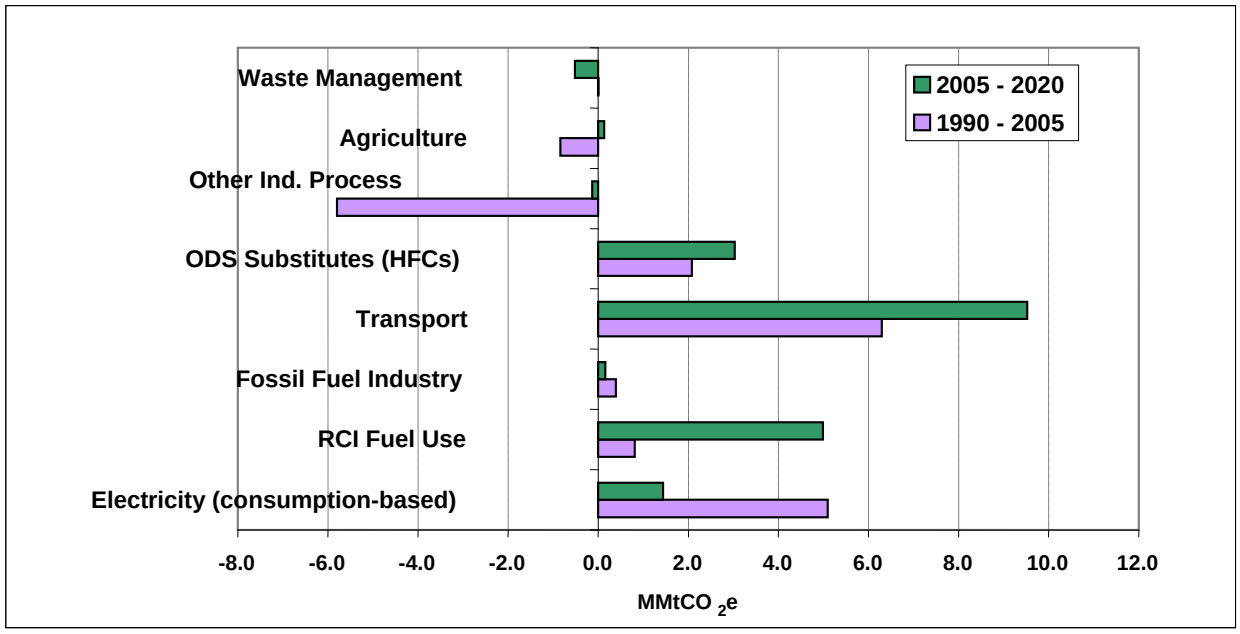


Figure ES-2. Washington Gross GHG Emissions by Sector, 1990-2020: Historical and Projected



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

Figure ES-3. Sector Contributions to Gross Emissions Growth in Washington, 1990-2020: Reference Case Projections



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

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Acronyms and Key Terms

AEO – *Annual Energy Outlook, EIA*

Ag – Agriculture

bbls – Barrels

BC – Black Carbon*

Bcf – Billion Cubic Feet

BLM – United States Bureau of Land Management

BOD – Biochemical Oxygen Demand

BTU – British Thermal Unit

C – Carbon*

$CaCO_3$ – Calcium Carbonate

CBM – Coal Bed Methane

CCS – Center for Climate Strategies

CFCs – Chlorofluorocarbons*

CH_4 – Methane*

CO – Carbon Monoxide*

CO_2 – Carbon Dioxide*

CO_2e – Carbon Dioxide Equivalent*

CRP – Federal Conservation Reserve Program

EC – Elemental Carbon*

EFSEC – Energy Facility Site Evaluation Council

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

EGU – Electricity Generating Unit

EIA – US DOE Energy Information Administration

EIIP – Emissions Inventory Improvement Program

Eq. – Equivalent

FIA – Forest Inventory and Analysis

Gg – Gigagram

GHG – Greenhouse Gases*

GSP – Gross State Product

GWh – Gigawatt-hour

GWP - Global Warming Potential*

HFCs – Hydrofluorocarbons*

IPCC – Intergovernmental Panel on Climate Change*

kWh – Kilowatt-hour

LF – Landfill

LFGTE – Landfill Gas 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

MSW – Municipal Solid Waste

MW – Megawatt

N – Nitrogen*

N_2O – Nitrous Oxide*

NO_2 – Nitrogen Dioxide*

NO_x – Nitrogen Oxides*

NAICS – North American Industry Classification System

NASS – National Agricultural Statistics Service

NF – National Forest

NMVOCs – Nonmethane Volatile Organic Compounds*

O_3 – Ozone*

ODS – Ozone-Depleting Substances*

OM – Organic Matter*

PADD – Petroleum Administration for Defense Districts

PFCs – Perfluorocarbons*

PM – Particulate Matter*

ppb – parts per billion

ppm – parts per million

ppt – parts per trillion

PV – Photovoltaic

RCI – Residential, Commercial, and Industrial

RPA – Resources Planning Act Assessment

SAR – Second Assessment Report*

SED – State Energy Data

SF_6 – Sulfur Hexafluoride*

SGIT – State Greenhouse Gas Inventory Tool

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

TAR – Third Assessment Report*

T&D – Transmission and Distribution

Tg – Teragram

TWh – Terawatt-hours

UNFCCC – United Nations Framework Convention on Climate Change

US EPA – United States Environmental Protection Agency

US DOE – United States Department of Energy

USDA – United States Department of Agriculture

USFS – United States Forest Service

USGS – United States Geological Survey

VMT – Vehicle-Miles Traveled

WA Ecology – Washington State Department of Ecology

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

WW – Wastewater

* - See Appendix J for more information.

Acknowledgements

CCS appreciates all of the time and assistance provided by numerous contacts throughout the State of Washington, as well as in neighboring states, and at federal agencies. Thanks go to the many staff at several Washington state agencies for their inputs, and in particular to Gail Sandlin and Sally Otterson of the Washington State Department of Ecology and to Stacey Waterman-Hoey of the Washington Department of Community, Trade and Economic Development, who provided key guidance and review for this analytical effort.

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

Summary of Preliminary Findings

Introduction

The Center for Climate Strategies (CCS) prepared this report for Washington State Department of Ecology (WA Ecology) through an effort of the Western Regional Air Partnership (WRAP). 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)[4] were developed using a set of generally accepted principles and guidelines for state GHG emissions inventories, as described in Section 2, relying to the extent possible on Washington-specific data and inputs. The initial reference case projections (2006-2020) are based on a compilation of various existing projections of electricity generation, fuel use, and other GHG-emitting activities, along with a set of simple, transparent assumptions described in the appendices of this report. These reference case projections include the expected impacts of policies that have been implemented, or are sufficiently close to implementation (such as the Washington Clean Energy Initiative, I-937) that the impacts can be estimated.

This report covers the six types of gases included in the US Greenhouse Gas Inventory: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Emissions of these GHGs are presented using a common metric, CO_2 equivalence (CO_2e), which indicates the relative contribution of each gas to global average radiative forcing on a Global Warming Potential- (GWP-) weighted basis. The final appendix to this report provides a more complete discussion of GHGs and GWPs. Emissions of black carbon (BC) were also estimated. Black carbon is an aerosol species with a positive climate forcing potential (that is, the potential to warm the atmosphere, as GHGs do); however, black carbon currently does not have a GWP defined by the IPCC due to uncertainties in both the direct and indirect effects of BC on atmospheric processes (see Appendices I and J for more details).

It is important to note that the preliminary 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 of accounting for emissions, but for consistency, all total results are reported as *consumption-based.*

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

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

Appendix I provides information on 2002 and 2018 BC estimates for Washington. CCS estimated that BC emissions in 2002 ranged from 6.1 – 12.9 $MMtCO_2e$ with a mid-point of 4.9 $MMtCO_2e$. A range is estimated based on the uncertainty in the global modeling analyses that serve as the basis for converting BC mass emissions into their carbon dioxide equivalents (see Appendix I for more details). Since the IPCC has not yet assigned a global warming potential for BC, CCS has excluded these estimates from the GHG summary shown in Table 1 below. Based on an assessment of 2018 forecasted emissions for the primary BC contributors from the Western Regional Air Partnership (WRAP), it is estimated that BC emissions will decrease significantly by 2018 after new engine and fuel standards take effect in the onroad and nonroad diesel engine sectors. About 2.4 $MMtCO_2e$ was estimated for 2002 BC emissions. Emissions are expected to decrease to 0.4 $MMtCO_2e$ by 2018. Appendix I contains a detailed breakdown of emissions contribution by source sector.

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

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

(Million Metric Tons CO2e)	1990	2000	2005	2010	2020	Explanatory Notes for Projections
Energy	**63.7**	**79.4**	**76.3**	**81.3**	**92.4**	
Electricity, Production-based	7.5	14.0	13.8	14.3	16.2	
Coal	7.4	9.6	10.2	10.2	10.2	See electric sector assumptions
Natural Gas	0.0	4.0	3.5	4.1	5.7	
Petroleum	0.0	0.3	0.0	0.0	0.2	
Biomass & Waste (CH_4 and N_2O)	0.0	0.0	0.0	0.0	0.0	
Net Imported Electricity (negative for exports)	0.1	-0.1	-1.1	-2.0	-2.1	
Electricity, Net Consumption-based	**7.5**	**13.80**	**12.6**	**12.4**	**14.1**	
Residential/Commercial/Industrial	**18.6**	**20.3**	**19.4**	**21.3**	**24.4**	
Coal	0.6	0.3	0.2	0.3	0.3	Based on USDOE regional projections
Natural Gas	8.6	11.4	10.3	11.0	12.7	Based on USDOE regional projections
Oil	9.1	8.4	8.5	9.7	11.0	Based on USDOE regional projections
Wood (CH_4 and N_2O)	0.2	0.2	0.3	0.4	0.4	Based on USDOE regional projections
Transportation	**36.9**	**44.3**	**43.1**	**46.5**	**52.7**	
Onroad Gasoline	19.5	22.6	23.5	24.6	26.6	Based on WSDOT VMT projections
Onroad Diesel	3.5	7.1	7.6	9.1	11.8	Based on WSDOT VMT projections
Marine Vessels	3.8	3.7	4.2	4.6	5.6	Based on trend in historical emissions
Jet Fuel and Aviation Gasoline	9.0	10.0	7.1	7.4	7.7	Based on FAA projections
Rail	0.7	0.3	0.5	0.5	0.5	No growth assumed
Natural Gas, LPG, other	0.3	0.2	0.2	0.3	0.4	Based on USDOE regional projections
Fossil Fuel Industry	**0.7**	**1.0**	**1.1**	**1.2**	**1.3**	
Natural Gas Industry (CH_4)	0.68	0.94	1.07	1.12	1.24	
Coal Mining (CH_4)	0.03	0.02	0.03	0.00	0.00	
Industrial Processes	**7.0**	**6.6**	**3.3**	**4.2**	**6.2**	
Cement Manufacture (CO_2)	0.2	0.5	0.5	0.5	0.5	WA nonmetallic mineral employment growth
Aluminum Production (CO_2, PFC)	5.9	3.9	0.4	0.4	0.3	WA primary metals employment growth
Limestone & Dolomite Use (CO_2)	0.0	0.0	0.0	0.0	0.0	WA nonmetallic mineral employment growth
Soda Ash (CO_2)	0.1	0.1	0.1	0.1	0.1	Based on projections for US production
ODS Substitutes (HFC, PFC, SF_6)	0.0	1.6	2.1	3.0	5.1	EPA 2004 ODS cost study report
Semiconductor Manufacturing (HFC, PFC, and SF_6)	0.0	0.1	0.0	0.0	0.0	Based on national projections (USEPA)
Electric Power T & D (SF_6)	0.8	0.4	0.3	0.2	0.1	Based on national projections (USEPA)
Waste Management	**4.1**	**4.8**	**4.2**	**4.0**	**3.6**	
Solid Waste Management	3.6	4.2	3.5	3.3	3.0	Projections primarily based on population.
Wastewater Management	0.5	0.6	0.7	0.7	0.7	Projections based on population.
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	**81.3**	**97.2**	**89.1**	**94.5**	**107.1**	
increase relative to 1990		*20%*	*10%*	*17%*	*33%*	
Forestry and Land Use	-28.6	-28.6	-28.6	-28.6	-28.6	All years based on current (2005) estimates from the USFS
Agricultural Soils	-1.4	-1.4	-1.4	-1.4	-1.4	
Net Emissions (incl. forestry*)	**51.3**	**67.2**	**59.1**	**64.5**	**77.1**	

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

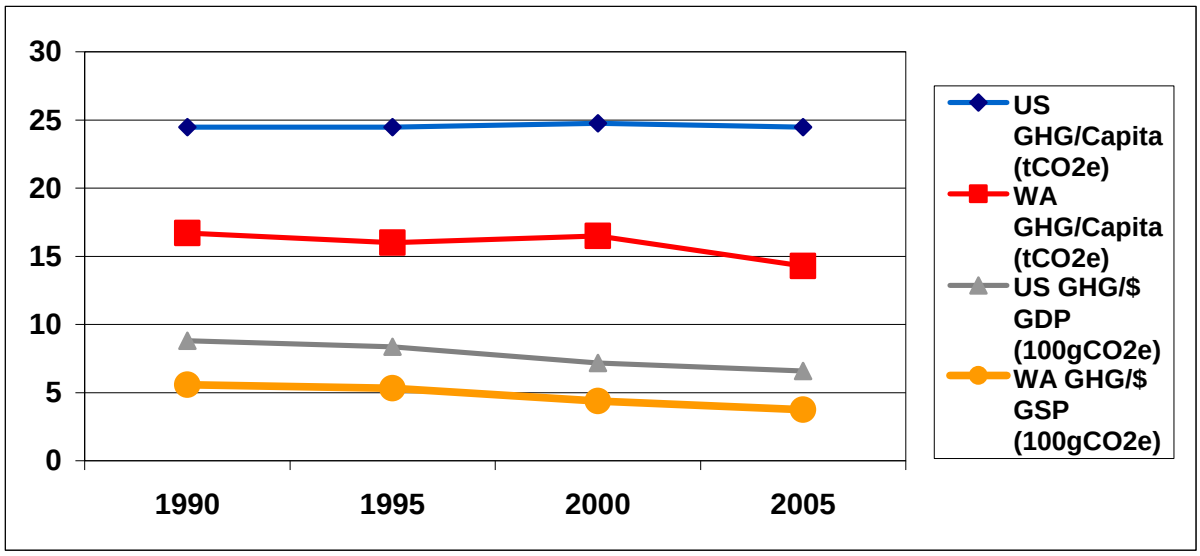
Historical Emissions

Overview

Our analyses suggest that in 2005, activities in Washington accounted for approximately 89 million metric tons (MMt) of *gross*[5] CO_2e emissions in 2005, an amount equal to 1% of total US gross GHG emissions. Washington's gross GHG emissions in 2005 were about 10% greater than emissions in 1990, but experienced a 7% decrease from 2000 to 2005.

On a per capita basis, Washington emitted about 14 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 changed relatively little from 1990 through 2000 but have shown a slight decrease in the post-2000 period. On the other hand, economic growth slightly exceeded emissions growth throughout the 1990-2005 period (leading to declining estimates of GHG emissions per unit of state product).[6]

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

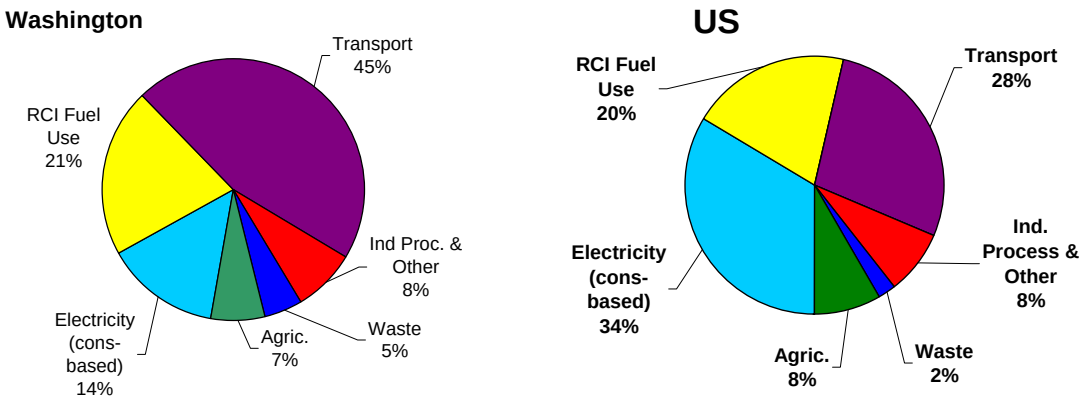


Electricity use, transportation and residential/commercial/industrial (RCI) fossil fuel combustion are the State's principal GHG emissions sources. A comparison of Washington and US emissions for 2000 is shown in Figure 2 below, which shows that in Washington a much larger fraction of the GHG emissions 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.

[5] Excluding GHG emissions removed due to forestry and other land uses and excluding GHG emissions associated with exported electricity.

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

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



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

The 1990-2004 historical emission estimates are comparable to estimates previously prepared by CTED.[7] In the CTED study, the total 1990 gross GHG emissions estimate was about 78 $MMtCO_2e$ compared to the estimate provided in Table 1 of 81 $MMtCO_2e$. The CTED study estimated 88 $MMtCO_2e$ of gross GHG emissions in 2004, compared with 91 $MMtCO_2e$ from this analysis. The main differences appear to be linked with data sources for transportation and the fossil fuel industry. Further analysis of the two studies would be needed to more define the differences more precisely.

As illustrated in Figure 3 and shown numerically in Table 1, under the reference case projections, Washington's gross GHG emissions continue to grow, and are projected to climb to 107 $MMtCO_2e$ per year by 2020, 32% above 1990 levels. As shown in Figure 4, emissions associated with transportation are projected to be the largest contributor to future emissions growth, followed by emissions from fossil fuel combustion in the residential, commercial and industrial sectors. The figure shows that transportation will add more than 9 $MMtCO_2e$ to Washington's emissions by 2020, while the residential, commercial and industrial sectors are projected to add almost 5 $MMtCO_2e$.

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

As shown in Table 1, electricity use accounted for about 13% of Washington's gross GHG emissions in 2005 (13 $MMtCO_2e$), which was lower than the national share of emissions from electricity production (32%).[8] In total (across the residential, commercial and industrial sectors), Washington has a higher per capita use of electricity than the US as a whole (13,000 kWh per

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

[8] 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.

person per year compared to 12,000 kWh/person-yr nationally). However, hydro-electric generation accounts for 70% to 85% of Washington's electricity generation (depending on water conditions each year). With no GHG emissions associated with this electricity source, Washington emits relatively low rates of GHGs per unit of electricity produced.

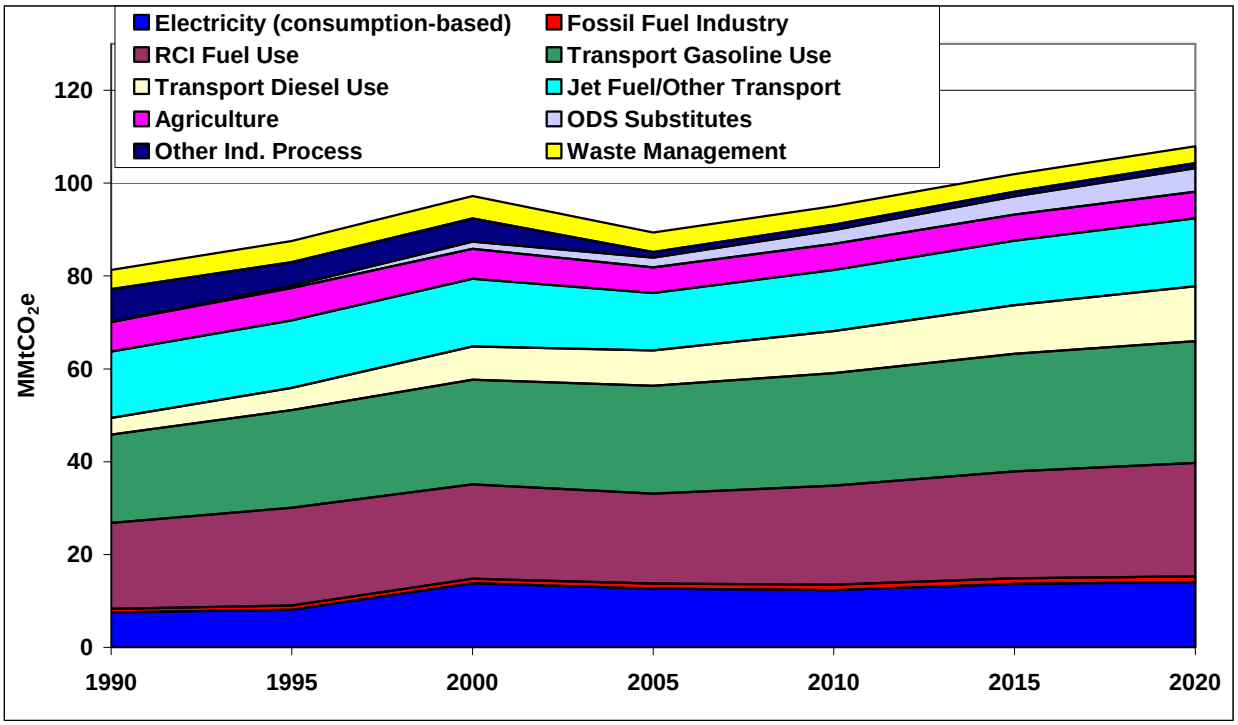
It is important to note that these preliminary electricity emissions estimates reflect the *GHG emissions associated with the electricity sources used to meet Washington demands,* corresponding to a *consumption-based* approach to emissions accounting (see Section 2). Another way to look at electricity emissions is to consider the *GHG emissions produced by electricity generation facilities in the State.* In that recent past, Washington power plants have produced more electricity than is consumed in the State – in the year 2000, for example, Washington had net exports of about 1% of the electricity produced in the State. As a result, in 2000, emissions associated with electricity consumption (13.8 $MMtCO_2e$) were slightly lower than those associated with electricity production (14.0 $MMtCO_2e$).[9]

While CCS estimated emissions associated with both electricity production and consumption, unless otherwise indicated, tables, figures, and totals in this report reflect electricity consumption-based emissions. The consumption-based approach can better reflect the emissions (and emissions reductions) associated with activities occurring in the State, 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.) Data to account for the electricity imported into Washington were not factored into the analysis conducted for this report but are likely to have a large impact on GHG emissions. More sophisticated approaches to estimating GHG emissions from electricity consumption in Washington are being developed by Ecology and CTED and should be considered for further refinements of this work.[10]

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 55% of transportation GHG emissions in 2005. Diesel vehicles accounted for another 18% of emissions and air travel for roughly 16%. Marine, locomotives, and other sources [natural gas and liquefied petroleum gas (LPG) vehicles and lubricants] accounted for the remaining 11% of transportation emissions. As the result of Washington's population and economic expansion and an increase in total vehicle miles traveled during the 1990s, onroad gasoline use grew by 20% between 1990 and 2005. Meanwhile, onroad diesel use increased by 94% during this period, suggesting an even more rapid growth in freight movement within the State. Aviation fuel use declined from 1990-2005.

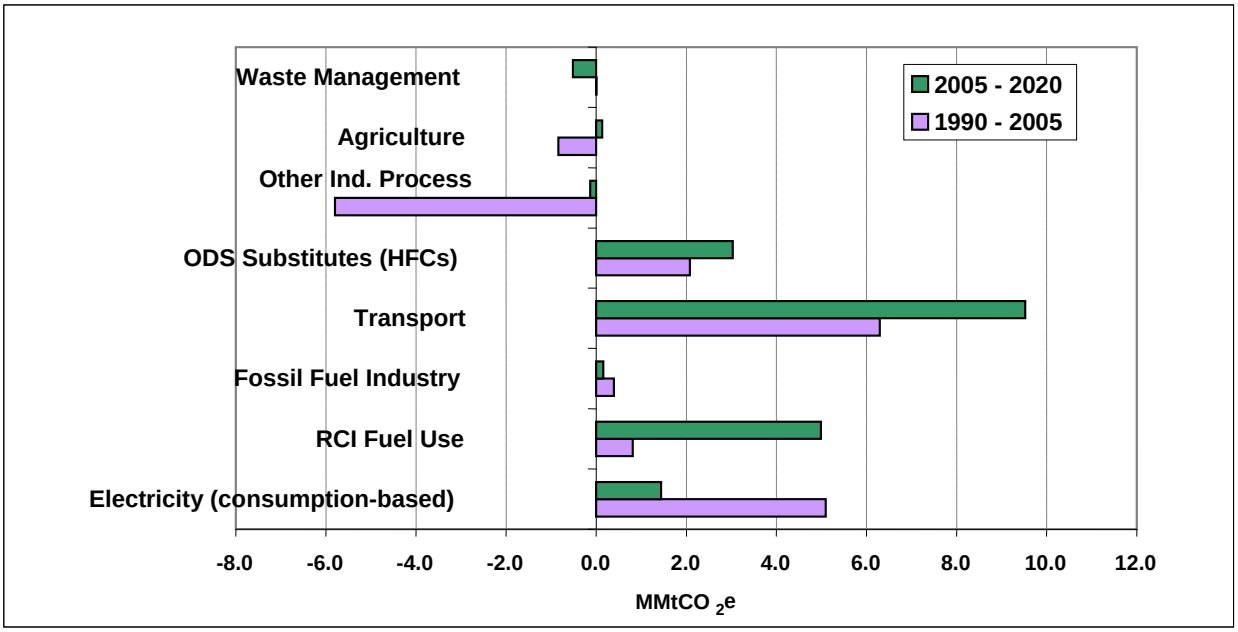
[9] Estimating the emissions associated with electricity use requires an understanding of the electricity sources (both in-state and out-of-state) used by utilities to meet consumer demand. The current estimate reflects some very simple assumptions described in Appendix A.
[10] For progress by CTED and others, check the Washington State Climate Advisory Team website. http://www.ecy.wa.gov/climatechange/cat_overview.htm

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



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

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



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

Reference Case Projections

Relying on a variety of sources for projections of electricity and fuel use, as noted below and in the Appendices, we developed a simple reference case projection of GHG emissions through 2020. As illustrated in Figure 3 and shown numerically in Table 1, under the reference case projections, Washington gross GHG emissions continue to grow steadily, climbing to 107 $MMTCO_2e$ by 2020. The transportation sector is projected to be the largest contributor to future emissions growth, followed by fossil fuel use in the residential, commercial and industrial (RCI) sectors.

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%	1.7%	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.

Emissions of aerosols, particularly black carbon from fossil fuel combustion, could have significant impacts in terms of radiative forcing (that is, climate impacts). Methodologies for conversion of black carbon mass estimates and projections to global warming potential involve

significant uncertainty at present, but CCS has developed and used a recommended approach for estimating black carbon emissions based on methods used in other States. Current estimates suggest a relatively small CO_2e contribution overall from BC emissions, as compared to the CO_2e contributed from the gases.

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 WA 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 US EPA in its national GHG emissions inventory[11] and its guidelines for States.[12] These inventory guidelines were developed based on the guidelines from the Intergovernmental Panel on Climate Change, the international organization responsible for developing coordinated methods for national GHG inventories.[13] The inventory methods provide flexibility to account for local conditions. The key sources of activity and projection data 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.

[11] 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.
[12] http://yosemite.epa.gov/oar/globalwarming.nsf/content/EmissionsStateInventoryGuidance.html.
[13] http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

Table 4. Key Sources for Washington Data, Inventory Methods, and Growth Rates

Source	Information provided	Use of Information in this Analysis
US EPA State Greenhouse Gas Inventory Tool (SGIT)	US EPA SGIT is a collection of linked spreadsheets designed to help users develop State GHG inventories. US EPA SGIT contains default data for each State for most of the information required for an inventory. The SGIT methods are based on the methods provided in the Volume 8 document series published by the Emissions Inventory Improvement Program (http://www.epa.gov/ttn/chief/eiip/techreport/volume08/index.html)	Where not indicated otherwise, SGIT is used to calculate emissions from residential/commercial/industrial fuel combustion, industrial processes, transportation, agriculture and forestry, and waste. We use SGIT emission factors (CO_2, CH_4 and N_2O per BTU consumed) to calculate energy use emissions.
US DOE Energy Information Administration (EIA) State Energy Data (SED)	EIA SED 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.
US DOE Energy Information Administration Annual Energy Outlook 2006 (AEO2006)	EIA AEO2006 projects energy supply and demand for the US 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
American Gas Association – Gas Facts	Natural gas transmission and distribution pipeline mileage.	Pipeline mileage from Gas Facts used with SGIT to estimate natural gas transmission and distribution emissions.
US EPA Landfill Methane Outreach Program (LMOP)	LMOP provides landfill waste-in-place data.	Waste-in-place data used to estimate annual disposal rate, which was used with SGIT to estimate emissions from solid waste).
US Forest Service	Data on forest carbon stocks for multiple years.	Data are used to calculate 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

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

- **Comprehensive Coverage of Gases, Sectors, State Activities, and Time Periods.** This analysis aims to comprehensively cover GHG emissions associated with activities in Washington. It covers all six GHGs covered by US and other national inventories: 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 the emissions related to electricity *consumed* in Washington, in addition to the emissions due to fuels combusted at electricity plants in the State,. This would

[14] "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).

ideally entail accounting for the electricity sources used by Washington utilities to meet consumer demands. However, this analysis focused on a simplified approach of accounting for net electricity exports and assuming the mix of net exports will resemble the average mix of electricity produced in the State. Washington State Ecology and CTED are developing more sophisticated approaches, using data provided directly by the utilities. As that work proceeds, it will provide an opportunity to further refine this GHG inventory and projections. If Ecology and CTED decide to refine this analysis, they may also consider estimating other sectoral 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, CCS recommends considering a consumption-based approach where it will significantly improve the estimation of the emissions impact of potential mitigation strategies. (For example re-use, recycling, and source reduction can lead to emission reductions resulting from lower energy requirements for material production (such as paper, cardboard, and aluminum), even though production of those materials, and emissions associated with materials production, may not occur within the State.)

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

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

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

Appendix A. Electricity Use and Supply

Washington's electricity sector is dominated by hydro-electric generation, which accounts for over 70% of the electricity generated in the state. The Centralia coal plant accounts for another 10% of generation, and about 80% of the state's GHG emissions from power production. The remaining generation, and the primary source of recent growth in capacity in the State, is natural gas and wind power.

With the state's hydroelectric potential largely tapped, a key question is the source of future growth in capacity. The recent voter-supported renewable energy standard (Initiative 937) coming into force starting in 2012 – which requires utilities to undertake cost-effective energy conservation and to obtain 3% of their load from new renewable resources by 2012, increasing to 15% in 2020 - could have a significant impact in this respect. Estimated impacts of Initiative 937 are included in the reference case projections in this report.

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 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 this question still needs to be resolved, this section examines electricity-related emissions from both a production and consumption basis.

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

Electricity Generation – Washington's Power Plants

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

section, *Electricity trade and the allocation of GHG emissions*, reports net consumption-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 renewables (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.

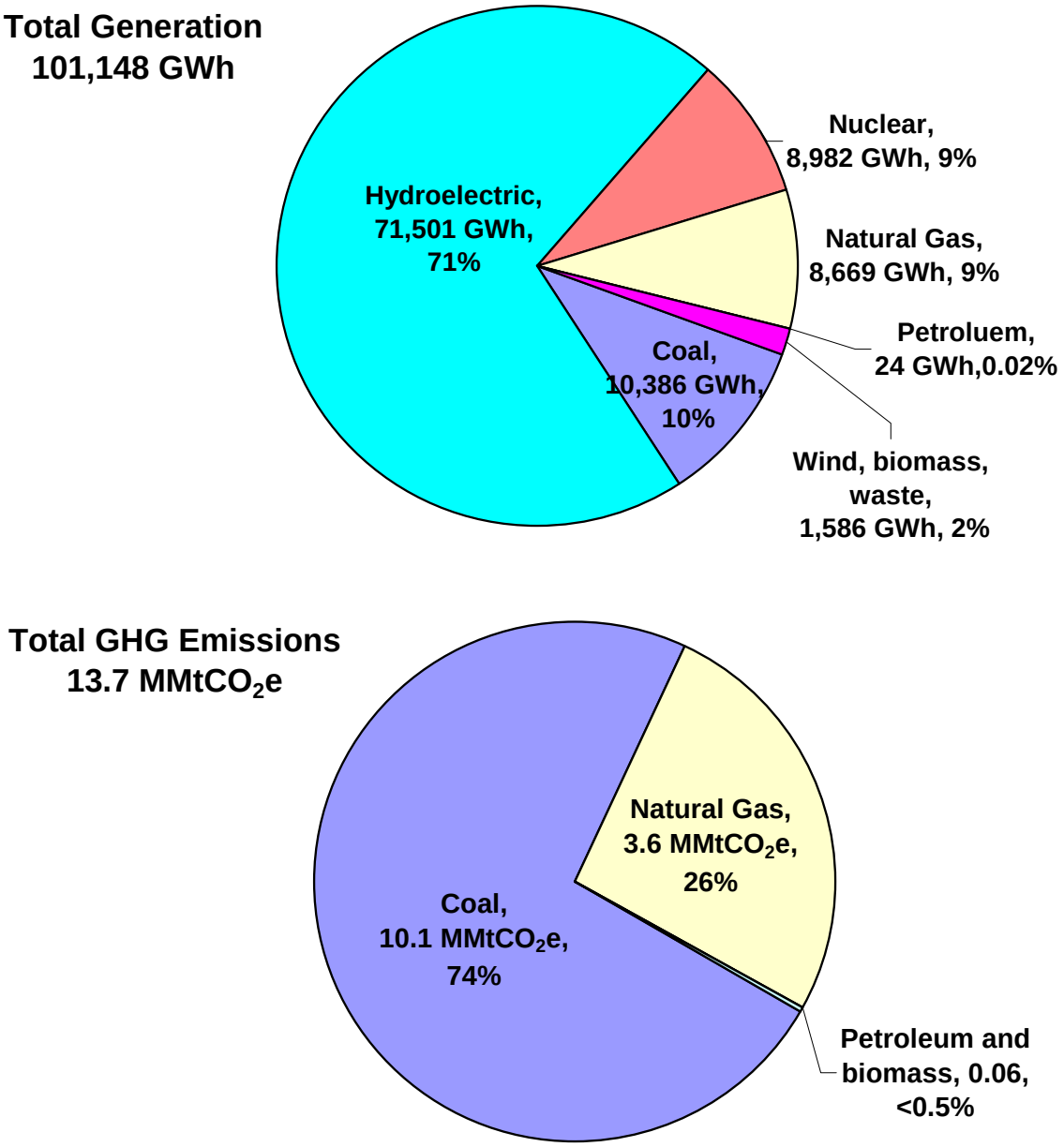
We considered two sources of data in developing the historic inventory of GHG emissions from Washington power plants – EIA State Energy Data (SED), which need to be multiplied by GHG emission factors for each type of fuel consumed, and EPA data on CO_2 emissions by power plant. To calculate total GHG emissions from electricity production in 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.[15] The GHG emissions from plants not listed individually in Table A2 is 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 A1 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 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.[16] 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.

[15] 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.

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

Figure A1. Electricity Generation and CO_2 Emissions from Washington Power Plants, 2004



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

Table A1. CO_2 Emissions from Individual Washington Power Plants, 2000-2005

(Million metric tons CO2)	2000	2001	2002	2003	2004	2005
Centralia	*9.4*	*9.2*	*9.5*	*12.1*	*11.1*	*11.5*
Chehalis Generation Facility	*0.0*	*0.0*	*0.0*	*0.3*	*1.0*	*0.9*
Frederickson Power LP	*n/a*	*n/a*	*0.1*	*0.3*	*0.3*	*0.3*
Goldendale Energy Project	*0.0*	*0.0*	*0.0*	*0.0*	*0.1*	*0.4*
River Road	*0.7*	*0.7*	*0.6*	*0.6*	*0.7*	*0.6*
Other Plants	*3.8*	*3.9*	*1.1*	*0.5*	*0.4*	*0.1*
Total CO2 emissions	**13.9**	**13.8**	**11.2**	**13.8**	**13.7**	**13.7**

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

Table A2 shows the growth in generation by fuel type between 1990 and 2004. 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. Coal generation grew more slowly but accounted for over 10% of total generation in 2004. Hydro-electric generation was the only source to show a decrease between 1990 and 2004, but it remains the dominant energy resource in the State. The table masks the year by year variation from hydro-electricity. In the 15 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 A2. Growth in Electricity Generation in Washington 1990-2004.

	Generation (GWh)		Growth
	1990	2004	
Coal	7,352	10,386	41%
Hydroelectric	87,193	71,501	-18%
Natural Gas	24	8,669	36082%
Nuclear	5,742	8,982	56%
Wind	0	467	n/a
biomass and waste	340	1,120	230%
Petroleum	14	24	65%
Total	100,664	101,148	0.5%

Source: EIA Electric Power Annual Data

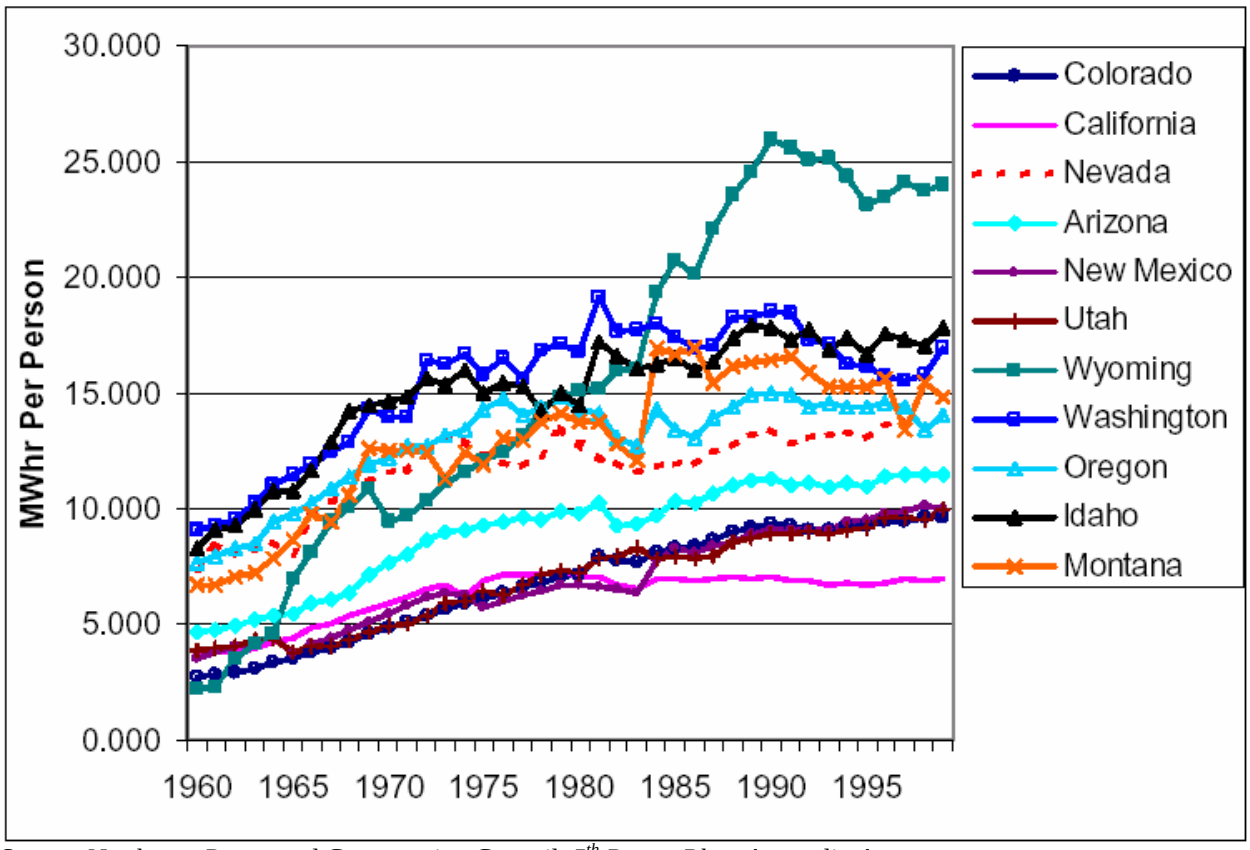
Electricity Consumption

At about 13,000 kWh/capita (2004 data), Washington's electricity use per person is higher than typical for the US. By way of comparison, the per capita consumption for the US was about 12,000 kWh per year.[17] Figure A2 shows Washington's rank compared to other western states from 1960-1999; Washington's per capita consumption was relatively for states in this region. Many components influence a state's per capita electricity consumption including the impact of weather on demand for cooling, the size and type of industries in the State, and the type and

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

efficiency of equipment in the residential, commercial and industrial sectors. During the time period illustrated, Washington had a relatively high portion of industries with large electric loads (such as aluminum manufactures).

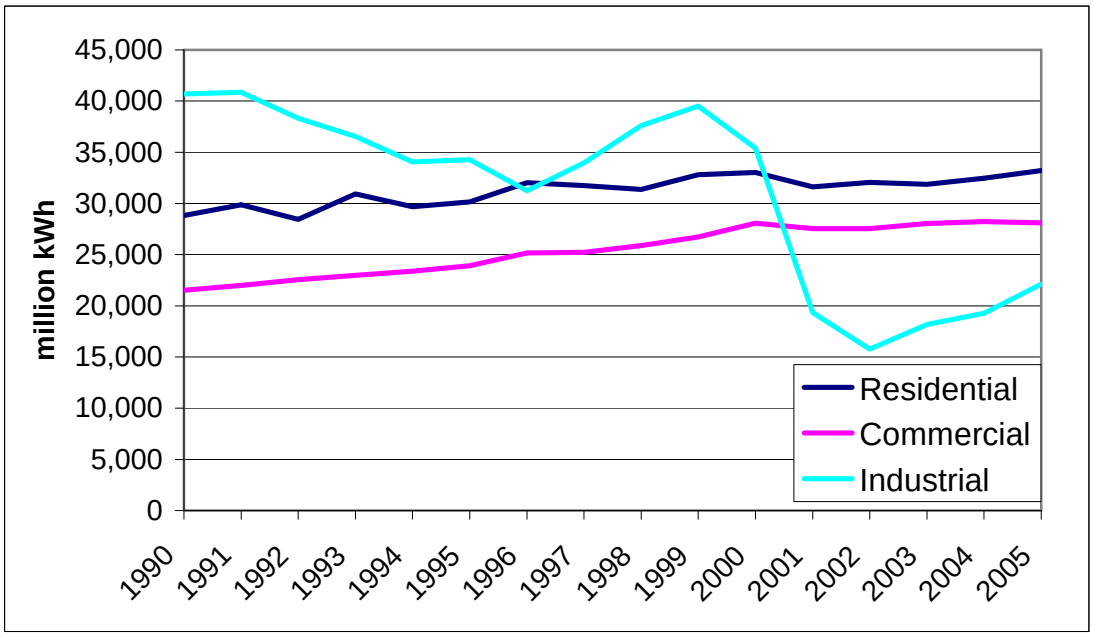
Figure A2. Electricity Consumption per capita in Western States, 1960-1999



Source: Northwest Power and Conservation Council, *5th Power Plan*, Appendix A

As shown in Figure A3, 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. 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 A3. Electricity Consumption by Sector in Washington, 1990-2005



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

Future Electricity Generation

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

The future mix of plants in Washington remains uncertain as the trends in type of new builds are influenced by many factors. Since 2000, new power plants in Washington have been predominantly natural gas-fired with some wind and biomass. Most plants that are currently under construction or *planned*[18] are wind. Several large natural gas plants have been proposed. Table A3 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.

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

Table A3. 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
Under Construction and Planned Plants	Big Horn	Wind	2006	200	612	0.0
	Cedar Hills	Biomass	2006	26	114	0.0
	Goodnoe Hills East	Wind	Nov-07	56	172	0.0
	Goodnoe Hills West	Wind	Nov-07	56	172	0.0
	Marengo	Wind	Aug-07	140	430	0.0
	Nine Canyon Phase III	Wind	2007	32	98	0.0
	White Creek Ph I	Wind	2007	100	307	0.0
	White Creek Ph II	Wind	2008	100	307	0.0
	Wild Horse	Wind	Dec-06	229	701	0.0
Permitted and Proposed plants	BP Cherry Point Cogeneration Project	Natural gas	Permitted	720.0	5,361	2.0
	Grays Harbor Energy Facility (Satsop) (Phase II)	Natural gas	Proposed	650.0	4,840	1.8
	Kittitas Valley	Wind	Proposed	150.0	460	0.0
	Longview Power Station	Natural gas	Permitted	290.0	2,159	0.8
	Morgan Stanley Frederickson	Natural gas	Proposed	324.0	2,413	0.9
	Pacific Mountain Energy Center	Petroleum	Proposed	600.0	4,468	3.6
	Plymouth Generating Facility	Natural gas	Proposed	307.0	2,286	0.8
	Reardan Twin Buttes	Wind	Proposed	50.0	110	0.0
	Wallula	Natural gas	Permitted	1300	9,680	3.6
	Windy Point I & II	Wind	Permitted	242.5	744	0.0

Sources: Northwest Power and Conservation Council. October 2006. *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 0.239 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).

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.[19]

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 2.8% per year from 2005-2009, based on generation estimates from plants that are currently under construction (see Table A3).
- Generation from power plants in Washington grows at 1% per year from 2010 to 2015 and 1.1% from 2015 to 2020. This reflects the generation growth rate for the Pacific Northwest region in Annual Energy Outlook 2006 (AEO2006).
- Generation from existing non-hydro plants is based on holding generation at 2005 levels. Generation from existing hydro-electric plants is assumed to be 81,051 GWh per year, the average generation from the last ten years. New plants and changes to existing plants due to plant renovations and overhauls that result in higher capacity factors are considered as new generation (thus the mix of new generation discussed below would also apply to plant upgrades).
- The I-937 renewable generation requirements are assumed to be met by utilities with over 25,000, which account for about 84% of electricity sales in the State. The resources used to meet the renewable generation requirements are projected to be 5% biomass and 95% wind. To comply with I-937, 761 aMW (6666 GWh) of new energy efficiency are projected to be acquired by 2020.[20]
- New non-renewable power plants built between 2010 and 2020 will be a mix of 95% natural gas and 5% petroleum (fuel oil). This mix of proposed plants is based on regional projections from the EIA AEO2006, adjusted to remove coal plants, since none are currently actively proposed in the State. Discussions with Department of Community, Trade and Economic Development staff indicated the possibility of a 600 MW coal- or petroleum coke-fired plant being built in Kalama and noted that it would likely need to be an integrated gasification combined-cycle (IGCC) plant with CO_2 sequestration (no such plants are in commercial operation in the United States). If sequestering technologies can capture and store 85-90% of CO2 emissions, the total emissions from such a plant would

[19] Database of State Incentives for Renewables and Efficiency. Accessed December 10, 2006. http://www.dsireusa.org/library/includes/incentive2.cfm?Incentive_Code=WA15R&state=WA&CurrentPageID=1&RE=1&EE=1

[20] Parameters for I-937 were based on J Deyette and S Clemmer. *The Washington Clean Energy Initiative: Effects of I-937 on Consumers, Jobs and the Economy.* Union of Concerned Scientists. October 2006.

be in the order of 0.5 $MMTCO_2e$ per year.[21] Given the uncertainties surrounding such a project, it is not included in the reference case.

Future Electricity Consumption

Projections of electricity sales from 2006 through 2020 are based a sales-weighted average of projections by the 4 largest utilities in the State (Puget Sound Energy, City of Seattle, Snohomish County PUD, and Avista Corporation).[22] 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.

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). Sectoral breakdowns based on Puget Sound Energy projections.

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 2004, 68 entities were involved in providing electricity to Washington customers. The State's four investor-owned utilities serve approximately 45% of the customers, and provide 37% of the electricity sales. The State's 18 electric cooperatives serve 5% of the customers and account for 5% of sales. One federal and 40 public utilities account for the remaining 50% of customers and 58% of sales. The top 5 providers of retail electricity in the State are reported in Table A5.

[21] Based on the plant emitting 4.4 million tons of GHG emissions per year, from the developer's estimate. http://www.tdn.com/articles/2006/11/07/area_news/news04.txt

[22] 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 A5. Retail Electricity Providers in Washington (2004)

Entity	Ownership Type	2004 GWh
Puget Sound Energy Inc	Investor-Owned	19,877
Seattle City of	Public	9,021
PUD No 1 of Snohomish County	Public	6,152
Avista Corporation	Investor-Owned	5,137
Tacoma City of	Public	4,638
Total Sales, Top Five Providers		44,824
Total, All Washington		**79,982**

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.[23] By accounting for emissions from imported electricity, states can account for increases or decreases in fossil fuel consumed in power plants outside of the State, due to demand growth, efficiency programs, and other actions in the state. The difficulty with this approach is properly accounting for the emissions from imports and exports. To address this issue, Washington House Bill 2565 requires retail electricity suppliers in Washington to supply provide a disclosure label to their retail customers, at least semi-annually. This requirement started in May 2001 and the information has been collected and reported by the Department of Community, Trade, and Economic Development.[24] This information was used in the report, *Washington's Greenhouse Gas Emissions: Sources and Trends* (December 2006)[25] to report GHG emissions for Washington on a consumption-basis for 2002 through 2005. While, it would

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

[24] Database of State Incentives for Renewables and Efficiency. http://www.dsireusa.org/library/includes /incentive2.cfm?Incentive_Code=WA04R&state=WA&CurrentPageID=1&RE=1&EE=1 and http://www.cted.wa.gov/site/539/default.aspx

[25] S Waterman-Hoey and G Nothstein. Department of Community, Trade and Economic Development. December 2006. http://www.cted.wa.gov/DesktopModules/CTEDPublications/ CTEDPublicationsView.aspx?tabID=0&ItemID=3956&MId=863&wversion=Staging

be desirable to use the consumption-based emission estimates for this analysis, the fuel disclosure data are not available prior to 2002 (rather than 1990) and estimating consumption-based emissions for the future would increase the assumptions required[26] for this analysis, adding greater uncertainty to the results.

Instead, the approach taken in this initial inventory is a simplification of the consumption-based approach. This approach, which one could term "*Net-Consumption-based*," estimates consumption-based emissions as in-state (production-based) emissions times the ratio of total in-state electricity consumption to in-state generation (net of losses) plus the emissions from the net imports. If the state is a net exporter of electricity, the net-consumption-based emissions are less than the production-based emissions, based on the fraction of exported electricity. If the state is a net importer of electricity, the consumption-based emissions are greater than the production-based emissions, based on the amount and GHG emission-intensity of the imports.

Emissions for net imports are calculated as net imports in GWh multiplied by an emission factor in GHG emissions per electricity generated (MTCO2e/GWh) for the imports. As a proxy for estimating the mix of historic and future GHG emissions for Washington's electricity imports, emission factors that reflect the regional fuel mix were used. The region used to reflect electricity imports is the Northwest Power Pool[27] portion of the WECC (excluding Washington's emissions) from the AEO2006. This regional emission factor was 0.58 MtCO2e/MWh in 2004, decreasing to 0.50 MtCO2e/MWh in 2020, reflecting an increased regional contribution of renewables and natural gas to the electricity generation mix.

This method does not account for differences in the type of electricity that is imported or exported from the State, and as such, it provides a simplified method for reflecting the emissions impacts of electricity consumption in the State. The calculation also ignores "gross" imports – since Washington plants have contracts to out-of-state entities, some of the in-state electricity generation will be exported and gross imports will be greater than net imports.

The results section for this appendix reports both production-based and net consumption-based GHG emissions for Washington for 1990 to 2020. It also provides the consumption-based emissions calculated by the Department of Community, Trade and Economic Development based on the fuel disclosure information for 2002 to 2005.

Summary of Assumptions and Reference Case Projections

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

[26] Assumptions on mix of out-of-state generation for each utility would be needed.
[27] The Northwest Power Pool region in AEO2006 include Washington, Oregon, Idaho, Colorado, Utah and portions on Nevada, Montana and South Dakota. http://www.eia.doe.gov/oiaf/aeo/supplement/supmap.pdf

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

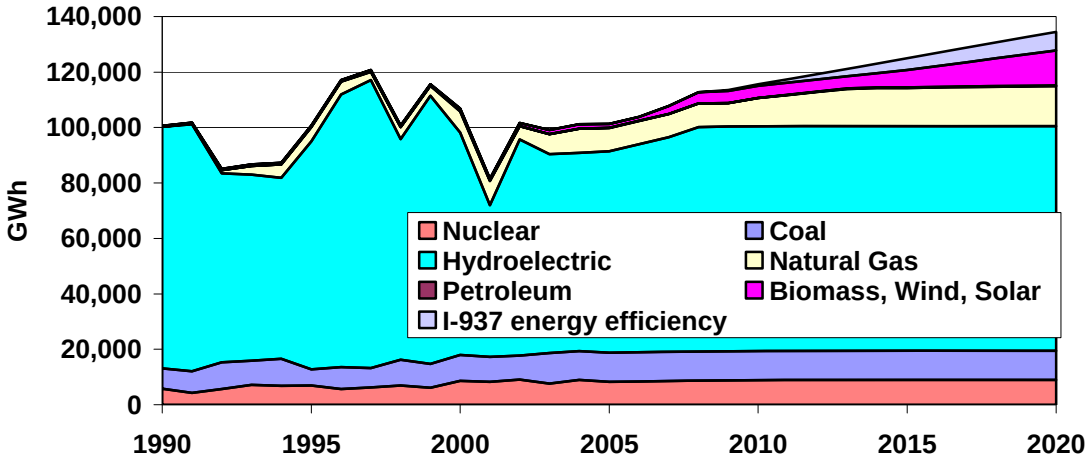
Electricity sales	Average annual growth of 1.4% from 2006 to 2010 and 1.3% from 2010 to 2020, based on growth rates reported by the 4 largest utilities.
Electricity generation	2.8% per year from 2005-2009, based on plants under construction and 1.1% per year from 2010 to 2020, based on regional growth rates in AEO2006.
Transmission and Distribution losses	10% losses are assumed, based on average statewide losses, 1994-2000, (data from the US EPA Emission & Generation Resource Integrated Database[28])
New Renewable Generation Sources	Washington's Renewable Energy Standard (I-937) will be met by qualifying utilities (about 84% of electricity sales). The requirements are 3% of the utilities' sales met by new renewable generation by 2012, increasing to 9% by 2016 and 15% in 2020 and subsequent years. Resources to meet the RPS are assumed to be 5% biomass and 95% wind
New Energy Efficiency Activities	I-937 is assumed to lead to 73 aMW (639 GWh) of new energy efficiency savings in 2010 increasing to 761 aMW (6,666 GWh) in 2020, based on estimates of cost-effective energy efficiency from the Northwest Power and Conservation Council.[29]
New Non-Renewable Generation Sources (2006-2009)	The mix of new non-renewable generation is based on plants under construction for this period (table A3).
New Non-Renewable Generation Sources (2010-2020)	The mix of new generation in this period is assumed to be 5% petroleum (light fuel oil or petroleum coke) 95% natural gas
Heat Rates	The assumed heat rate for new natural gas generation is 7000 Btu/kWh, based on estimates used in similar analyses.[30]
Operation of Existing Facilities	Existing non-hydro facilities are assumed to continue to operate as at 2005 levels. Existing hydro facilities are assumed to generate 81,051 GWh per year, the average generation over the period 1996-2005. Improvements in existing facilities that lead to higher capacity factors and more generation are captured under the new generation sources.

Figure A4 shows historical sources of electricity generation in the state by fuel source, along with projections to the year 2020 based on the assumptions described above. Renewables and energy efficiency show strong growth, relative to 2005 levels, resulting from implementation of the State initiative I-937. While not explicitly reported in the chart, energy efficiency savings have occurred and are continuing to proceed. Additional new natural gas generation is also projected in this time period, as shown. Any electricity generation beyond the needs of the State

[28] http://www.epa.gov/cleanenergy/egrid/index.htm.
[29] As reported in J Deyette and S Clemmer. *The Washington Clean Energy Initiative: Effects of I-937 on Consumers, Jobs and the Economy.* Union of Concerned Scientists. October 2006.
[30] See, for instance, the Oregon Governor's Advisory Group On Global Warming http://egov.oregon.gov/ENERGY/GBLWRM/Strategy.shtml.

is assumed to be exported to other states. Overall electricity generation (excluding savings from energy efficiency) grows at 1.6% per year from 2006 to 2020. Following the assumptions described above, new natural gas generation is not projected to come on-line until 2010; additional gas generation then increases through 2014. After this year, the increasing requirement for renewable generation under I-937 leads to strong growth in wind generation. Additional increases in new natural gas generation are projected to continue from 2015 through 2020, but at a slower rate of increase than in the preceding 5 years.

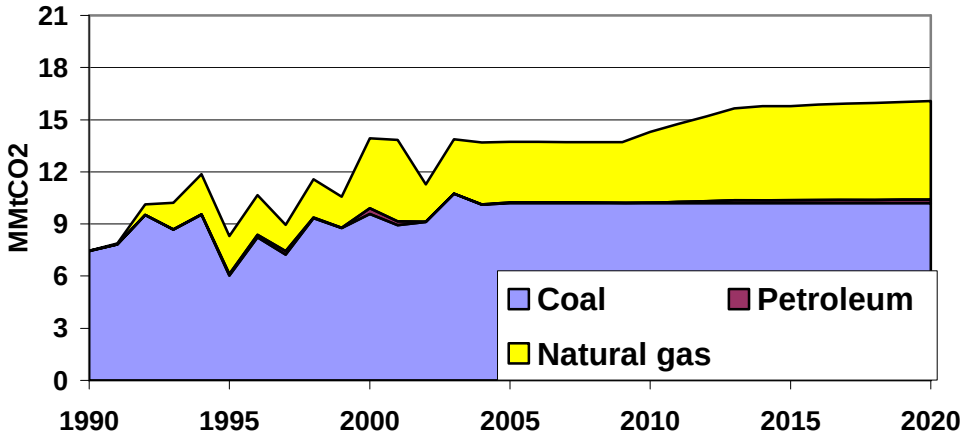
Figure A4. Electricity Generated by Washington Power Plants 1990-2020



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

Figure A5 illustrates the GHG emissions associated with the mix of electricity generation shown in Figure A4. From 2006 to 2020, the emissions from Washington electricity generation are projected to grow at 1.1% per year, lower than the growth in electricity generation, due to an increased fraction of generation from renewables and natural gas. The patterns of increased GHG emissions from natural gas generation shown in Figure A5 – no increase from 2006 to 2009, strong increases from 2010 to2014, then lower rate of increases through 2020 – match the changes in natural gas generation in Figure A4 (see previous paragraph for explanation of pattern). The GHG emission intensity (emissions per MWh) of Washington electricity generation is projected to decrease from 0.14 $MtCO_2$/MWh in 2005 to 0.12 $MtCO_2$/MWh in 2020.

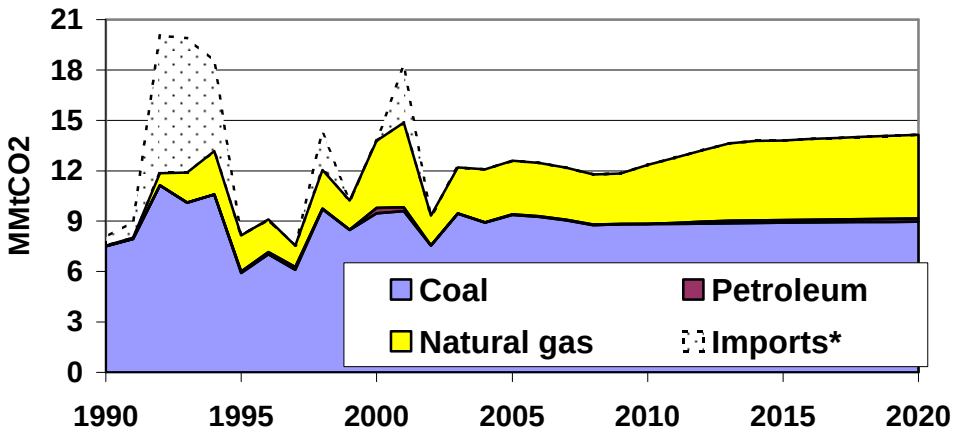
Figure A5. Washington GHG Emissions Associated with Electricity Production (Production-Basis)



Source: CCS calculations based on approach described in text.

Figure A6 shows GHG emissions associated with Washington's electricity demand, using a net-consumption basis. For years when Washington was a net importer of electricity, the emissions from imports are based on the projected average generation mix from the Northwest Power Pool region of the WECC, based on results of the AEO2006. The chart indicates the strong relationship of the variation in hydro-electric generation on net-consumption emissions. In years where hydro-electricity generation in the State was low (for example, 1992-1994, 1998 and 2001), Washington's net-consumption based emissions increase dramatically. The GHG emission increases are due to both increased fossil-fuel generation in-state and increased net imports from out-of-state. GHG emissions that are based on actual import/export information from utilities may show less variation, if the utilities' electricity sources are less dependent on hydro-electric power. The GHG emission reported in Figure A6 from 2002 to 2020 are lower than the production-based emissions reported in Figure A5. This reflects assumptions about the GHG emissions associated with net-exports of electricity. In 2020, based on the assumptions described in this appendix, net electricity exports from Washington account for about 2.1 MMTCO2e of GHG emissions. Consumption-based emissions for the State increase by 0.7% per year from 2006 to 2020.

Figure A6. Washington GHG Emissions Associated with Electricity Use (Consumption-Basis), showing imports



Source: CCS calculations based on approach described in text.

Table A7 summarizes the GHG emissions for Washington's electric sector from 1990 to 2020. During this time period, emissions are projected to increase by 33% on a production-basis and 111% on a consumption-basis.

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

(Million Metric Tons CO_2e)	1990	2000	2005	2010	2020
Electricity, Production-based	**7.5**	**13.9**	**13.7**	**14.3**	**16.1**
Coal	7.4	9.6	10.2	10.2	10.2
CO_2	7.4	9.5	10.1	10.1	10.1
CH_4 and N_2O	0.0	0.0	0.0	0.0	0.0
Natural Gas	0.0	4.0	3.5	4.1	5.7
CO_2	0.0	4.0	3.5	4.1	5.7
CH_4 and N_2O	0.0	0.0	0.0	0.0	0.0
Petroleum	0.0	0.3	0.0	0.0	0.2
CO_2	*0.0*	*0.3*	*0.0*	*0.0*	*0.2*
CH_4 and N_2O	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
Biomass and Waste (CH_4 and N_2O)	0.0	0.0	0.0	0.0	0.0
Net Imported Electricity	**0.1**	**-0.1**	**-1.1**	**-2.0**	**-2.1**
Electricity, Net Consumption-based	**7.5**	**13.8**	**12.6**	**12.3**	**14.0**

Note: Values that are less than 0.05 MMTCO2e are listed as 0.0 in Table A7.

Comparison to Washington State GHG Inventory

In December 2006, the Washington Departments of Community, Trade and Economic Development (CTED) released the report, *Washington's Greenhouse Gas Emissions: Sources*

and Trends.[31] This report covers historic GHG emissions from energy consumption in the State from about 1960 to 2004 (GHG emissions from other sources are also covered). The production-based estimates of GHG emissions from the electric sector in this CCS report match, both in calculation method and in value, the estimates in the CTED report.[32]

The CTED report also includes consumption-based GHG emission estimates for the electric sector for 2002-2005. CTED was able to calculate these values based on utility reporting of actual imports. This approach differs from the CCS simplified net-consumption based approach, based on the State-wide difference in generation and electricity demand (which calculates net imports or exports). (See the previous section on *Electricity Trade* for descriptions on the difference in approaches and reasons for using net-consumption for this analysis.)

Not surprisingly, the results of the CTED methodology are quite different from the ones presented above, as illustrated in Table A8. CTED's methodology is far closer to a true load or consumption-based approach, since it considers each utility's portfolio of power plant claims (ownership or contractual) as well as its market purchases. Washington is one of the few states that requires disclosure of, and thus can track, utility fuel mixes – it is thus rather unique in its ability to generate statewide emissions estimates that reflect the power actually relied upon to meet customer loads.[33] The limitations of this approach are that it cannot be applied prior to 2002 (first year of fuel mix reporting) and that somewhat less straightforward to use for emissions projections and policy analysis.

Table A8. Washington GHG Emissions from Electric Sector, Consumption, Net-Consumption and Production-based estimates, 2002-2005.

(Million Metric Tons CO_2e)	2002	2003	2004	2005
Consumption-based (CTED)	**14.6**	**18.1**	**18.3**	**18.9**
Net Consumption-based (CCS)	**9.3**	**12.2**	**12.1**	**12.6**
Production-based (CCS)	**11.3**	**13.9**	**13.7**	**13.7**

Sources: CCS refers to values in this appendix, CTED refers to values from *Washington's Greenhouse Gas Emissions: Sources and Trends* (Washington State CTED, December 2006)

The "net-consumption-based" methodology on the other hand is a very rough simplification that does not consider individual utility portfolios. Instead it implicitly assumes that the mix of in-state generation resources is representative of the power mix supplied to consumers. In fact, none of the in-state utilities have claims on the principal in-state coal plant (Centralia), while two utilities have significant claims on the Colstrip coal plant located in Eastern Montana, emissions from these claims adding about 6 MMtCO2 to CTED emissions estimates. Furthermore, the CTED fuel mix estimates also reflect the emissions associated market purchases, especially

[31] S Waterman-Hoey and G Nothstein. Department of Community, Trade and Economic Development. December 2006. http://www.cted.wa.gov/DesktopModules/CTEDPublications/CTEDPublicationsView.aspx?tabID=0&ItemID=3956&MId=863&wversion=Staging

[32] One discrepancy was found between the two reports, due to emission factors from coal consumption, but it was a small difference (about 1%) and CTED is revising their values.

[33] The fuel mix approach is not without its limitations (e.g. consistency of methods across utilities, verification of utility claims and) and simplifications (e.g. treatment of market purchases), however it represents one of the best examples of load-based emissions estimates.

significant during periods of low hydro availability. One advantage of the "net-consumption methodology is that it can be applied to historical data prior to 2002. Another is that it is less dependent on changing patterns of plant ownership and contracts.

Input is welcomed from reviewers in terms of methodologies to use for reporting consumption-based emissions.

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.
- Consumption-based emissions. Washington State CTED has made strong progress in collecting and reporting GHG emissions from electricity delivered to its electricity consumers. Evaluations thus far indicate that these emissions differ significantly from production-based and net-consumption based emissions used for the reference case projections in this CCS analysis. Future research could focus on developing approaches for estimating future consumption-based emissions.

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

Overview

Activities in the RCI[34] 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 on a million metric tons (MMt) of CO_2 equivalent (CO_2e) basis in Washington. 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.[35] 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 17.6 $MMtCO_2e$ (21%) of gross GHG emissions in 2005.[36]

Emissions and Reference Case Projections

Emissions for direct fuel use were estimated using the United States Environmental Protection Agency's (US EPA) State Greenhouse Gas Inventory Tool (SGIT) software and the methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for RCI fossil fuel combustion.[37] 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;[38] (2) 2003 SED information for coal, and wood and wood waste;[39] (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

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

[35] 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.

[36] 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.

[37] 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.

[38] 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).

[39] 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;[40] and (5) 2005 natural gas consumption data from the EIA's *Natural Gas Navigator*.[41] Washington CTED estimated 2004 coal consumption for all three sectors and these estimates were included in the inventory described in this appendix. Washington 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.

Washington CTED prepared a GHG inventory for the RCI sectors using the default SED information. For the inventory described in this Appendix B, the SED information used is essentially the same as that used by Washington CTED with the exception that the Center for Climate Strategies (CCS) updated SED information for 2004 and 2005 published by the EIA after Washington CTED completed its inventory. In addition, Washington CTED's inventory for residential wood consumption contained SED 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.[42] 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,[43] 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),[44] with adjustments for Washington's projected population[45] and employment growth. Washington employment data for the manufacturing (goods producing) and non-manufacturing (commercial or services providing)

[40] EIA *Electric Power Annual 2005 - State Data Tables*, (http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html).
[41] EIA *Natural Gas Navigator* (http://tonto.eia.doe.gov/dnav/ng/ng_cons_sum_dcu_SWA_a.htm).
[42] EIIP, Volume VIII: Chapter 1 "Methods for Estimating Carbon Dioxide Emissions from Combustion of Fossil Fuels", August 2004.
[43] A mixture of hydrocarbons, mostly pentanes and heavier fractions, extracted from natural gas.
[44] EIA AEO2006 with Projections to 2030, (http://www.eia.doe.gov/oiaf/aeo/index.html).
[45] 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).

sectors were obtained from the Washington State Employment Security Department.[46] Regional employment data for the same sectors were obtained from EIA for the EIA's Pacific region.[47] 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 Department'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. 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

[46] 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).

[47] AEO2006 employment projections for EIA's Pacific region obtained through special request from EIA (dated September 27, 2006).

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%

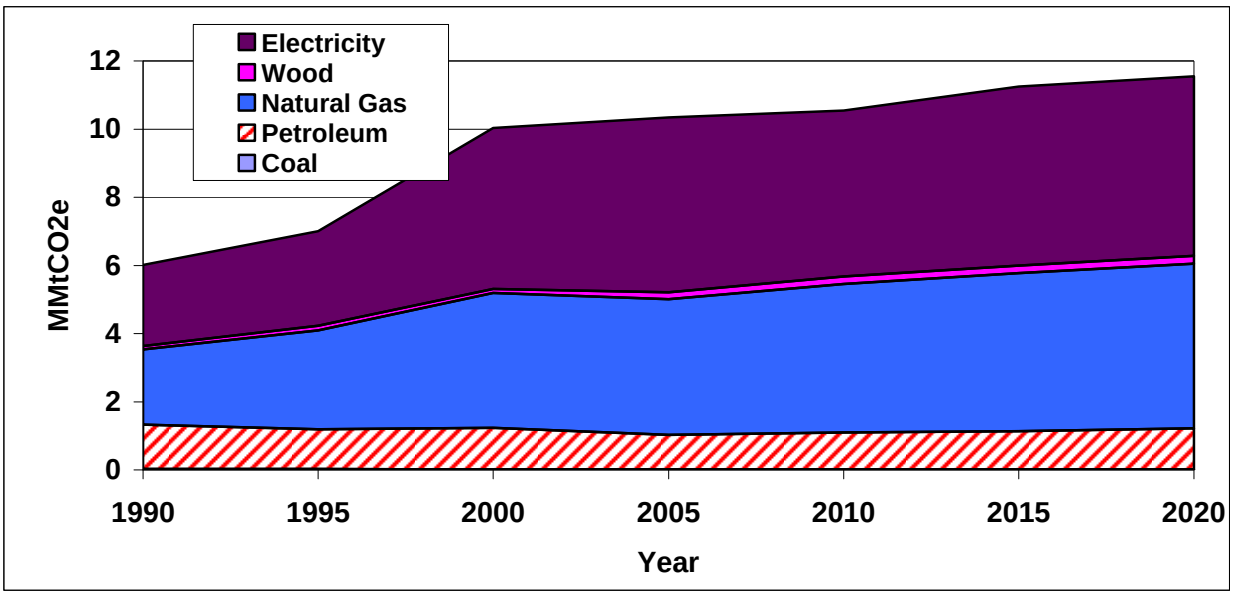
* Compound annual growth rates calculated from EIA SED historical consumption by sector and fuel type for Washington. Latest year for which EIA SED information was available for each fuel type is 2003 for coal and wood/wood waste, 2004 for petroleum, and 2005 for natural gas. Petroleum includes distillate fuel, kerosene, and liquefied petroleum gases for all sectors plus residual oil for the commercial and industrial sectors. Washington CTED 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 6 $MMtCO_2e$, and are estimated to increase to about 12 $MMtCO_2e$ by 2020. Emissions associated with the generation of electricity to meet residential energy consumption demand accounted for about 42% of total residential emissions in 1990 and are estimated to increase to 48% of total residential emissions by 2020. In 1990, natural gas consumption accounted for about 35% of total residential emissions and is estimated to account for about 40% of total residential emissions by 2020. Residential-sector emissions associated with the use of petroleum accounted for about 21% of total residential emissions in 1990 and are estimated to decline to 10% 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 2% of total residential emissions. By 2020, emissions associated with the consumption of these two fuels are

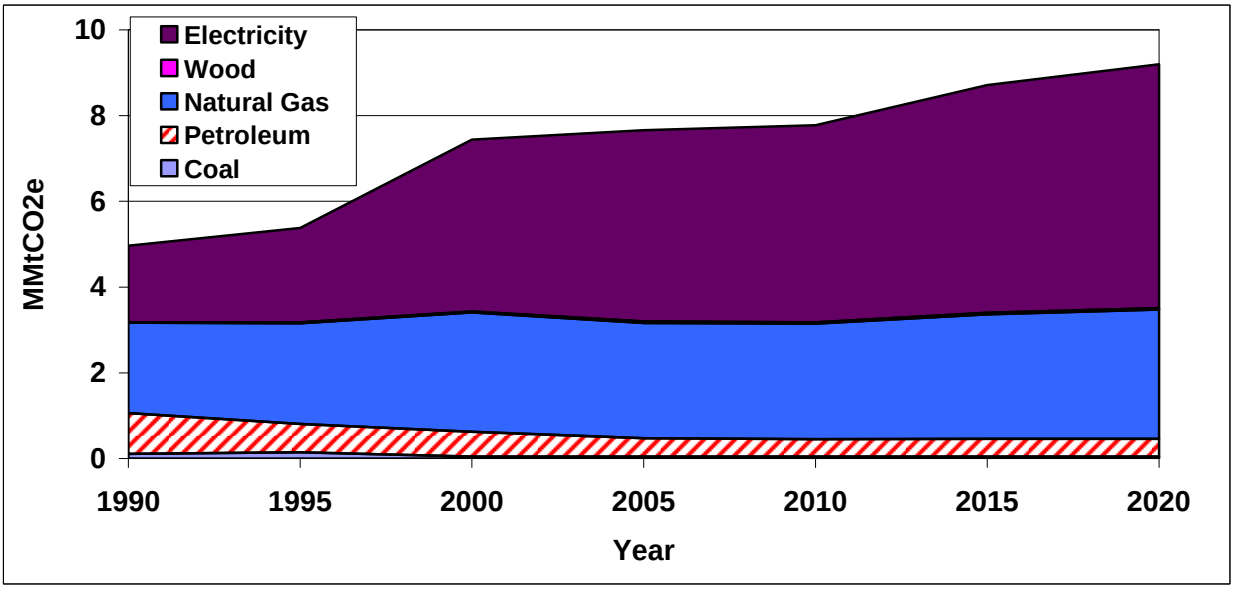
estimated to be 0.22 $MMtCO_2e$ and to account for 2% of total residential sector emissions by that time.

Figure B1. Residential Sector GHG Emissions from Fuel Consumption



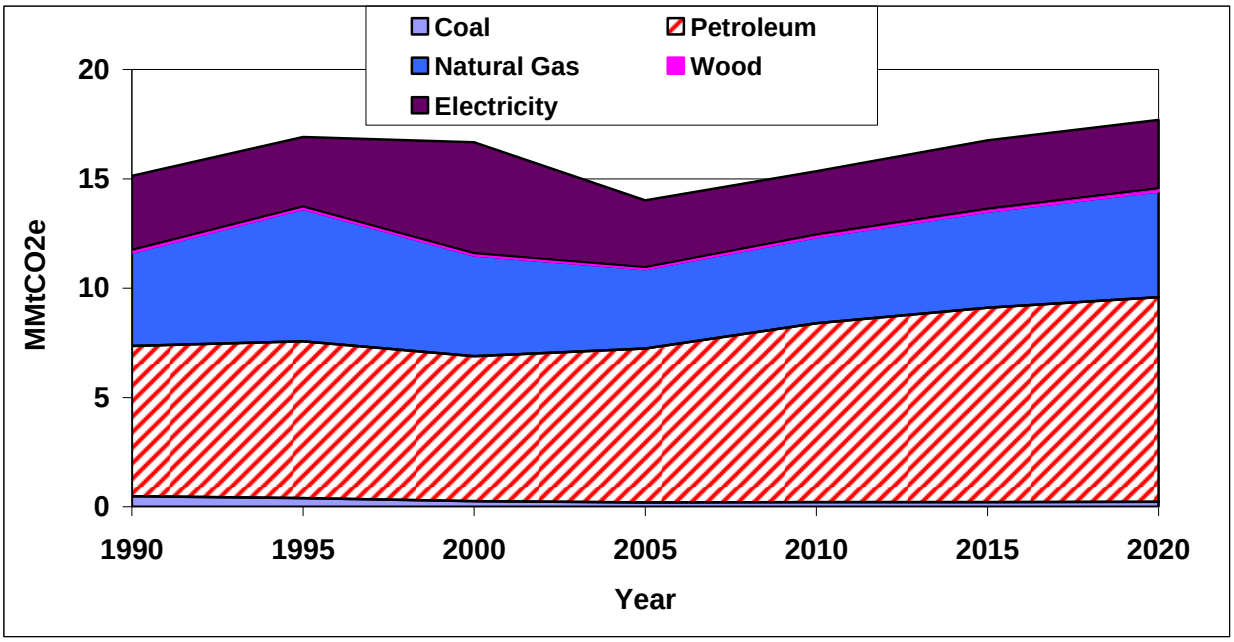
Source: CCS calculations based on approach described in text.
Note: Emissions associated with coal combustion are too small to be seen on this graph.

Figure 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 0.2%, 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 0.7% 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 Washington CTED, this is most likely associated with households switching to using wood for home heating due to increases in electricity prices during this time period. Note, however, that this significant increase in wood consumption resulted in only a very low contribution to total residential emissions (associated with CH_4 and N_2O on a $MMtCO_2e$ basis) because CO_2 emissions associated with renewable fuels such as wood are excluded from the inventory to be consistent with US EPA and IPCC methodologies.

For the commercial sector, emissions from electricity and direct fuel use in 1990 were about 5 $MMtCO_2e$ and are estimated to increase to about 9 $MMtCO_2e$ by 2020. Emissions associated with the generation of electricity to meet commercial demand accounted for about 39% of total commercial emissions in 1990, and are estimated to increase to about 64% 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 41% of total commercial emissions, and is estimated to account for about 31% of total commercial emissions by 2020. Commercial-sector emissions associated with the use of petroleum accounted for about 18% of total commercial emissions in 1990, and are projected to decline to about 4.2% of total commercial emissions by 2020. Commercial-sector emissions associated with the use of coal accounted for

about 2.0% of total commercial emissions in 1990, and are estimated to decline to about 0.4% of total commercial emissions by 2020. Commercial-sector emissions associated with the use of wood accounted for about 0.2% of total commercial emissions in 1990, and are projected to increase slightly to account for 0.3% 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 1.7% 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 1.3% annually over the 15-year period.

For the industrial sector, emissions in 1990 were about 15 $MMtCO_2e$, and are estimated to increase to about 18 $MMtCO_2e$ by 2020. Emissions associated with the generation of electricity to meet industrial demand accounted for about 24.4% of total industrial emissions in 1990 and are estimated to decline to about 19.2% of total industrial emissions by 2020. In 1990, natural gas consumption accounted for about 27.4% of total industrial emissions, and this fraction is estimated to decline slightly, to about 26.8% of total industrial emissions by 2020. Industrial-sector emissions associated with the use of petroleum accounted for about 44.1% of total commercial emissions in 1990, and are projected increase to about 51.8% of total commercial emissions by 2020. Industrial-sector emissions associated with the use of coal accounted for about 3.1% of total industrial emissions in 1990, and are estimated to decline to about 1.3% of total industrial emissions by 2020. Industrial-sector emissions associated with the use of wood accounted for about 1.0% of total industrial emissions in 1990, and are projected to continue to account for about 1.0% 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 0.2%, 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 1.6% 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 generating electricity to meet the residential and commercial sectors' increased demand for electricity over this period. As a consequence, the increases in residential and commercial 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 1995 to 2000, 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 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 Washington 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).[48] 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 Section Assessment Report (SAR).[49] Thus, the emissions for CH_4 and N_2O on a CO_2-equivalent basis will differ slightly from the emissions calculated by Washington CTED. The following compares the global warming potential factors in the IPCC's SAR and TAR:

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

[48] 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.

[49] 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 (onroad) 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.

Emissions and Reference Case Projections

GHG emissions for 1990 through 2002 were estimated using SGIT and the methods provided in the EIIP guidance document for the sector.[50,51] For onroad vehicles, the CO_2 emission factors are in units of lb/MMBtu and the CH_4 and N_2O emission factors are both in units of grams/VMT. Key assumptions in this analysis are listed in Table C1. The default fuel consumption data within SGIT were used to estimate emissions, with the most recently available fuel consumption data (2002) from EIA SED added.[52] The default annual VMT data for in SGIT was the same as that provided by WSDOT.[53] The state-level VMT was allocated to vehicle types using vehicle mix data from FHWA.[54]

Onroad Vehicles

Onroad vehicle gasoline and diesel emissions were projected based on VMT forecasts provided by WSDOT[4] and growth rates developed from national vehicle type VMT forecasts reported in EIA's *Annual Energy Outlook* 2006 (AEO2006). The AEO2006 data were incorporated because they indicate significantly different VMT growth rates for certain vehicle types (e.g., 34 percent growth between 2002 and 2020 in heavy-duty gasoline vehicle VMT versus 284 percent growth in light-duty diesel truck VMT over this period). The procedure first applied the AEO2006 vehicle type-based national growth rates to 2002 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.

[50] 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.
[51] 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.
[52] Energy Information Administration, State Energy Consumption, Price, and Expenditure Estimates (SED), http://www.eia.doe.gov/emeu/states/_seds.html
[53] Pat Whittaker, Highway Performance Monitoring System Functional Classification Manager, Transportation Data Office, Washington Department of Transportation
[54] Highway Statistics, Federal Highway Administration, http://www.fhwa.dot.gov/policy/ohpi/hss/index.htm.

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

Vehicle Type and Pollutants	Methods
Onroad gasoline, diesel, natural gas, and LPG vehicles – CO_2	**Inventory (1990 – 2002)** EPA SGIT and fuel consumption from EIA SED **Reference Case Projections (2003 – 2020)** Gasoline and diesel fuel projected using VMT projections 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 – 2002)** EPA SGIT, onroad vehicle CH_4 and N_2O emission factors by vehicle type and technology type within SGIT were updated to the latest factors used in the US EPA's *Inventory of U..S. Greenhouse Gas Emissions and Sinks: 1990-2003.* State total VMT replaced with VMT provided by WSDOT, VMT allocated to vehicle types using default data in SGIT. **Reference Case Projections (2003 – 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 – 2002)** EPA SGIT and fuel consumption from EIA SED, except for commercial marine, which was taken from PSCAA and Corbett inventories and allocation of national fuel consumption data using port freight tonnage data. **Reference Case Projections (2003 – 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	4,094	4,835	5,480	6,144
Heavy Duty Gasoline Vehicle	524	574	629	694	762
Light Duty Diesel Truck	538	639	893	1,216	1,657
Light Duty Diesel Vehicle	170	201	281	383	523
Light Duty Gasoline Truck	17,901	18,798	20,693	22,164	23,487
Light Duty Gasoline Vehicle	31,858	33,454	36,827	39,445	41,799
Motorcycle	182	191	211	226	239
Total	**54,776**	**57,951**	**64,369**	**69,608**	**74,610**

Table C3. Washington Vehicle Miles Traveled Compound Annual Growth Rates

Vehicle Type	2002-2005	2005-2010	2010-2015	2015-2020
Heavy Duty Diesel Vehicle	4.36%	3.38%	2.53%	2.31%
Heavy Duty Gasoline Vehicle	3.06%	1.86%	1.99%	1.88%
Light Duty Diesel Truck	5.85%	6.93%	6.37%	6.40%
Light Duty Diesel Vehicle	5.85%	6.93%	6.37%	6.40%
Light Duty Gasoline Truck	1.64%	1.94%	1.38%	1.17%
Light Duty Gasoline Vehicle	1.64%	1.94%	1.38%	1.17%
Motorcycle	1.64%	1.94%	1.38%	1.17%

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 and diesel consumption projections were also adjusted to account for ethanol and biodiesel consumption. Recent legislation passed by the Washington Legislature mandates that ethanol shall comprise 2% of total motor gasoline and that biodiesel shall comprise 2% of total diesel fuel sold in Washington by 2008. According to fuel consumption data from EIA, motor gasoline consumed in Washington already contained 2.7% ethanol in 2002. Since no dates have been set for additional ethanol consumption targets, ethanol consumption was assumed to remain at 2.7% of ethanol through 2020 for the reference case projections. Biodiesel consumption was assumed to increase to 2% of diesel consumption between 2002 and 2008, and remain at 2% of diesel consumption through 2020. The onroad gasoline and diesel projections adjusted for fuel efficiency improvements and biofuel consumption suggest average onroad fuel consumption growth rates of 0.7% per year for gasoline and 3.1% per year for diesel between 2002 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. If these standards are allowed to take effect, the resulting emission reductions may be included as a mitigation strategy.

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 and Marine

For the rail and recreational marine sectors, 1990 – 2004 estimates are based on SGIT methods and fuel consumption from EIA. Marine gasoline consumption was projected to 2020 using historical data, which shows an average annual growth rate of -0.5%. The historic data for rail shows no significant positive or negative trend; therefore, no growth was assumed for this sector.

For marine vessel fuel consumption, the SGIT default relies on marine vessel fuel consumption estimates that represent the State in which fuel is sold rather than consumed; therefore, an alternative method was used to estimate commercial marine emissions for Washington. Estimates of commercial marine emissions and fuel consumption were taken from different sources for three areas: The Puget Sound Clean Air Agency (PSCAA) Region (King, Kitsap, Pierce, and Snohomish counties), Columbia and Snake Rivers, and all other ports. Commercial marine emissions for King, Kitsap, Pierce, and Snohomish were taken from an inventory developed by PSCAA.[57] This inventory includes emission estimates for 1990, 1999, and 2002. Estimates for intervening years were interpolated and estimates for 2003 and 2004 were forecast based on the historical data. For the Columbia and Snake Rivers, total 1999 fuel consumption by commercial marine vessels was taken from an inventory developed by Corbett for WA

[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] 1990 - 2002 GHG Emissions for Central Puget Sound Area, WA, Prepared by Puget Sound Clean Air Agency, Nov 2004. Provided by Kwame Agyei Puget Sound Clean Air Agency.

Ecology.[58] Table C5 shows the fuel consumption estimates for the Columbia and Snake Rivers and the amount of fuel included in this inventory.[59] Fuel consumption was allocated to residual and diesel fuel and scaled to other years using the fuel consumption estimates described below.

Table C5. 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 the remaining ports not covered by the inventories described above (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 each area using the marine vessel activity allocation methods/data compiled to support the 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 these areas 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. Puget Sound emissions will likely be replaced by newer estimates being developed by the Puget Sound Maritime Forum when the inventory is released later this month.

[58] Corbett, J., "Commercial Marine Vessel Inventory Review and Preparation for the Northwest U.S.", Prepared for the Washington Department of Ecology, May, 2001.
[59] For sections of river along the border between Washington and Oregon, half of the fuel consumption is assumed to occur in Washington.
[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).
[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.

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 speciating 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 estimated port fuel consumption.

Historical freight tonnage data (1990-2004) indicates an average annual growth rate of -0.3%. However, the CEC inventory developed by Corbett predicts an annual growth rate of 5.9% for the West Coast. Also, contacts at the Port of Seattle and Port of Tacoma indicate that they are expecting significant annual growth (3-10%) in container traffic over the next decade, based on projections of TEU data (twenty-foot equivalents).[65,66] Table C6 shows 2001-2005 vessel capacity calling at Pacific Northwest ports in thousand deadweights (DWT) for all vessel types and TEU for container ships from the US Department of Transportation Maritime Administration.[67] This data shows that while TEUs for container ships grew by 26% between 2001 and 2005, the growth in capacity for all vessel types grew by 13% during this period. For this inventory, port and offshore commercial marine emissions were projected by linearly extrapolating the 2001-2005 total vessel capacity data to 2020, which resulted in a 2005-2020 compound annual growth rate of 2.1%

[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.
[65] Jason Jordon, Senior Planner, Port of Seattle
[66] Cindy Lin, Manage of Environmental Compliance, Port of Tacoma
[67] U.S. Department of Transportation Maritime Administration, " Vessel Calls at U.S. & World Ports 2005", http://www.marad.dot.gov/MARAD_statistics/2005%20STATISTICS/Vessel%20Calls%20at%20U%20S%20&%20World%20Ports%202005.pdf

Table C6. Vessel Capacity Calling at Pacific Northwest Ports, 2001-2005 (Thousand DWT)

Vessel Type	2001	2002	2003	2004	2005	% Change 01-05
Tanker	158,030	155,389	176,978	151,484	172,189	9%
Container	75,230	81,326	84,963	86,731	88,295	17%
Container (TEU)	5,534	6,053	6,397	6,825	6,975	26%
Dry Bulk	95,401	83,800	63,452	99,616	107,063	12%
RORO	12,952	13,329	12,777	12,101	11,978	-8%
Gas Carrier	2,504	1,839	1,790	1,046	3,316	32%
Combination	135	0	103	140	350	159%
General Cargo	5,337	6,510	9,566	8,845	10,896	104%
All Types	349,589	342,193	349,629	359,963	394,087	13%

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

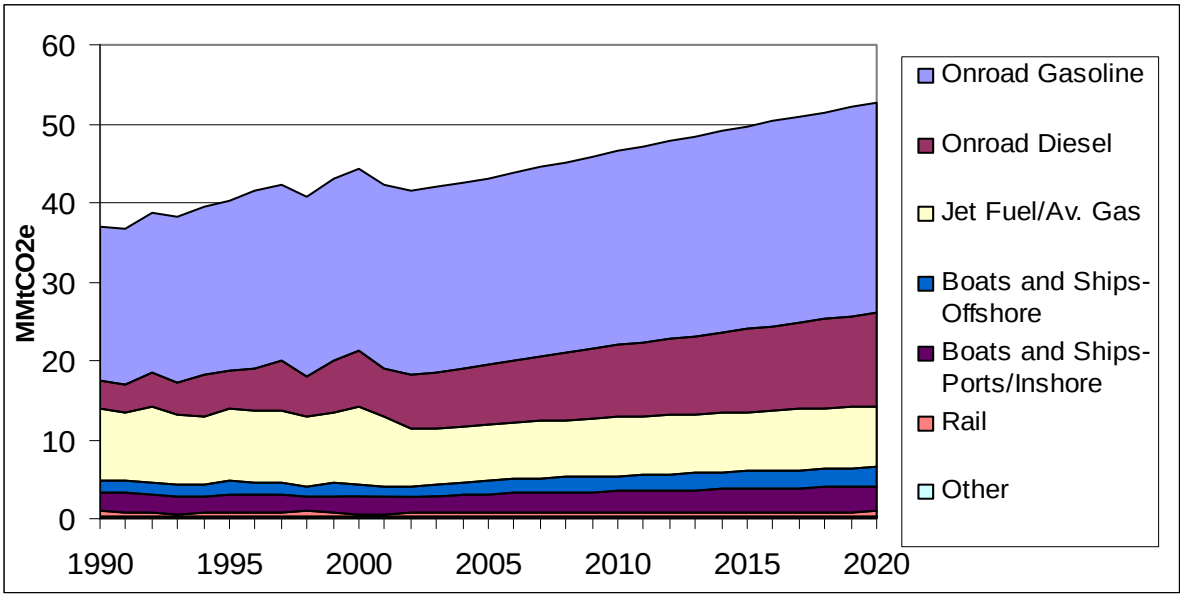
Results

As shown in Figure C1, onroad gasoline consumption accounts for the largest share of transportation GHG emissions. Emissions from onroad gasoline vehicles increased by about 20% from 1990-2002 to cover 56% of total transportation emissions in 2002. GHG emissions from onroad diesel fuel consumption increased by 94% from 1990 to 2002, and by 2002 accounted for 17% of GHG emissions from the transportation sector. The historical data shows a marked decrease in fuel consumption, especially apparent for diesel and aviation fuels, between 2000 and 2002, most likely due to an economic downturn during these years. 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 last two years of the historical period, emissions from aviation decreased by 19% between 1990 and 2002. Marine emissions decreased by 11% during this period. In 2002 jet fuel and marine fuels accounted for 18% and 8% of total transportation emissions, respectively. Emissions from all other categories combined (locomotives, natural gas

and LPG, and oxidation of lubricants) contributed under 2% of total transportation emissions in 2002.

GHG emissions from all onroad vehicles combined are projected to increase by 28% between 2002 and 2020, due to a 36% 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 2002-2020 period, with gasoline and diesel fuel consumption projected to increase by 14% and 72%, respectively. Jet fuel and aviation gasoline consumption is projected to increase by 6% between 2002 and 2020.

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



Source: CCS calculations based on approach described in text.

Key Uncertainties

Projections of Vehicle Miles of Travel (VMT) and Biofuels Consumption

One source of uncertainty is the future year vehicle mix, which was calculated based on national growth rates for specific vehicle types. These growth rates may not reflect vehicle-specific VMT growth rates for the state. Also, onroad gasoline and diesel growth rates may be slightly overestimated because increased consumption of biofuels between 2005 and 2020 was not taken into account (due to a lack of data).

Uncertainties in Aviation Fuel Consumption

The 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.

Uncertainties in Marine Fuel Consumption

There are several assumptions that introduce uncertainty into the estimates of commercial marine fuel consumption for the areas not covered by other inventories. These assumptions include:

- 75% of marine diesel and 25% of residual fuel is consumed in port
- The proportion of freight tonnage at the major ports in Washington to the total freight tonnage for the top 150 US ports reflects the proportion of national marine fuel that is consumed in Washington.

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, 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.

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

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

Emissions and Reference Case Projections

GHG emissions for 1990 through 2005 were estimated using the United States Environmental Protection Agency's (US EPA) State Greenhouse Gas Inventory Tool (SGIT) software and the methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for this sector.[68] Table D1 identifies for each emissions source category the information needed for input into SGIT to calculate emissions, the data sources used for the analysis described here, and the historical years for which emissions were calculated based on the availability of data. The Washington Department of Ecology's (WA Ecology) GHG inventory for 1990 through 2004 (recently undated in 2006) 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

[68] 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.

consumption of limestone, dolomite, and soda ash in the inventory to be consistent 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 (WA 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.	WA 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) 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.
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.	WA 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.	WA 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.	WA Ecology provided annual emission estimates based on the SGIT methodology for 1990 through 2004.

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*.[69] 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

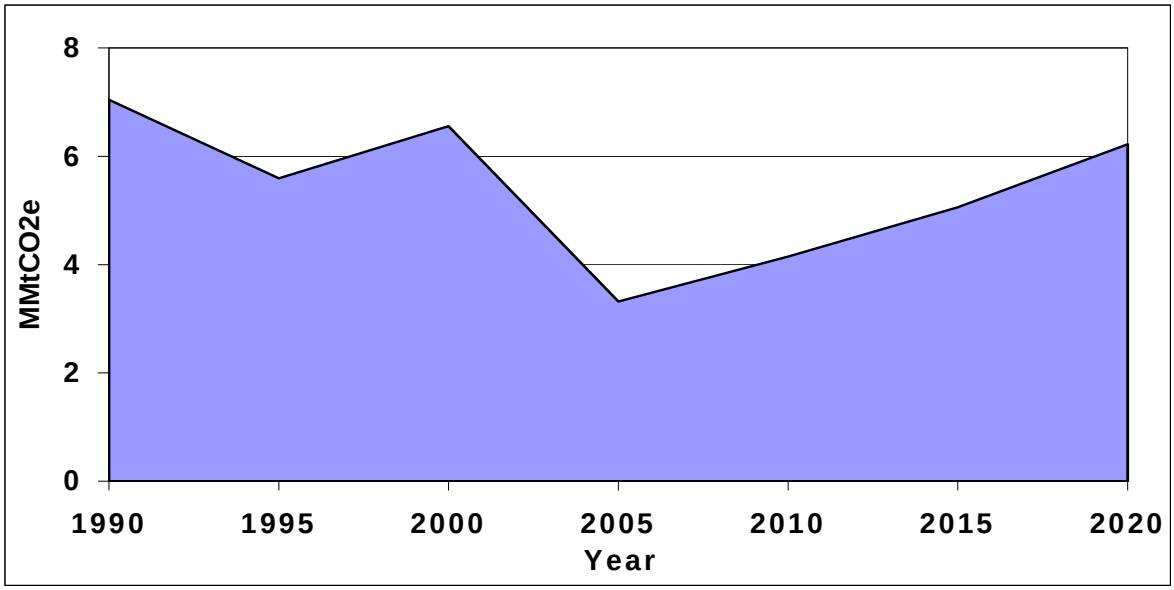
WA Ecology prepared annual emission estimates for primary aluminum production for 1990 through 2004 based on actual production data for each year. The aluminum production industry is thought to be the largest source of two perfluorocarbons (PFCs) – tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6). Emissions of these two potent GHGs occur during the reduction of alumina in the primary smelting process (see Chapter 6 of the 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.

[69] 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.

Electricity Distribution

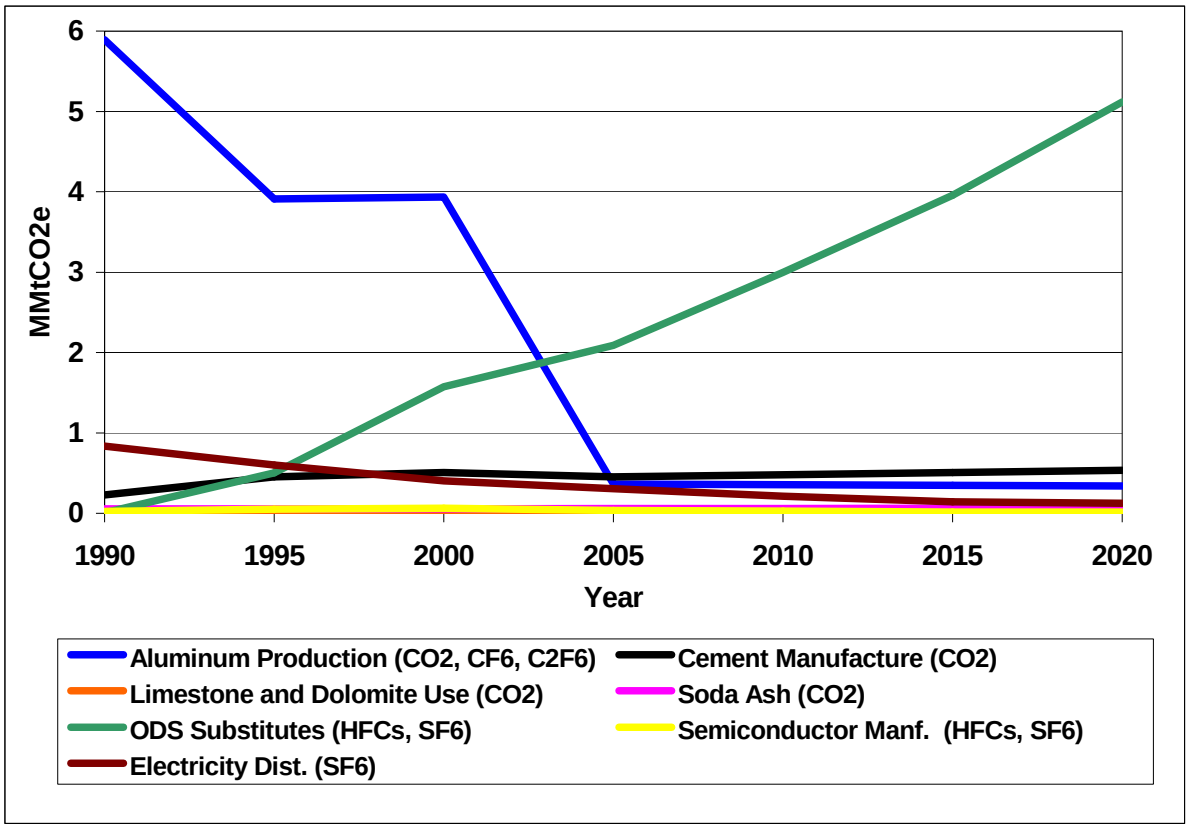
Emissions of SF_6 from electrical equipment have experienced declines since the early nineties (see brown line in Figure D2), mostly due to voluntary action by industry. SF_6 is used as an electrical insulator and interrupter in electricity T&D systems. Emissions for Washington from 1990 to 2002 were 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

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



Source: CCS calculations based on approach described in text.

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



Source: CCS calculations based on approach described in text.

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

WA 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 Chapter 6 of the EIIP guidance document). Emissions are calculated by multiplying annual clinker production and annual production of masonry cement by emission factors for these processes. Information on 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, chemical, glass manufacturing, and environmental pollution control industries, as well as in metallurgical industries such as magnesium production.[70] 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 Chapter 6 of the EIIP guidance document). SGIT estimates historical emissions (see dark pink line in Figure D2) based on the state's population and national per capita emissions from the US EPA national GHG inventory. According to the USGS, this industry is expected to grow at an annual rate of 0.5% from 2004 through 2009 for the US as a whole. Information on growth trends for years later than 2009 was not available; therefore the same 0.5% annual growth rate was applied for estimating emissions to 2020. Relative to total industrial non-combustion process emissions, emissions associated with soda ash consumption are low (about 0.053 $MMtCO_2e$ in 1990 and 0.061 $MMtCO_2e$ in 2020), and therefore cannot be seen in the graph due to scaling effects in Figure D2.

[70] 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).

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.
- State-specific industrial consumption data were not available for limestone and 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. 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 and carbon dioxide 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.[71] 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 Canada and have a combined capacity of 624 thousand barrels per day, supplying markets throughout the Northwest region.

Oil and Gas Industry Emissions

Since there is no oil or gas production in Washington, emissions of methane (CH_4) occur only from processing, transmission and distribution systems. Washington has five oil refineries, one LNG storage compressor station and over 2,000 miles of gas pipelines.[72] 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.

The State Greenhouse Gas Inventory Tool (SGIT), developed by the US EPA, facilitates estimation of state-level greenhouse gas emissions.[73] 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[74] and American Gas Association's annual publication *Gas Facts*.[75] 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.

[71] "The *U.S. Inventory of Greenhouse Gas Emissions and Sinks*", US EPA, 2005.
[72] Data from EIA and Gas Facts.
[73] 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.
[74] "Petroleum Navigator" and "Natural Gas Navigator", US DOE Energy Information Administration website, November 2006, Accessed at http://www.eia.doe.gov
[75] American Gas Association "Gas Facts, A Statistical Record of the Gas Industry" Referenced annual publications from 1992 to 2004.

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 Drilling and Field Production	Number wells	EIA	Washington has no oil or gas production.[76]
	Miles of gathering pipeline	Gas Facts	
Natural Gas Processing	Number gas processing plants	EIA[77]	There are no gas processing plants in Washington State.
Natural Gas Transmission	Miles of transmission pipeline	Gas Facts[78]	Emissions are held flat at 2004 levels.[79]
	Number of gas transmission compressor stations	EIIP[80]	
	Number of gas storage compressor stations	EIIP[81]	
	Number of LNG storage compressor stations	Federal Energy Regulatory Commission[82]	
Natural Gas Distribution	Miles of distribution pipeline	Gas Facts[78]	Distribution emissions follow State gas consumption trend - annual average growth rate of 1.5% between 2006 and 2020.[83]
	Total number of services	Gas Facts	
	Number of unprotected steel services	Ratio estimated from 2002 data[84]	
	Number of protected steel services	Ratio estimated from 2002 data[84]	

[76] As reported by the EIA.
[77] EIA reported data for 1995 and 2004.
[78] No Gas Facts available for 1991 and 1993, so a linear relationship was assumed to extrapolate from the previous and subsequent year.
[79] 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.
[80] Number of gas transmission compressor stations = miles of transmission pipeline x 0.006 EIIP. Volume VIII: Chapt. 5. March 2005.
[81] Number of gas storage compressor stations = miles of transmission pipeline x 0.0015 EIIP. Volume VIII: Chapt. 5. March 2005.
[82] 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
[83] Based on US DOE regional projections and electric sector growth assumptions (see Appendix A and B).
[84] 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.

	Approach to Estimating Historical Emissions		Approach to Estimating Projections
Activity	***Required Data for SGIT***	***Data Source***	***Projection Assumptions***
Oil Production	Annual production	EIA[85]	There is currently no oil production in Washington and no apparent prospects for future production.
Oil Refining	Annual amount refined	EIA[86]	Emissions projected to follow trend of 1.6% annual growth in state oil refining.[87]
Oil Transport	Annual oil transported	Unavailable, assumed oil refined = oil transported	Emissions follow trend of state oil refining, as above.

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.[88] In late 2006, TransAlta closed 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.[89]

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.[90] As a result of the Centralia mine closure, future emissions of coal mine methane were estimated to decrease to zero by 2007. 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

[85] Data extracted from the Petroleum Supply Annual for each year.
[86] 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.
[87] Based on EIA data, average growth in crude refined annually was 1.6% between 2000 and 2004.
[88] EIA Annual Coal Report 2005 Accessed at http://www.eia.doe.gov/cneaf/coal/page/acr/acr_sum.html#fes1
[89] 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.
[90] Emissions from EPA *U.S. Inventory of Greenhouse Gas Emissions and Sinks: 1990-2004* (April 2006) http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2006.html

report any methane emissions from abandoned Washington coal mines.[91] Any input from reviewers is welcomed.

Results

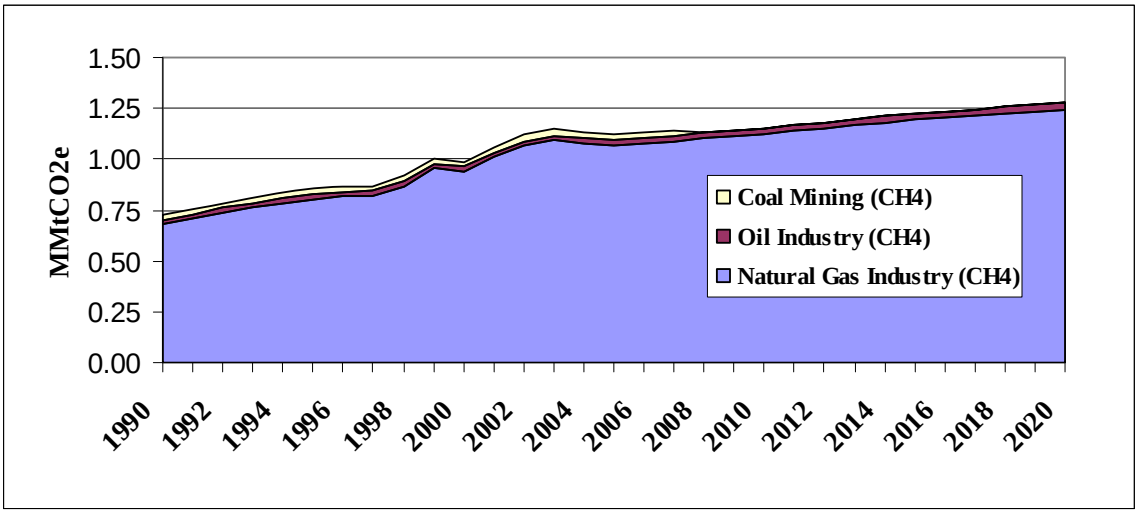
Table E2 displays the estimated methane emissions from the fossil fuel industry in Washington from 1990 to 2005, with projections to 2020. Emissions from this sector grew by 54% from 1990 to 2005 and are projected to increase by a further 14% from 2005 to 2020. Natural gas transmission and distribution 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.

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

(Million Metric Tons CO2e)	1990	1995	2000	2005	2010	2015	2020
Fossil Fuel Industry	**0.73**	**0.85**	**0.99**	**1.12**	**1.15**	**1.23**	**1.28**
Natural Gas Industry (CH4)	0.68	0.80	0.94	1.07	1.12	1.20	1.24
Production	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Processing	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Transmission	0.36	0.38	0.34	0.37	0.37	0.37	0.37
Distribution	0.32	0.42	0.60	0.69	0.75	0.82	0.87
Oil Industry (CH4)	0.02	0.02	0.02	0.03	0.03	0.03	0.03
Production	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Refineries	0.02	0.02	0.02	0.03	0.03	0.03	0.03
Coal Mining (CH4)	0.03	0.03	0.02	0.03	0.00	0.00	0.00

Figure E1 displays the methane emissions from coal mining and natural gas and oil systems, on a CO_2 equivalent basis.

Figure E1. Fossil Fuel Industry Emission Trends



Source: CCS calculations based on approach described in text.

[91] 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.

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.
- Other uncertainties include any methane emissions from abandoned coal mines in Washington and potential emission reduction improvements to processing, transportation, and pipeline technologies.

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

Appendix F. Agriculture

Overview

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

There are two livestock sources of 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.

Emissions and Reference Case Projections

Methane and Nitrous Oxide

GHG emissions for 1990 through 2005 were estimated using SGIT and the methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for the sector.[92] 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.[93]

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.[94] 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

[92] 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.

[93] 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/).

[94] 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 *U.S. Inventory of Greenhouse Gas Emissions and Sinks*[95] and the *U.S. Agriculture and Forestry Greenhouse Gas Inventory*. The estimates are based on the IPCC methodology for soil carbon adapted to conditions in the US. Preliminary state-level estimates of CO_2 fluxes from mineral soils and emissions from the cultivation of organic soils were reported in the *U.S. Agriculture and Forestry Greenhouse Gas Inventory*. Currently, these are the best available data at the state-level for this category. The inventory did not report state-level estimates of CO_2 emissions from limestone and dolomite applications; hence, this source is not included in this inventory at present.

[95] *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 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 summary of the latest estimates available from the USDA, which are for 1997.[96] 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.

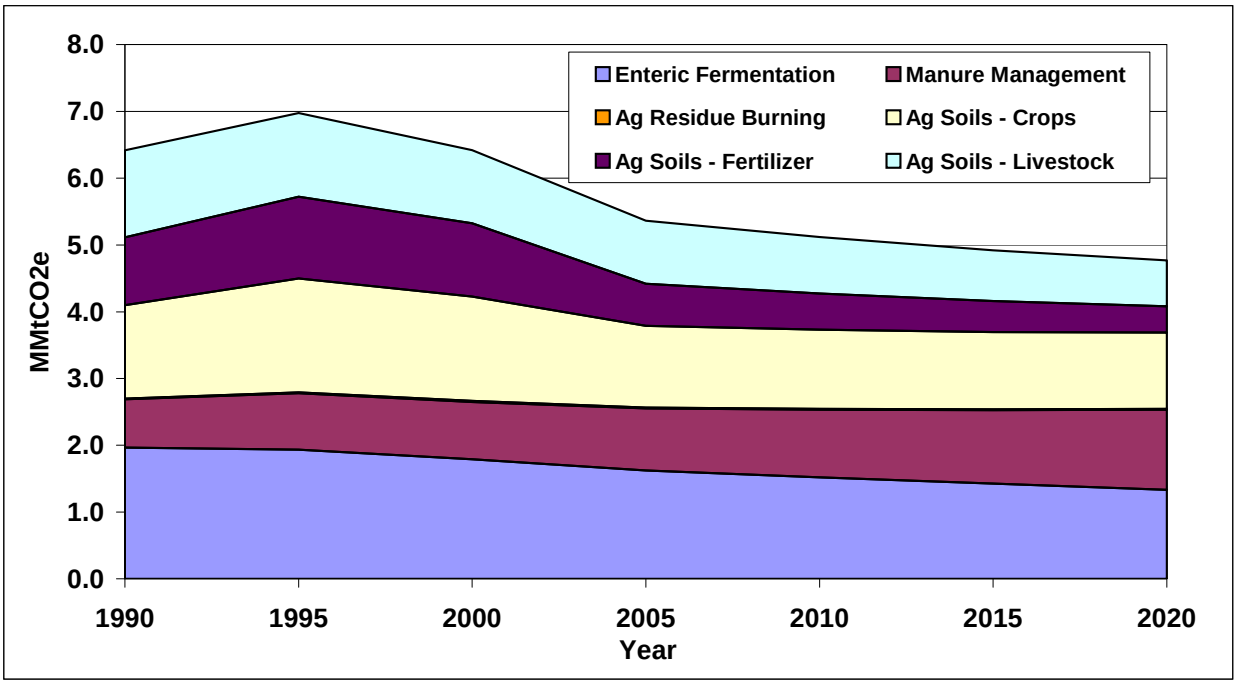
Results

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

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

$MMtCO_2e$/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).

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.[97]

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.

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.

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

Appendix G. Waste Management

Overview

GHG emissions from waste management include:

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

Inventory and Reference Case Projections

Solid Waste Management
For solid waste management, we used the US EPA SGIT and the US EPA Landfill Methane Outreach Program (LMOP) landfills database[98] as starting points to estimate emissions. The LMOP data serve as input data to estimate annual waste emplacement for each landfill needed by SGIT. SGIT then estimates CH_4 generation for each landfill site. Additional post-processing outside of SGIT to account for controls is then performed to estimate CH_4 emissions.

The LMOP database was shared with WA Ecology solid waste staff; however, these staff indicated that they did not have any information that could be used to fill data gaps (e.g. missing sites, missing waste emplacement data, information on controls). Therefore, the EPA LMOP data were used as received to estimate landfill emissions. There are a total of 52 sites in the LMOP database. Eight of these sites collect landfill gas for use in a landfill gas to energy (LFGTE) plant. Another three sites collect and flare landfill gas. These 11 sites are listed in the table below. The rest of the sites were assumed to be uncontrolled.

Site Name	County	Control
Roosevelt Regional LF	Klickitat	LFGTE
Cedar Hills LF	King	LFGTE
Hidden Valley LF	Pierce	LFGTE
Olympic View LF	Kitsap	LFGTE
Northside LF	Spokane	LFGTE
Tacoma LF	Pierce	LFGTE
Cowlitz County LF	Cowlitz	LFGTE
Centralia LF	Lewis	LFGTE
Cathcart LF	Snohomish	Flare
Greater Wenatchee LF	Lewis	Flare
Thurston Co. Waste & Recovery Center	Thurston	Flare

[98] LMOP database is available at: http://www.epa.gov/lmop/proj/index.htm. Updated version of the database provided by Rachel Goldstein, Program Manager, EPA Landfill Methane Outreach Program, October 2006.

To obtain the annual waste emplacement rate needed by SGIT for each landfill, the waste-in-place was divided by the number of years of operation. This average annual disposal rate for each landfill was assumed for all years that the landfill was operating. Data were available to calculate the average emplacement rate for each of the 11 controlled sites and 15 of the uncontrolled sites. For the other 26 uncontrolled sites, CCS developed an estimate for the average waste emplaced in closed sites and in open sites by using the available data on closed and open sites in the database. Of the 26 sites, 16 are closed and 10 are open. Hence, for closed sites the total annual waste emplacement was estimated by multiplying the average emplacement rate for closed sites with data by 16. A similar estimate was made for open sites by using the available data for open sites and multiplying the average by 10.

CCS performed three different runs of SGIT to estimate emissions from municipal solid waste (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%.[99] 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).

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 during the period from 1990 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: -2.1% for uncontrolled sites; 0.89% for flared sites; and 1.1% for LFGTE landfills. The negative growth in the first two categories is due to smaller rates of waste emplacement at these sites in the post-1995 period.

CCS used the SGIT default for industrial landfills. This default is based on national data indicating that industrial landfilled waste is emplaced at approximately 7% of the rate of MSW emplacement. We assumed that this additional industrial waste emplacement occurs beyond that already addressed in the emplacement rates for MSW sites. Due to a lack of data, no controls were assumed for industrial waste landfilling. For industrial landfills, the overall growth rate in MSW emissions from 1996 to 2005 (-0.36%/yr) was used to project emissions to 2010 and 2020 (based on the assumption that industrial waste landfilling will continue to grow at the same rate as MSW landfilling).

Solid Waste Combustion

WA 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

[99] As per EPA's AP-42 Section on Municipal Solid Waste Landfills: http://www.epa.gov/ttn/chief/ap42/ch02/final/c02s04.pdf.
[100] Sally Otterson, Ecology, personal communication with S. Roe, CCS, December 2006.

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
GHG emissions from municipal and industrial wastewater treatment were also estimated. For municipal wastewater treatment, emissions are calculated in EPA's SGIT based on state population, assumed biochemical oxygen demand (BOD) and protein consumption per capita, and emission factors for N_2O and CH_4. The key SGIT default values are shown in Table G1 below.

For industrial wastewater emissions, SGIT provides default assumptions and emission factors for three industrial sectors: Fruits & Vegetables, Red Meat & Poultry, and Pulp & Paper. WA 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 WA 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.

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

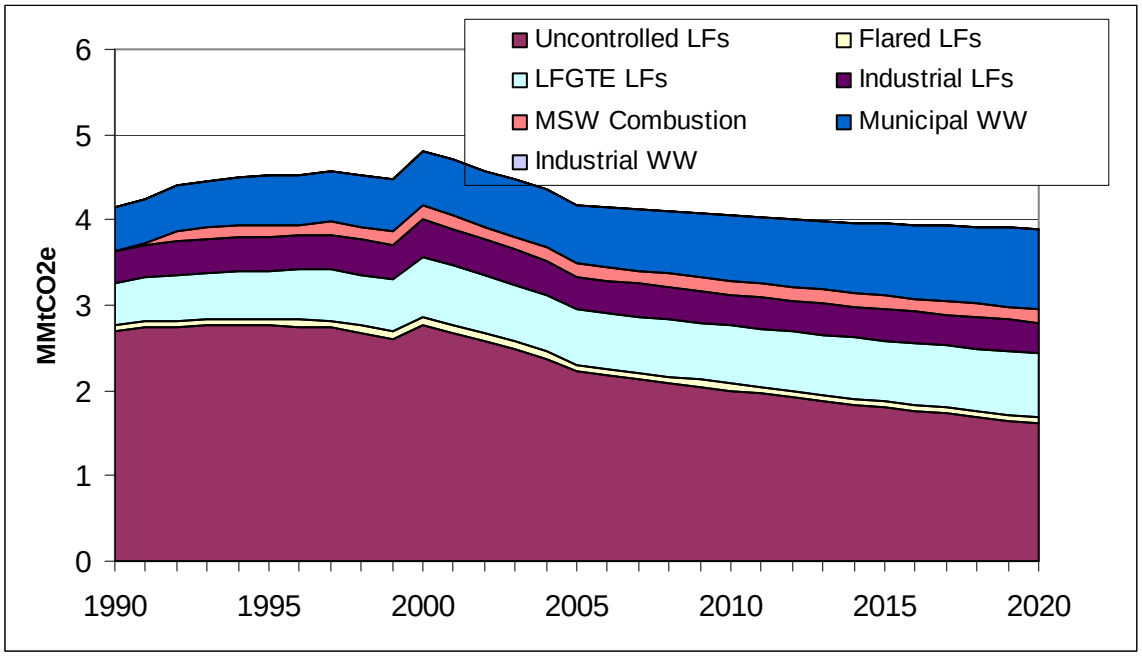
Figure G1 shows the emission estimates for the waste management sector. Overall, the sector accounts for 4.2 $MMtCO_2e$ in 2005. By 2020, emissions are expected to decline slightly to 3.9 $MMtCO_2e$/yr. For solid waste management sector, emissions are expected to decline overall due to less waste being emplaced in uncontrolled landfills and the declining rates of methane generation in existing uncontrolled landfills. In 1990, about two-thirds of the waste management

[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.

sector emissions were contributed by the uncontrolled landfills; however by 2020 the contribution from these sites is expected to decline to about 42%.

As mentioned above, due to data availability, CCS 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, 16% 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 24% of the waste management sector emissions.

Figure G1. Washington GHG Emissions from Waste Management



Source: CCS calculations based on approach described in text.
Notes: LF – landfill; WW – wastewater; LFGTE – landfill gas to energy.

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.

For industrial landfills, these were estimated using national defaults (7% of the rate of MSW emplacement). It could be that the available MSW emplacement data within the combined LMOP data used to model the MSW emissions already captures industrial LF emplacement. As with overall MSW landfill emissions, industrial landfill emissions are projected to decline between 2005 and 2020. 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 that are not already represented in the LMOP database should be determined.

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

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

CO_2 flux is estimated as the change in carbon mass for each carbon pool over a specified time frame. Forest volume data from at least two points in time are required. The change in carbon stocks between time intervals is estimated at the plot level for specific carbon pools (Live Tree, Standing Dead Wood, Under-story, Down & Dead Wood, Forest Floor, and Soil Organic Carbon) and divided by the number of years between inventory samples. Annual increases in carbon density reflect carbon sequestration in a specific pool; decreases in carbon density reveal CO_2 emissions or carbon transfers out of that pool (e.g., death of a standing tree transfers carbon

[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.

from the live tree to standing dead wood pool). The amount of carbon in each pool is also influenced by changes in forest area (e.g. an increase in area could lead to an increase in the associated forest carbon pools and the estimated flux). The sum of carbon stock changes for all forest carbon pools yields a total net CO_2 flux for forest ecosystems.

In preparing these estimates, USFS estimates the amount of forest carbon in different forest types as well as different carbon pools. The different forests include those in the national forest (NF) system and those that are not federally-owned (private and other public forests). USFS also provides information on forests categorized as being either woodlands (forests with low productivity) and non-woodlands (e.g. timberlands or productive forest systems). In WA, there is very little of the woodlands forest type (e.g. pinyon-juniper forests).

Carbon pool data for two periods are used to estimate CO_2 flux for each pool. The data shown in Table H1 are based on the most recent estimates from the USFS and are included in the upcoming 2005 estimates in EPA's national GHG inventory. CCS provided totals with and without the soil carbon pool. Discussions with USFS have indicated that the soil carbon pool estimates carry a high level of uncertainty.[105]

Table H1. Forest Carbon Flux Estimates for Washington

Forest Pool	Carbon Flux (MMtC)	Carbon Flux ($MMtCO_2$)
Live Tree (above ground)	-2.8	-10.3
Live Tree (below ground)	-0.6	-2.2
Standing Dead & Down Dead	-0.5	-1.8
Forest Floor	-0.7	-2.6
Soil Carbon	-2.1	-7.7
Harvested Wood Products	-3.2	-11.8
Totals	**-9.9**	**-36.3**
Totals (excluding soil carbon)	**-7.8**	**-28.6**

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

In addition to the forest carbon pools, additional carbon stored as biomass is removed from the forest for the production of durable wood products. Carbon remains stored in the products pool or is transferred to landfills where much of the carbon remains stored over a long period of time. As shown in the table above, nearly 12 $MMtCO_2$/yr is estimated to be sequestered annually in wood products.[106] Additional details on the forest carbon inventory methods can be found in Annex 3 to EPA's 2006 GHG inventory for the US.[107]

For the 1990 and 2000 historic emission estimates as well as the reference case projections, the forest area and carbon densities of forestlands were assumed to be at the same levels as those shown in the Table H1 above. Information is not currently available on the near term effects of

[105] Rich Birdsey, USFS, personal communication with CCS, May 2007.
[106] Jim Smith, USFS, personal communication with S. Roe, CCS, October 2006.
[107] Annex 3 to EPA's 2006 report, which contains estimates for calendar year 2004, can be downloaded at: http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR6MBLNQ/$File/06_annex_Chapter3.pdf.

climate change and their impacts on forest productivity. Hence, there is no change in the estimated future sinks for 2010 and 2020.

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 US driven by a longer fire season and higher temperatures.[108]

CCS used 2002 emissions data developed by the Western Regional Air Partnership (WRAP) to estimate CO_2e emissions for wildfires and prescribed burns.[109] The CO_2e from 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 carbon dioxide emissions from fires are captured within the carbon pool accounting methods described above). 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.[110] 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[111] 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 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

It is important to note that there were methodological differences in the two FIA cycles (used to calculate carbon pools and flux) that can produce different estimates of forested area and carbon density. For example, the FIA program modified the definition of forest cover for the woodlands

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

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.

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 the USFS. 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.

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

Appendix I. Inventory and Forecast for Black Carbon

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.[112] This appendix describes these data and methods for estimating mass emissions of BC and then transforming the mass emission estimates into CO_2 equivalents (CO_2e) in order to present the emissions within a GHG context.

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

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

Development of BC and OM Mass Emission Estimates

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

After estimating both BC and OM emissions for each source category, we used the BC estimate as described below to estimate the CO_2e emissions. Also, as described further below, the OM

[112] 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.
[113] 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.[114] These methods are based on the modeling of Jacobson (2002)[115] and his updates to this work (Jacobson, 2005a).[116] Jacobson (2005a) estimated a range of 90:1 to 190:1 for the climate response effects of BC+OM emissions as compared to CO_2 carbon emissions (depending on either a 30-year or 95-year atmospheric lifetime for CO_2). It is important to note that the BC+OM emissions used by Jacobson were based on a 2:1 ratio of OM:BC (his work in these papers focused on fossil fuel BC+OM; primarily diesel combustion, which has an OM:BC ratio of 2:1 or less).

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

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

BC mass = (10 short tons $PM_{2.5}$) x (0.613 ton EC/ton $PM_{2.5}$) = 6.13 short tons BC

Low estimate CO_2e = (6.13 tons BC) (330 tons CO_2e/ton BC+OM) (3 tons BC+OM/ton BC) (0.907 metric ton/ton) = 5,504 metric tons CO_2e

High estimate CO_2e = (6.13 tons BC) (697 tons CO_2e/ton BC+OM) (3 tons BC+OM/ton BC) (0.907 metric ton/ton) = 11,626 metric tons CO_2e

NOTE: The factor 3 tons BC+OM/ton BC comes directly from the global modeling inputs used by Jacobson (2002, 2005a; i.e., 2 tons of OM/ton of BC).

[114] ENE, 2004. Memorandum: "Diesel Black Carbon Calculations – Reductions and Baseline" from Michael Stoddard, Environment Northeast, prepared for the Connecticut Stakeholder Dialog, Transportation Work Group, October 23, 2003.
[115] Jacobson, 2002. Jacobson, M.Z., "Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming", *Journal of Geophysical Physical Research*, volume 107, No. D19, 4410, 2002.
[116] Jacobson, 2005a. Jacobson, M.Z., "Updates to 'Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming", *Journal of Geophysical Research Atmospheres*, February 15, 2005.

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.[117]

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.

[117] 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).[118] 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.

[118] 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		
Electricity 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[119] 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

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

"natural greenhouse effect." Without the natural heat-trapping properties of these atmospheric gases, the average surface temperature of the Earth would be about 33°C lower (IPCC 2001).

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

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

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

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

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

Greenhouse Gases

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

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

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part,

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

There are also several gases that, although they do not have a commonly agreed upon direct radiative forcing effect, do influence the global radiation budget. These tropospheric gases—referred to as ambient air pollutants—include carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and tropospheric (ground level) ozone (O_3). Tropospheric ozone is formed by two precursor pollutants, volatile organic compounds (VOCs) and nitrogen oxides (NO_x) in the presence of ultraviolet light (sunlight). Aerosols—extremely small particles or liquid droplets—often composed of sulfur compounds, carbonaceous combustion products, crustal materials and other human induced pollutants—can affect the absorptive characteristics of the atmosphere. However, the level of scientific understanding of aerosols is still very low (IPCC 2001).

Carbon dioxide, methane, and nitrous oxide are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities, however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes—except when directly or indirectly perturbed out of equilibrium by anthropogenic activities—generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 10.

Table 10. Global Atmospheric Concentration (ppm Unless Otherwise Specified), Rate of Concentration Change (ppb/year) and Atmospheric Lifetime (Years) of Selected Greenhouse Gases

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

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

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

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

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

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

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

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

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

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

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

and its subsequent amendments. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable.

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

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

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

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

(N_2O). Concentrations of NO_x are both relatively short-lived in the atmosphere and spatially variable.

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

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

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

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

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

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

Global Warming Potentials

Global Warming Potentials (GWPs) are intended as a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas. It is defined as the

cumulative radiative forcing—both direct and indirect effects—integrated over a period of time from the emission of a unit mass of gas relative to some reference gas (IPCC 1996). Carbon dioxide (CO_2) was chosen as this reference gas. Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The relationship between gigagrams (Gg) of a gas and Tg CO_2 Eq. can be expressed as follows:

$$\text{Tg } CO_2 \text{ Eq} = (\text{Gg of gas}) \times (\text{GWP}) \times \left(\frac{\text{Tg}}{1{,}000 \text{ Gg}} \right) \text{where,}$$

Tg CO_2 Eq. = Teragrams of Carbon Dioxide Equivalents
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.

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