



STATE OF WASHINGTON
DEPARTMENT OF COMMUNITY,
TRADE AND ECONOMIC DEVELOPMENT

Washington State

1990 Greenhouse Gas Emissions Inventory

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Acronyms and Key Terms

AEO – Annual Energy Outlook, EIA

Ag – Agriculture

BTU – British Thermal Unit

C – Carbon

CFCs – Chlorofluorocarbons

CH₄ – Methane

CO₂ – Carbon Dioxide

CO_{2e} – Carbon Dioxide Equivalent

EIA – U.S. DOE Energy Information Administration

EIIP – Emissions Inventory Improvement Project (US EPA)

GHG – Greenhouse Gases

GWP – Global Warming Potential

HFCs – Hydrofluorocarbons

IPCC – Intergovernmental Panel on Climate Change

LMOP – Landfill Methane Outreach Program

LNG – Liquefied Natural Gas

LPG – Liquefied Petroleum Gas

Mt – Metric Ton (equivalent to 1.102 short tons)

MMt – Million Metric Tons

MSW – Municipal Solid Waste

MW – Megawatt

N – Nitrogen

N₂O – Nitrous Oxide

NO₂ – Nitrogen Dioxide

NAICS – North American Industry Classification System

NASS – National Agricultural Statistics Service

NO_x – Nitrogen Oxides

ODS – Ozone-Depleting Substances

PFCs – Perfluorocarbons

RCI – Residential, Commercial, and Industrial

SAR – Second Assessment Report

SED – State Energy Data

SF₆ – 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

UNFCCC – United Nations Framework Convention on Climate Change

U.S. EPA – United States Environmental Protection Agency

U.S. DOE – United States Department of Energy

USDA – United States Department of Agriculture

USFS – United States Forest Service

USGS – United States Geological Survey

VMT – Vehicle-Miles Traveled

WMO – World Meteorological Organization

WSDOT – Washington State Department of Transportation

Executive Summary

In 2007, the Washington State Legislature directed the Departments of Ecology (Ecology) and Community, Trade, and Economic Development (CTED) to estimate the amount of greenhouse gas (GHG) emissions from Washington in 1990 and report the findings by December 31, 2007.¹

This report fulfills that request and describes the assumptions and methods used to calculate the estimate. The 1990 GHG emissions estimate includes total emissions for each of the seven major sectors that contribute to greenhouse gases in Washington:

- Electricity use and supply
- Residential, commercial and industrial fossil fuel combustion
- Transportation
- Industrial processes
- Fossil fuel industry (fugitive emissions)
- Waste management
- Agriculture

In 1990, Washington emitted about 88.4 million metric tons (MMt) of total carbon dioxide equivalent (CO₂e). This amount is the second highest in the western states, with California being the highest. Table 1 below shows the top three sources of Washington's GHG emissions and the percent each source contributed to the state's total emissions in 1990.

Table 1: GHG Emission Sources - 1990

GHG Emission Sources for 1990	Percentage of Contribution
Transportation	42.4%
Fossil fuel combustion in the residential, commercial, and industrial sectors.	21.0%
Electricity consumption for the sectors listed above.	19.1%

The report is divided into three major parts.

- Part 1: A summary of Washington State's 1990 Greenhouse Gas Emissions and the breakdown by the major seven sectors.
- Part 2: The general methodology for calculating GHG emissions and an illustration of the top down GHG emissions inventory approach.
- Part 3: A description of the GHG emissions for the individual major sectors, including calculations and an analysis of key uncertainties.

We have also included an extensive appendix that provides more in depth technical information.

¹ See RCW 80.80.020(2)(a)

The Center for Climate Strategies (CCS), Ecology, and CTED managed a larger study on Washington's GHG emissions, from 1990 through 2005 with projections to 2020.² Please refer to this study for further details about assumptions and methods used to calculate the 1990 GHG emissions.

Part 1: Summary of Washington State's 1990 Greenhouse Gas Emissions

CSS, Ecology and CTED developed Washington's 1990 greenhouse gas (GHG) emissions estimates using protocols consistent with the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance.³ This report covers the six types of gases included in the U.S. Greenhouse Gas Inventory:

1. Carbon dioxide (CO₂)
2. Methane (CH₄)
3. Nitrous oxide (N₂O)
4. Hydrofluorocarbons (HFCs)
5. Perfluorocarbons (PFCs)
6. Sulfur hexafluoride (SF₆)

A common metric called CO₂ equivalence is used to present the GHG emissions data in this report. This metric incorporates the Global Warming Potential (GWP) of each gas so that the impacts of emissions from different gases can be compared. See the appendix for more details about GHGs and GWPs.

1.1. Breakdown by sector

Our analysis showed that activities performed by the major seven sectors accounted for approximately 88.4 million metric tons (MMt) of Washington State's total carbon dioxide equivalent (CO₂e) emissions in 1990. It is important to note that for the Electricity Sector, we used a consumption-based or "load-based" approach to calculate emissions. This methodology determines GHG emissions from electricity delivered to Washington consumers, regardless of where those electrical generation facilities are located.

Table 2 provides a summary of the total emissions from each major sector that contributed to the 1990 GHG emissions for Washington State.

² Greenhouse Gas Inventory and Reference Case Projections, 1990 – 2020;
<http://www.ecy.wa.gov/climatechange/CATdocs/71907DraftWACATGHGReport.pdf>

³ Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, Intergovernmental Panel on Climate Change, May 2000

Table 2: Washington State 1990 GHG Emissions, by Sector ⁴

Million Metric Tons CO ₂ e	1990	Percent Total
Energy	73.0	82.6
Electricity, Net-Consumption-based	16.9	19.1
Coal ⁵	16.8	
Natural Gas ⁵	0.1	
Petroleum	0.0	
Residential / Commercial / Industrial (RCI)	18.6	21.0
Coal	0.6	
Natural Gas	8.6	
Petroleum	9.1	
Wood (CH ₄ and N ₂ O)	0.2	
Transportation	37.5	42.4
Onroad Gasoline	20.4	
Onroad Diesel	4.1	
Marine Vessels	2.6	
Jet Fuel and Aviation Gasoline	9.1	
Rail	0.8	
Natural Gas, LPG other	0.6	
Industrial Processes	7.0	7.9
Cement Manufacture (CO ₂)	0.2	
Aluminum Production (CO ₂ , PFC)	5.9	
Limestone and Dolomite Use (CO ₂)	0.0	
Soda Ash (CO ₂)	0.1	
ODS Substitutes (HFC, PFC and SF ₆)	0.0	
Semiconductor Mfg. (HFC, PFC and SF ₆)	0.0	
Electric Power Transmission/Distribution (SF ₆)	0.8	
Fossil Fuel Industry	0.5	0.5
Natural Gas Industry (CH ₄)	0.4	
Coal Mining (CH ₄)	0.0	
Petroleum Industry (CH ₄)	0.0	
Waste Management	1.5	1.7
Solid Waste Management	1.0	
Wastewater Management	0.5	
Agriculture	6.4	7.2
Enteric Fermentation	2.0	
Manure Management	0.7	
Agriculture Soils	3.7	
Total Gross Emissions	88.4	

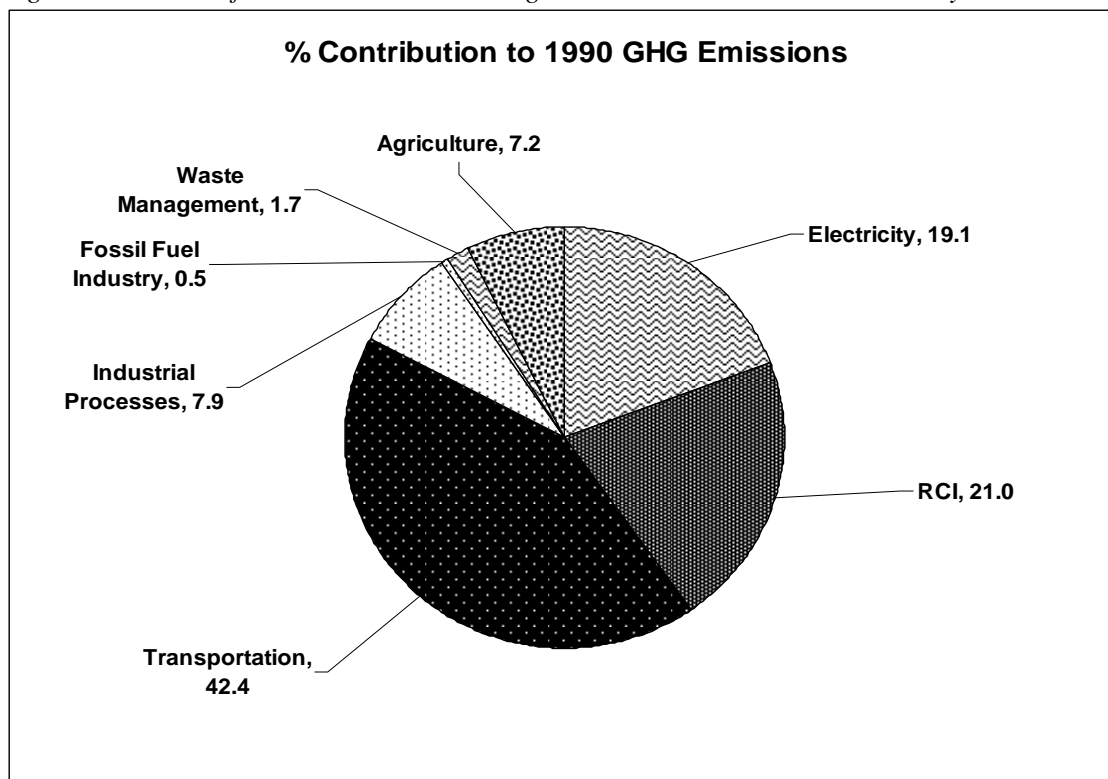
⁴Totals may not equal exact sum of subtotals shown in this table due to independent rounding.

⁵ Includes Market Purchases from Net System Mix (4.1 MMT CO₂e)

Figure 1 below shows how much each of the seven major sectors contributed to Washington's total 1990 GHG emissions. The top three contributors to Washington's GHG emissions are:

1. Transportation – accounting for 42.4% of the state's total GHG emissions
2. Fossil fuel combustion (residential, commercial, and industrial sectors) – 21.0%
3. Electricity consumption ((residential, commercial, and industrial sectors) – 19.1 %

Figure 1: Percent of Contribution to Washington State's 1990 GHG Emissions by Sector



Part 2: General Methodology

We used the IPCC Guidelines for National Greenhouse Gas Inventories to estimate Washington State's 1990 GHG emissions. The guidelines provide a standard method to calculate a "top down" inventory.⁶ While the IPCC developed these inventory methods for use at a national scale, they also provide flexibility for incorporating data, from other local sources, into the analysis.

Table 3 below shows the key sources for where we got our information and the data used to provide the estimates for this 1990 GHG emissions inventory.

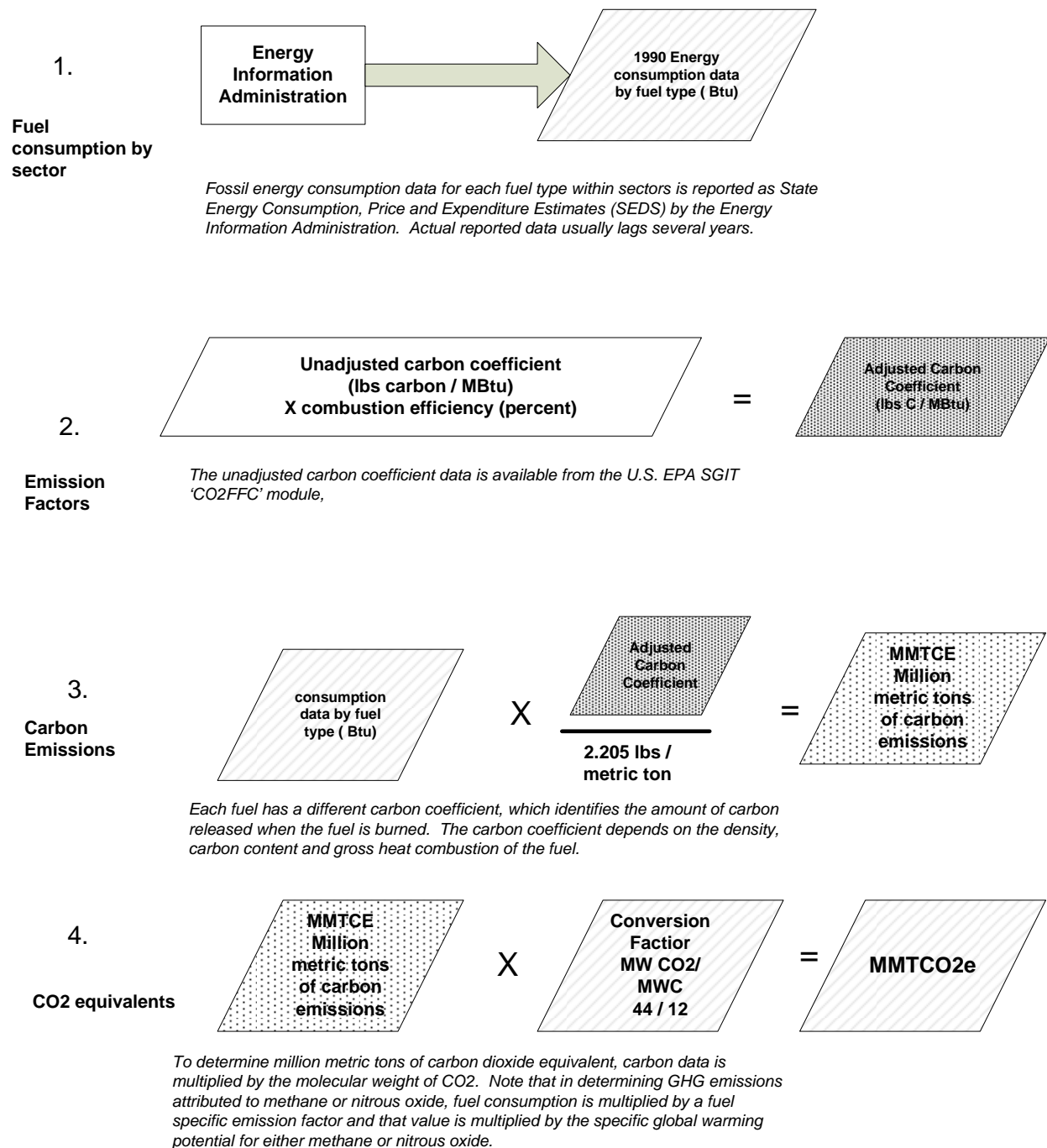
⁶ <http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm>

Table 3. Key Sources for Washington State Data and Inventory Methods

Source	Type of Information provided	How information was used in this analysis
Community Trade and Economic Development Report: Washington's Greenhouse Gas Emissions: Sources and Trends	Data on GHG emissions from energy consumption (including electric sector) and industrial processes.	GHG emissions from the Washington state inventory were used directly in this analysis
U.S. EPA State Greenhouse Gas Inventory Tool (SGIT)	US EPA SGIT is a collection of linked spreadsheets designed to help users develop State GHG inventories. US EPA SGIT contains default data for each State for most of the information required for an inventory. The SGIT methods are based on the methods provided in the Volume 8 document series published by the Emissions Inventory Improvement Program (http://www.epa.gov/ttn/chief/eiip/techreport/volume08/index.html)	Unless otherwise indicated, SGIT is used to calculate emissions.
U.S. Department of Energy - Energy Information Administration (EIA) State Energy Data (SED)	Energy use data for each State up to the year 2004.	Emission factors from US EPA SGIT are used to calculate energy-related emissions.
Office of Pipeline Security (OPS), Distribution and Transmission Annuals	Natural gas transmission and distribution pipeline mileage data.	Pipeline mileage from OPS used with SGIT to estimate natural gas transmission and distribution emissions.
U.S. EPA Landfill Methane Outreach Program (LMOP)	LMOP provided 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.
Department of Ecology Solid Waste in Washington State Annual Status Report	Provided information on status of landfills and types of waste disposed.	Used with SGIT to estimate emissions.
USDS National Agricultural Statistics Service (NASS)	USDA NASS provided 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.

Graph 1 below shows how the ‘top down’ methodology works which begins with the aggregation of fuel consumption data by activity.

Graph 1. TOP DOWN GHG EMISSIONS INVENTORY PROCESS



Part 3: Description of GHG Emissions by Sector

3.1 Electricity Use and Supply

Washington's electricity sector is dominated by hydro-electric generation which does not produce GHG emissions. However, the seasonal and annual variations in hydro availability results in the use of electricity generated by fossil fuels that produce GHG emissions.

To determine how much GHG emissions came from electric power generation, sold to Washington consumers, we performed a consumption -based analysis.⁷ To do this we collected generation and fuel use data for individual facilities within the Western Intertie.^{8,9} We then converted the data to CO₂ emissions by applying fuel specific emissions rates.

We assumed that utility companies used their resources (owned or contracted) to meet the needs of their own customer load first. To estimate this, we looked at utility ownership shares in the Pacific Northwest region.¹⁰ Ownership data for utilities outside the Pacific Northwest region could only be found for investor-owned utilities (IOU).

Table 3.1 below shows the electricity generation and emissions assigned to Washington customers, including an allocation from the Net System Mix which is defined as the fuel mix in the Northwest power pool.¹¹

Table 3.1 Estimated 1990 load-based fuel mix and CO₂ emissions

	MWh	Metric Tons CO₂
Biomass	170,734	-
Coal	11,754,471	12,763,017
Gas	20,006	14,964
Geothermal	11,778	-
Hydro	64,460,956	-
Nuclear	5,295,251	-
Oil	2,081	2,684
Net System Mix	9,330,873	4,128,412
Total	97,419,382	16,909,077

⁷ Methodology for Estimating 1990 Electricity Load-based Emissions for Washington State, S. Waterman-Hoey, CTED Energy Policy Division, 10/11/07

⁸ Data source: Energy Information Administration (EIA).

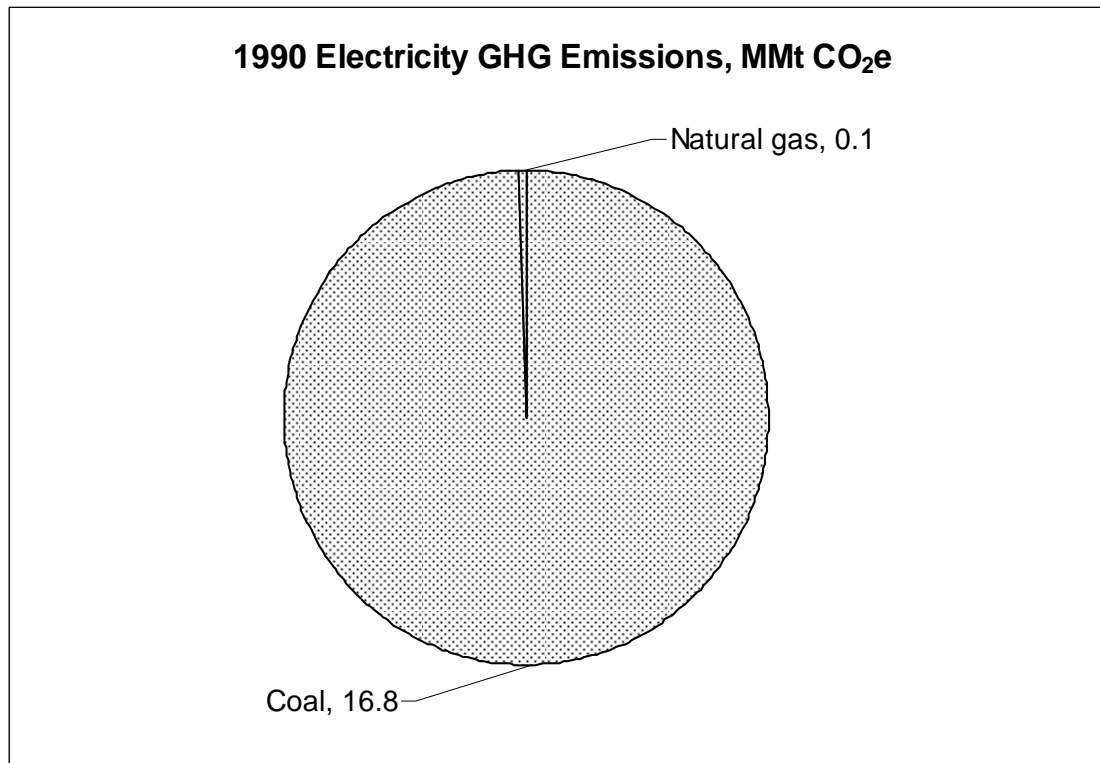
⁹ ,An interconnected grid system consisting of western states and two Canadian provinces.

¹⁰ Data source: Pacific Northwest Utility Conference Committee Northwest Regional Forecast of Power Loads and Resources, July 1990 – June 2010.

¹¹ RCW 19.29A.010(23)

Figure 3.1 below shows the distribution of GHG emissions sources for consumption based electricity.

Figure 3.1: Electricity Net-Consumption Base 1990 GHG emissions: Total 16.9 MMtCO₂e



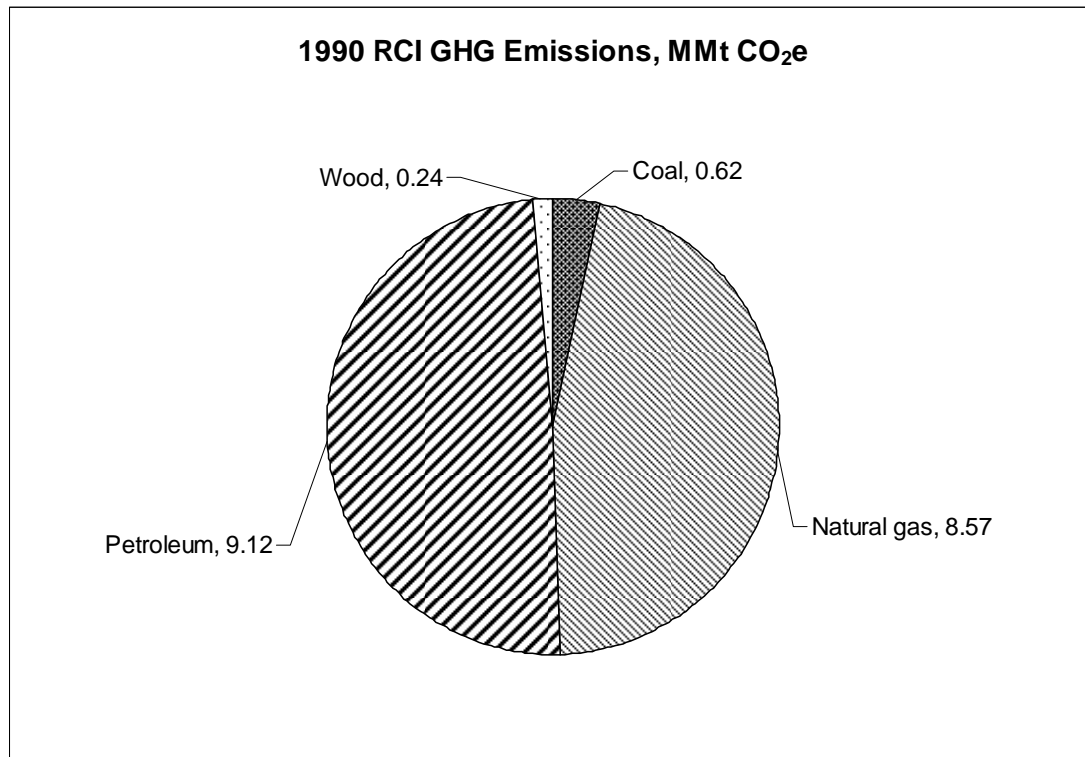
3.2 Residential, Commercial, and Industrial (RCI) Fossil Fuel Combustion

The RCI sectors are the second largest contributor to the total greenhouse gas (GHG) emissions in Washington. Activities in the RCI¹² sectors produce carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emissions when fuels are combusted to provide space heating, process heating i.e. heat necessary for the production process, or other applications.

Carbon dioxide accounts for over 98% of these emissions in Washington on a CO₂ equivalent (CO₂e) basis. Direct use of oil, natural gas, coal, and wood in the RCI sectors accounted for an estimated 18.6 MMt CO₂e (21.0%) of gross GHG emissions in 1990 (see Figure 3.2).

¹² The industrial sector includes emissions associated with agricultural energy use and fuel used by the fossil fuel production industry.

Figure 3.2: RCI 1990 GHG emissions– Total 18.6 MMt CO₂e



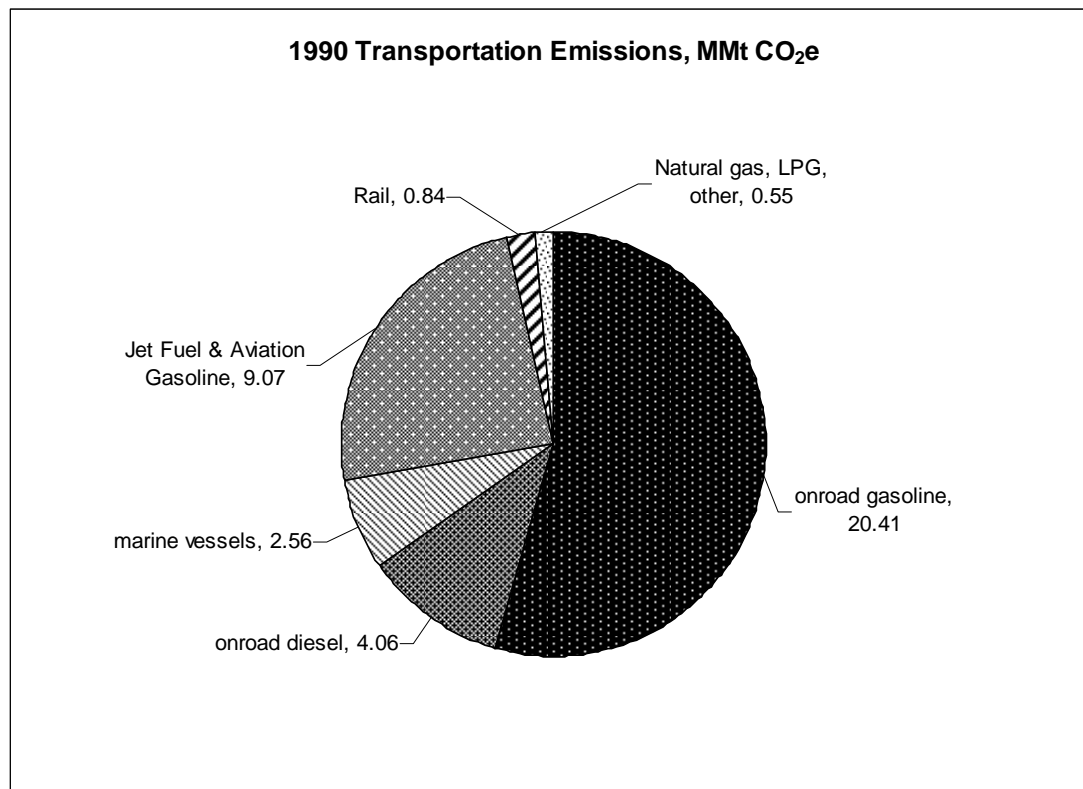
3.3 Transportation Energy

Transportation is the largest contributor to the total GHG emissions in Washington, with 37.5 MMtCO₂e in 1990 (see Figure 3.3). The transportation sector includes:

- Light and heavy-duty (on-road) vehicles
- Aircraft
- Rail engines
- 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 N₂O emissions from gasoline engines.

Figure 3.3 Transportation 1990 GHG Emissions – Total 37.5 MMt CO₂e



Key assumptions for determining GHG emissions from the transportation sector are outlined in Table 3.3.

Table 3.3. Key Assumptions and Methods for the Transportation Inventory

Vehicle Type and Pollutants	Methods
Onroad gasoline, diesel, natural gas, and LPG vehicles – CO ₂	EPA SGIT and fuel consumption from EIA SED and Washington Fuel Tax Receipts
Onroad gasoline and diesel vehicles – CH ₄ and N ₂ O	EPA SGIT, onroad vehicle CH ₄ and N ₂ O emission factors by vehicle type and technology type within SGIT were updated to the latest factors used in the U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003. State total VMT replaced with VMT provided by WSDOT, however, VMT is allocated to vehicle types using default data in SGIT.
Non-highway fuel consumption (jet aircraft, gasoline-fueled piston aircraft, boats, locomotives) – CO ₂ , CH ₄ and N ₂ O	EPA SGIT and fuel consumption from EIA SED, except for commercial marine, which was taken from Puget Sound Maritime Air Forum inventories and allocation of national fuel consumption data using port freight tonnage data.

3.4 Industrial Processes

The total amount of Washington GHG emissions from industrial processes were about 7.0 MMTCO₂e in 1990. Most of these GHG emissions were from the aluminum production industry, (see Figure 3.4).

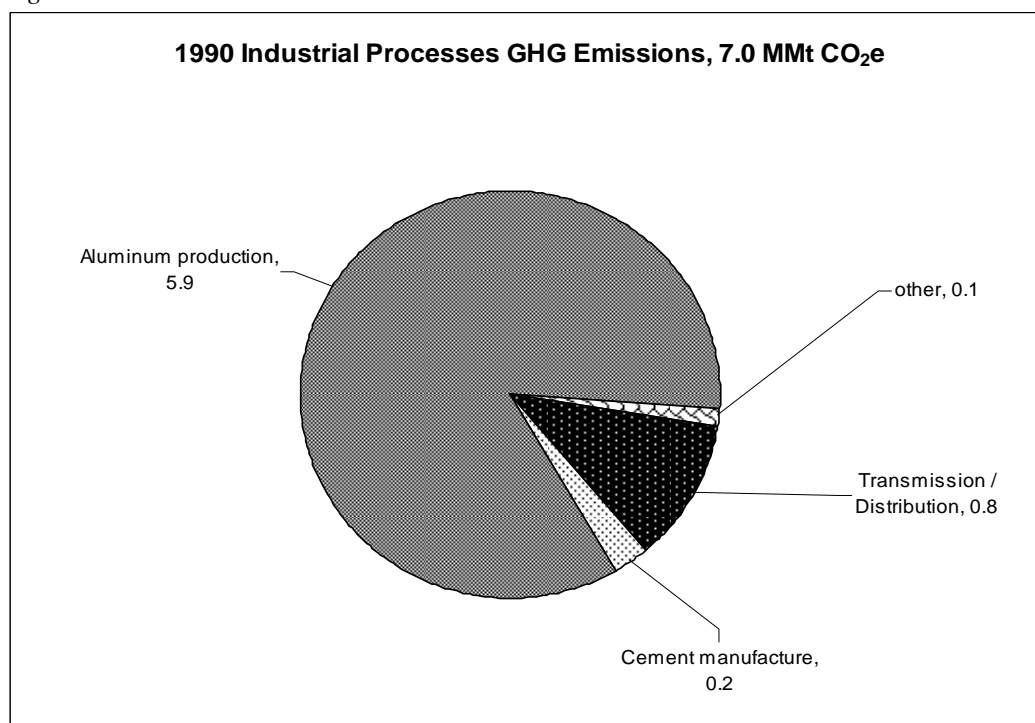
We used the State Greenhouse Gas Inventory Tool (SGIT) software and the methods provided in the Emission Inventory Improvement Program (EIIP) guidance document to estimate the industrial processes sectors contribution to Washington's GHG emissions for 1990.¹³ Table 3.4 below shows the data source and the required data entered into the SGIT software to calculate emissions for each source category.

Table 3.4: Approaches to Estimating Industrial Processes GHG Emissions

Source Category	Required Data for SGIT	Data Source
Aluminum Production	Mt of aluminum produced each year.	Washington Department of Ecology
Electric Power T&D Systems	Emissions based on the national emissions per kWh and state's electricity use provided in SGIT.	Washington Department of Ecology
Cement Manufacturing - Clinker Production	Metric tons (Mt) of clinker produced each year.	Washington Department of Ecology
Soda Ash Consumption	Mt of soda ash consumed.	USGS Minerals Yearbook, 2004: Volume I, Metals and Minerals, (http://minerals.usgs.gov/minerals/pubs/commodity/soda_ash/).
Limestone and Dolomite Consumption	Mt of limestone and dolomite consumed.	Default data for 1990 was not available in SGIT. For default data, the state's total limestone consumption (as reported by USGS ₂₀) is multiplied by the ratio of national limestone consumption for industrial uses to total national limestone consumption.
ODS Substitutes	Based on state's population and estimates of emissions per capita from the US EPA national GHG inventory.	Washington Department of Ecology
Semiconductor Manufacturing	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	Washington Department of Ecology

¹³ 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", United States Environmental Protection Agency's (US EPA), August 2004.

Figure 3.4: Industrial Processes 1990 GHG Emissions – Total 7.0 MMt CO₂e



3.5 Fugitive Emissions from Fossil Fuel Industries

During the production, processing, transmission, and distribution of fossil fuels, additional GHG emissions are released. These emissions are known as fugitive emissions. Examples include methane emissions released via leakage and venting at coal mines, oil and gas fields, processing facilities, and pipelines. Figure 3.5 displays the methane emissions from coal mining and natural gas and oil systems.

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

There is no active oil or gas production in Washington; a few exploratory wells are drilled each year or two but no commercial production is occurring. Thus, emissions of methane occur only from processing, transmission and distribution systems. In 1990, Washington had five oil refineries, one natural gas geologic storage reservoir, two LNG storage compressor stations and over 2,000 miles of gas pipelines.¹⁴ 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 CO₂ or methane emissions. Therefore, estimates based on actual emissions measurements in Washington are not possible at this time. Methane emission estimates are calculated by multiplying emissions-related activity levels (e.g. miles of pipeline, number of compressor stations) by the aggregate industry-average emission factors. Key data sources are listed in Table 3.5.

¹⁴ Data from EIA and Gas Facts.

Table 3.5: Approach to Estimating Historical Methane Emissions from Natural Gas and Oil Systems.

Activity	Required Data for SGIT	Data Source
Natural Gas Transmission	Miles of transmission pipeline.	Office of Pipeline Safety
	Number of gas transmission compressor stations.	EIIP ¹⁵
	Number of gas storage compressor stations.	EIIP ¹⁶
	Number of LNG storage compressor stations.	Federal Energy Regulatory Commission ¹⁷
Natural Gas Distribution	Miles of distribution pipeline.	Office of Pipeline Safety
	Total number of services.	
Oil Refining	Annual amount refined.	EIA ¹⁸
Oil Transport	Annual oil transported.	Unavailable, assumed oil refined = oil transported

GHG emissions can also occur from coal mines. 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. 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.¹⁹ Note that any methane emissions from abandoned coal mines are not included in this inventory, as the EPA's emission inventory for abandoned coal mines does not include surface mines and does not report any methane emissions from abandoned Washington coal mines.²⁰

¹⁵ Number of gas transmission compressor stations = miles of transmission pipeline x 0.006 EIIP. Volume VIII: Chapt. 5. March 2005.

¹⁶ Number of gas storage compressor stations = miles of transmission pipeline x 0.0015 EIIP. Volume VIII: Chapt. 5. March 2005.

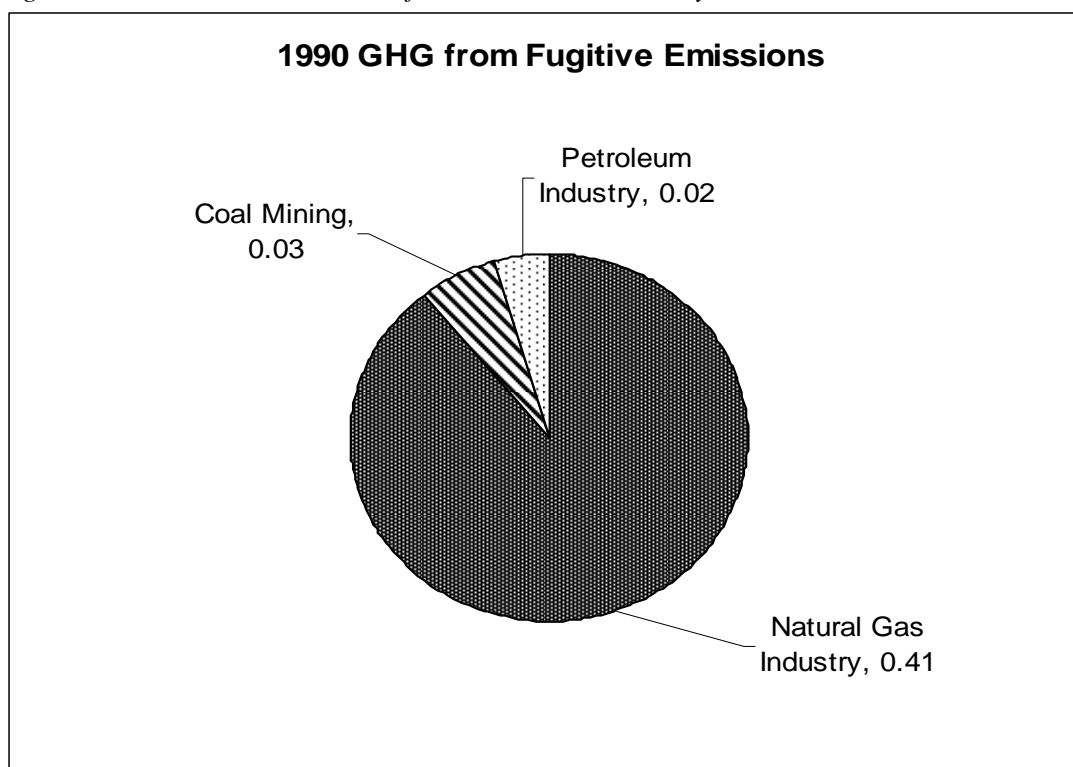
¹⁷ Northwest Pipeline Corporation Filing with Federal Energy Regulatory Committee Issued July 31, 2006 Accessed at <http://www.ferc.gov/eventcalendar/Files/20060731183500-RP06-416-000.pdf>

¹⁸ 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.

¹⁹ Emissions from EPA *Inventory of Greenhouse Gas Emissions and Sinks: 1990-2004* (April 2006) <http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2006.html>

²⁰ US EPA, "Methane Emissions from Abandoned Coal Mines in the United States: Emission inventory methodology and 1990-2002 emissions estimates", April 2004. Note that this inventory does not include emissions data for abandoned surface mines.

Figure 3.5: 1990 GHG Emissions from Fossil Fuel Industry – 0.5 MMt CO₂e



Key Uncertainties

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

- Current levels of fugitive emissions are based on industry-wide averages, and until estimates are available for local facilities, significant uncertainties remain.
- Other uncertainties include any methane emissions from abandoned coal mines in Washington and potential emission reduction improvements to processing, transportation, and pipeline technologies.

3.6 Waste Management

GHG emissions from the waste management sector include emissions from solid waste disposal and wastewater emissions that totaled 1.5 MMT in 1990 (see Figure 3.6). It is important to note this inventory only analyzes emissions for land filling activities that occur within Washington State it does not capture waste that is imported or exported.

GHG emissions from waste management come from a variety of sources:

- Municipal and industrial solid waste landfills emit CH₄ that is flared or captured for energy production (this includes both operating and closed landfills).
- Controlled burning of solid waste in incinerators and waste to energy plants and uncontrolled burning (e.g. in residential burn barrels) emit CH₄, CO₂, and N₂O.
- Municipal wastewater treatment facilities emit CH₄ and N₂O and industrial wastewater treatment facilities emit CH₄.

Municipal solid waste (MSW) is a category of solid waste generated by households and commercial businesses, consisting primarily of:

- Durable and non-durable goods
- Packaging
- Food waste
- Yard trimmings

The greenhouse gas impact of MSW depends on the:

- Composition and quantity of the waste generated.
- Strategy used to manage the waste such as burning, recycling or land filling.
- Characteristics of the landfill and the existence of methane flaring or energy conversion technology.²¹

We used a commonly-employed first order waste decomposition model and U.S. EPA's SGIT software to estimate how much CH₄ each landfill generated.²²

To estimate the emissions from municipal wastewater treatment facilities we used EPA's SGIT software and based our analysis on state population, assumed biochemical oxygen demand (BOD) and protein consumption per capita, and emission factors for N₂O and CH₄.

To estimate emissions from industrial wastewater treatment facilities we used EPA's SGIT software that provides default assumptions and emission factors for three industrial sectors:

- Fruits and Vegetables processing
- Red Meat and Poultry processing
- Pulp and Paper mills

Information was available on flows and chemical oxygen demand (COD) for Fruit and Vegetable processing, but only COD for the other two categories.²³ Therefore, we were only able to estimate emissions from the Fruit and Vegetable processing industry.

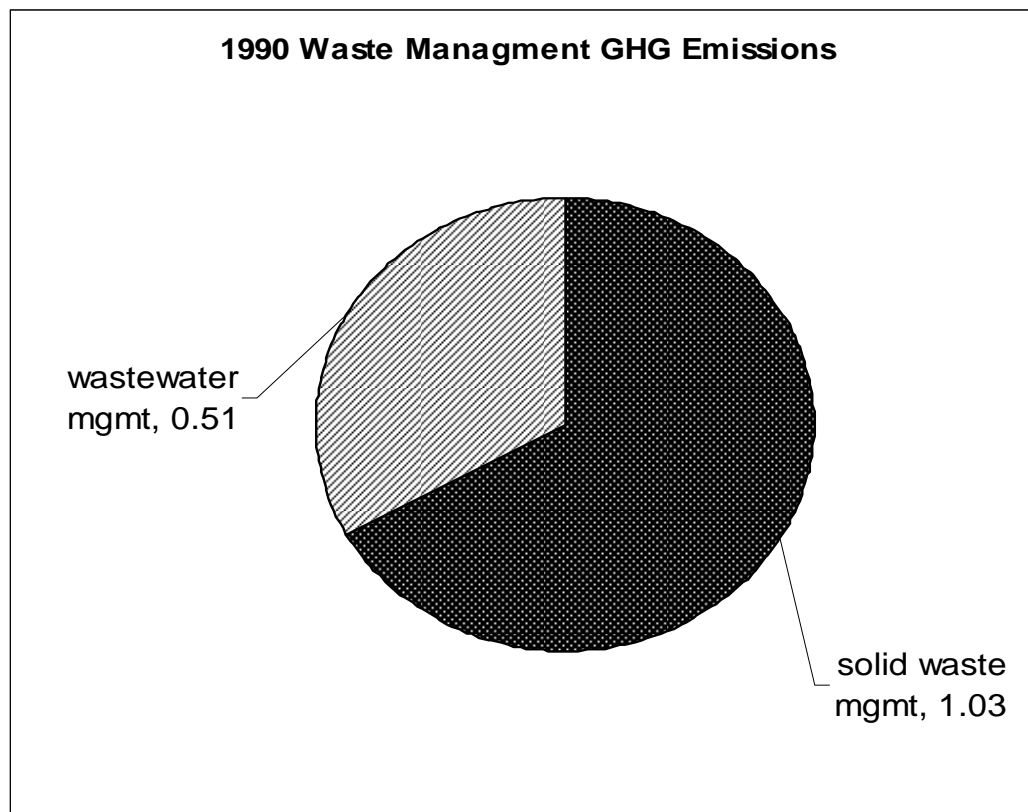
We used annual wastewater flow data to back-calculate an annual production value using SGIT data (3.8 cubic meters of wastewater for every ton processed).

²¹ *Solid Waste Management and Greenhouse Gases, A Life Cycle Assessment of Emissions and Sinks*, US EPA, pg ES-6; <http://www.epa.gov/climatechange/wycd/waste/SWMGHGreport.html>, September 2006.

²² EPA's AP-42 Section covering Municipal Solid Waste Landfills can be found at: <http://www.epa.gov/ttn/chief/ap42/ch02/final/c02s04.pdf>.

²³ 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. For seven fruit and vegetable processing facilities, an annual flow of 369 million gallons was estimated and used as input for all years.

Figure 3.6: 1990 GHG Emissions from Waste Management – 1.5 MMt CO₂e



Key Uncertainties

The methods we used to model landfill gas emissions does not adequately account for the points in time when controls were applied at individual sites. Therefore, the historical data we have for landfill emissions is less certain than current emissions data (since each site that currently has emission control devices was modeled as always having them). This results in a low result for historic emissions data .

As stated earlier, this inventory only analyzes emissions for land filling activities that occur within Washington State. It does not capture waste that is imported or exported. In addition, data was not available to estimate emissions from specific industry sectors such as the Meat & Poultry, Pulp & Paper industry and Fruit and Vegetables sector.

The industrial landfill inventory and forecast has a significant level of uncertainty because we had to use national default data from the SGIT software to estimate the emissions from this source.

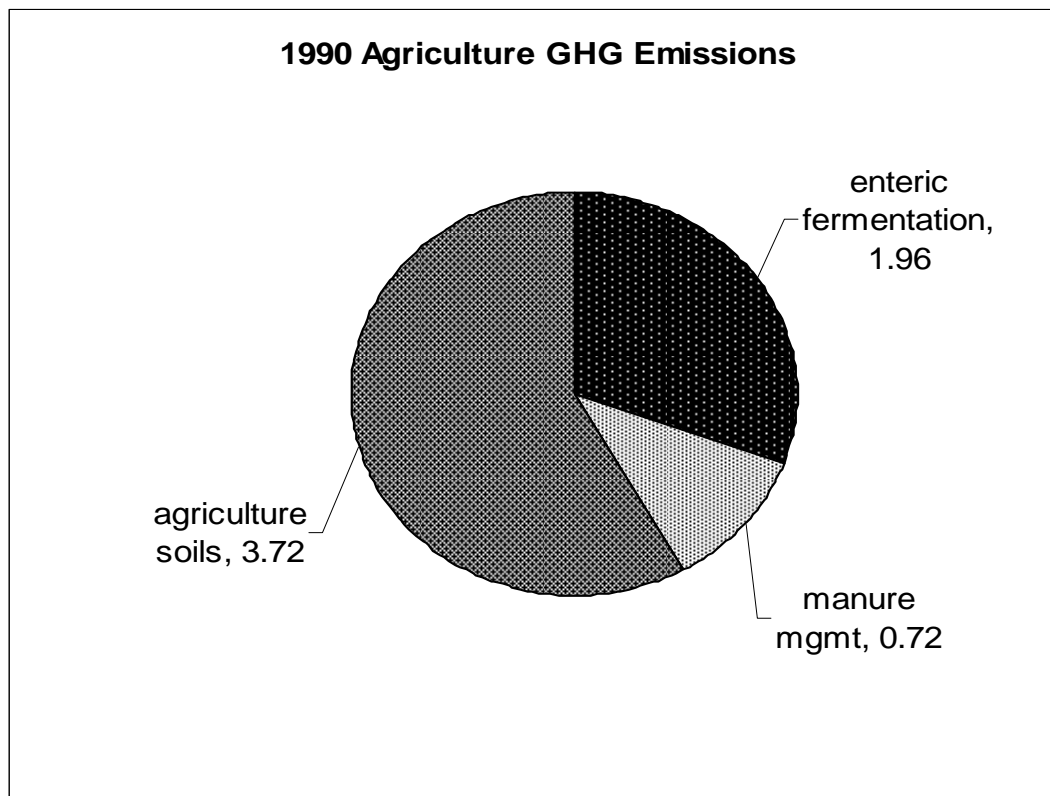
For the wastewater sector, the key uncertainties are also associated with using the SGIT software national default data.

3.7 Agriculture

The agriculture sector emits non-energy methane (CH₄) and nitrous oxide (N₂O) from enteric fermentation, manure management, and agricultural soils, totaling 6.4 MMtCO₂e in 1990. These emissions are detailed in Figure 3.7.

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.

Figure 3.7: 1990 GHG Emissions from the Agriculture Sector – 6.4 MMtCO₂e



There are two livestock sources of GHG emissions:

1. Enteric fermentation
2. Manure management

Enteric fermentation

Methane emissions from enteric fermentation come from the normal digestive processes in ruminant and non-ruminant livestock.²⁴ Microbes in the animal digestive system breakdown food and emit methane as a by-product. Ruminant livestock produce more methane because of the digestive activity in the large fore-stomach.

²⁴ Ruminant: Any cud-chewing hoofed mammal with an even number of toes and a stomach with multiple chambers, e.g. cattle, camels, and giraffes.

Manure management

The processes used to store and treat livestock manure (e.g., in compost piles or anaerobic treatment lagoons) also emit methane and nitrous oxide as a result of the manure decomposing. The amount of emissions that comes from the decomposing manure depends on the environmental conditions for where the manure is being composted. In general, the more anaerobic the conditions are, the more methane is produced because decomposition is aided by methane producing bacteria that thrive in oxygen-limited aerobic conditions. Under aerobic conditions, nitrous oxide emissions are dominant. To estimate the amount of emissions from manure management we based our analysis on manure that is stored and treated on livestock operations. We also included emissions from manure applied to agricultural soils as an amendment or deposited directly to pasture and grazing land in the agricultural soils emissions analysis below.

Agricultural soils

The management of agricultural soils can result in nitrous oxide emissions and net fluxes of carbon dioxide causing emissions or sinks. In general, soil amendments that add nitrogen to soils can also result in nitrous oxide emissions. The methods we used to estimate these emissions included nitrous oxide emissions from:

- Agricultural soils (including decomposition of crop residues).
- Synthetic and organic fertilizer application.
- Manure application.
- Sewage sludge.
- Nitrogen fixation.
- Histosols (high organic soils, such as wetlands or peatlands) cultivation.

Both direct and indirect emissions of nitrous oxide 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 nitrous oxide emissions also result when crop residues are burned.

The net flux of carbon dioxide 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 carbon dioxide into agricultural soils. However, 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 also results in carbon dioxide emissions.

We used the SGIT software and methods provided in the Emission Inventory Improvement Program (EIIP) guidance document to estimate the emissions for the agricultural sector.²⁵ The

²⁵ 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.

EIIP method is based on international guidelines developed by sector experts for preparing GHG emissions inventories.²⁶ In general, the SGIT methodology applies emission factors, developed for the US, to activity data for the agriculture sector. The activity data included:

- Livestock population statistics.
- Amounts of fertilizer applied to crops.
- Trends in manure management practices.

Data on crop production in Washington in 1990 and the number of animals in the state in 1990 were obtained from the United States Department of Agriculture (USDA), National Agriculture Statistical Service (NASS) and incorporated as defaults in SGIT.²⁷ 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.

Data on fertilizer usage came from Commercial Fertilizers, a report from the Fertilizer Institute. Data on crop production in Washington in 1990 from the USDA NASS were used to calculate N₂O emissions from crop residues and crops that use nitrogen (i.e., nitrogen fixation) and CH₄ emissions from agricultural residue burning. Emissions for the other agricultural crop production categories (i.e., synthetic and organic fertilizers) were also calculated.

Agricultural residue burning is conducted in Washington. The SGIT methodology calculates emissions from this activity by multiplying the amount (e.g., bushels or tons) of each crop produced by a series of factors to calculate the amount of crop residue produced and burned, the resultant dry matter, and the carbon/nitrogen content of the dry matter. For 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.

Soil Carbon

Soil carbon can also contribute to GHG emissions from the agriculture sector. Net carbon fluxes from agricultural soils have been estimated by researchers at the Natural Resources Ecology Laboratory at Colorado State University and are reported in the US Inventory of Greenhouse Gas Emissions and Sinks²⁸ and the US Agriculture and Forestry Greenhouse Gas Inventory. The estimates are based on the IPCC methodology for soil carbon adapted to conditions in the US. Preliminary state-level estimates of carbon dioxide fluxes from mineral soils and emissions from the cultivation of organic soils were reported in the US 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 carbon dioxide emissions from limestone and dolomite applications; therefore, this source is not included in this inventory.

In 1990, enteric fermentation accounted for about 31% (1.96 MMtCO₂e) of total agricultural emissions. The manure management category accounted for 11% (0.72 MMtCO₂e) of total

²⁶ Revised 1996 Intergovernmental 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/>).

²⁷ USDA, NASS (http://www.nass.usda.gov/Statistics_by_State/Washington/index.asp).

²⁸ US Inventory of Greenhouse Gas Emissions and Sinks: 1990-2004 (and earlier editions), US Environmental Protection Agency, Report # 430-R-06-002, April 2006. Available at: <http://www.epa.gov/climatechange/emissions/usinventoryreport.html>.

agricultural emissions in 1990. The agricultural soils category shows 1990 emissions accounting for 58% (3.72 MMtCO₂e) of total agricultural emissions. For Washington, agricultural burning 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 MMtCO₂e). 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.

Key Uncertainties

Emissions from enteric fermentation and manure management are dependent on the estimates of animal populations and the various factors used to estimate emissions for each animal type and manure management system (i.e., emission factors that are derived from several variables including manure production levels, volatile solids content, and CH₄ 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.

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.

Appendix

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.

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 (CO₂), methane (CH₄), nitrous oxide (N₂O), and ozone (O₃). 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 (SF₆)—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 (NO₂), sulfur dioxide (SO₂), and tropospheric (ground level) ozone (O₃). 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 4.1.

Table 4.1 Global Atmospheric Concentration (ppm Unless Otherwise Specified), Rate of Concentration Change (ppb/year) and Atmospheric Lifetime (Years) of Selected Greenhouse Gases

Atmospheric Variable	CO ₂	CH ₄	N ₂ O	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 CO₂ 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 CO₂ 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.

Water Vapor (H₂O)

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 emit ants, are similar to clouds in their radiative forcing effects (IPCC 1999).

Carbon Dioxide (CO₂)

In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO₂. 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 CO₂ increase is caused by anthropogenic emissions of CO₂” (IPCC 2001). Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of carbon dioxide.

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

Methane (CH₄)

Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH₄, 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 CH₄ 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 CO₂. Minor removal processes also include reaction with Cl in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of methane reduce the concentration of OH, a feedback which may increase methane’s atmospheric lifetime (IPCC 2001).

Nitrous Oxide (N₂O)

Anthropogenic sources of N₂O 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 (N₂O) 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 (O₃)

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 CO₂ and

CH₄. 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 (SO₂), nitrogen dioxide (NO₂) 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 (SF₆)

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 (SF₆) 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 SF₆ 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 SF₆ 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 CH₄ and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying CH₄ 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 CO₂. 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 NO₂) 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 (CO₂) 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 CO₂ 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 CO₂ 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 4.2).

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

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO₂, CH₄, N₂O, HFCs, PFCs, and SF₆) 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., SO₂ 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 4.2
Global Warming Potentials (GWP) and Atmospheric Lifetimes (Years) Used in the Inventory

Gas	Atmospheric Lifetime	100-year GWP ^a	20-year GWP	500-year GWP
Carbon dioxide (CO ₂)	50-200	1	1	1
Methane (CH ₄) ^b	12±3	21	56	6.5
Nitrous oxide (N ₂ O)	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 ₂ F ₆	10,000	9,200	6,200	14,000
C ₄ F ₁₀	2,600	7,000	4,800	10,100
C ₆ F 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 CO₂ is not included.

Table 4.3 presents direct and net (i.e., direct and indirect) GWPs for ozone-depleting substances (ODSs). Ozone-depleting substances directly absorb infrared radiation and contribute to positive radiative forcing; however, their effect as ozone-depleters also leads to a negative radiative forcing because ozone itself is a potent greenhouse gas. There is considerable uncertainty regarding this indirect effect; therefore, a range of net GWPs is provided for ozone depleting substances.

Table 4.3. Net 100-year Global Warming Potentials for Select Ozone Depleting Substances*

Gas	Direct	Net _{min}	Net _{max}
CFC-11	4,600	(600)	3,600
CFC-12	10,600	7,300	9,900
CFC-113	6,000	2,200	5,200
HCFC-22	1,700	1,400	1,700
HCFC-123	120	20	100
HCFC-124	620	480	590
HCFC-141b	700	(5)	570
HCFC-142b	2,400	1,900	2,300
CHCl ₃	140	(560)	0
CCl ₄	1,800	(3,900)	660
CH ₃ Br	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 CO₂ radiative forcing and an improved CO₂ 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 CO₂ is about 12 percent lower than that in the SAR, the GWPs of the other gases relative to CO₂ 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 CO₂ using an improved calculation of the CO₂ radiative forcing, the SAR response function for a CO₂ pulse, and new values for the radiative forcing and lifetimes for a number of halocarbons.

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