950445

LEGISLATIVE REFERENCE LIBRARY
TD885.5.G73 C4 1995
Ciborowski, Pet - Minnesota greenhouse gas inventory

3 0307 00062 8506

Minnesota Greenhouse Gas Inventory 1990



TD
885.5
.G73
C4
1995

Air Quality Division • March 1995

Minnesota Pollution Control Agency

MINNESOTA GREENHOUSE GAS INVENTORY: 1990

By Peter Ciborowski

March 30, 1995

Minnesota Pollution Control Agency Project Manager: Dr. Gregory C. Pratt

US Environmental Protection Agency Project Manager: Lee Ann Naue

Commissioned by the Minnesota Pollution Control Agency
under a grant from the US Environmental Protection Agency

RECEIVED
JUN 07 1995
LEGISLATIVE REFERENCE LIBRARY
STATE OFFICE BUILDING
ST. PAUL, MN 55155

EXECUTIVE SUMMARY

Anthropogenic emissions of infrared-active gases or their precursors result from a wide variety of human activities. Once emitted, these gases tend to accumulate in the atmosphere. In the atmosphere, they absorb a part of the heat that the earth emits to space and reflect a part of it back downward to the surface, effectively trapping it in the lower atmosphere and resulting in increased surface heating. These gases are known collectively as greenhouse gases and the larger phenomenon is known as the greenhouse effect.

As a result of industrial, transportation, and agricultural activities, it is thought likely that the mean global surface temperature of the earth will increase between 2 and 6 degrees Celsius in the next century, possibly resulting in large-scale climatic and environmental disruption.

The principal gases of concern include carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), the chlorofluorocarbons (CFCs), and tropospheric ozone (O_3). CO_2, N_2O, CH_4, and the CFCs are directly emitted to the atmosphere. Tropospheric ozone is produced *in situ* as a result of photochemical reactions involving nitrogen oxides (NO_x) and nonmethane hydrocarbons (NMVOCs). The principal source of CO_2 is fossil fuel combustion. The principal sources of CH_4 include livestock and manure production, rice cultivation, landfills, combustion and leakage from coal mines and natural gas production and transmission systems. The principal sources of N_2O are uncertain, but probably involve to some degree the use of commercial fertilizers. Carbon monoxide and NO_x result principally from combustion; NMVOCs are emitted during combustion and industrial processes, and from natural sources; and the CFCs are emitted as a result of industrial and domestic uses.

In the state of Minnesota, the principal sources of the emission of greenhouse gases or their precursors include fossil fuel combustion and transportation, landfills, the use of commercial fertilizers, animal husbandry and industrial and domestic processes.

In this inventory, emissions of greenhouse gases or their precursors from Minnesota are estimated for 1990 using methodologies drawn principally from the U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating greenhouse Gas Emissions* (1992). This study was funded by a

grant from the U.S. Environmental Protection Agency's Office of Policy, Planning and Evaluation, Climate Change Division.

Based on these methodologies, 89,070,822 to 89,163,827 tons of CO_2 are estimated to have been emitted to the atmosphere in 1990 from in-state activities involving fossil fuel uses or the uses of limestone. 524,020 to 558,341 tons of CH_4 are estimated to have been emitted from in-state activities, while total emissions of N_2O and CFCs (and other related ozone-depleting compounds) are estimated to have been 14,037 to 15,004 and 8,511 tons, respectively (see Table 1).

Table 1. Estimated 1990 In-State Emissions of Greenhouse Gases by Source and Gas [a]

	Emissions (in tons)			
	CO_2	CH_4	N_2O	ODCs
In-State Emissions				
Fossil Fuel Combustion	87,859,509	10,119 to 10,375	3,006	
Combustion CO Oxidation	910,847 to 962,541			
Natural Gas Leakage	1,129	37,293		
Refinery Leakage		124		
Pollution Control	3,744			
Nonfuel Fossil Fuel Uses	766			
Process Emissions	2,418			8,511
Landfill Leakage		222,237 to 253,367		
Incineration	266,140 to 307,451	264		
Manure Fertilizer Use			1,665	
Livestock		179,931		
Livestock Manure		72,595		
Wild Rice		1,457 to 4,392		
Liming of Fields	26,269			
Commercial Fertilizer Use			9,366 to 10,333	
Total In-State Emissions	**89,070,822 to 89,163,827**	**524,020 to 558,341**	**14,037 to 15,004**	**8,511**

(a) Rounded to the nearest ton.

It is possible to convert emissions of some nonCO_2 greenhouse gases to CO_2-equivalent emissions in a general way through the use of a weighting index known as the Global Warming Potential (GWP) index. Based on the GWP index developed by the Intergovernmental Panel on Climate Change (IPCC) and recommended by the U.S. Environmental Protection Agency, total long-term emissions of greenhouse gases from activities located in the state of Minnesota are estimated in 1990 to have been 98,990,846 to 126,333,216 CO_2-equivalent tons (see Table 2). These are dominated by fossil fuel combustion, processing and transportation, which account for between 71 and 91 percent of all weighted emissions.

Table 2. Estimated 1990 CO_2-Equivalent Emissions of Greenhouse Gases by Source and Gas[a]

Emissions Source	Emissions (in tons)
In-State	
Fossil Fuel Combustion and Fossil Fuel CO Oxidation	89,720,540
Other In-State Fossil Fuel Use, Transmissions & Processing	417,226
Landfill Leakage	2,615,822
Other Waste Disposal	289,700
Commercial Fertilizer Use	2,659,365
Livestock and Manure	3,227,336
Other Agriculture	58,439
Ozone Depleting Compounds	0 to 27,342,370
Other Process Emissions	2,418
Subtotal	**98,990,846 to 126,333,216**
Out-of-State	
Fossil Fuels Production	8,170,994
Process Emissions	935,582
Subtotal	**9,106,576**
Forest Carbon Storage	**(-)9,647,161**

(a) Mean value of the ranges calculated for each emissions source.
(b) Emissions occurring out-of-state by associated with in-state activities.

Emissions from agricultural sources are estimated to have accounted for another 5 to 6 percent, emissions from waste disposal activities another 2 to 3 percent, and industrial and domestic process emissions 0 to 22 percent of all weighted emissions.

In the short-term, Minnesota's forests can sequester substantial amounts of carbon through natural processes of regrowth. At present, roughly 2.6 million tons of carbon are annually sequestered in Minnesota's forests, in the short-term offsetting 9.6 million tons of CO_2 emissions from fossil fuel combustion.

Large out-of-state emissions are associated with in-state activities in Minnesota. Substantial amounts of energy are required to produce and transport the finished fossil fuels consumed in Minnesota. This results in emissions of CO_2, as does the production of cement, of most lime, and of at least some of the electricity imported into Minnesota. Out-of-state emissions associated with the in-state consumption of these products are estimated in 1990 to have totaled 9,106,576 CO_2-equivalent tons.

Overall, whether the focus is on in-state emissions or in-state plus out-of-state emissions, long-term emissions or short-term emissions, emissions from fossil fuel use, processing and transportation constitute the dominant emissions source of greenhouse gases, comprising roughly 70 to 90 percent of all weighted emissions across all emissions treatments. Emissions of CO_2 from fossil fuel combustion increased about 11 percent in the 1980s.

The science underlying the methodologies used to assemble this inventory is still developing and is far from mature. As such, the estimates given in this inventory for greenhouse gas emissions from Minnesota are of a provisional character, and should be treated as a first attempt to estimate emissions based on many relatively uncertain methods and only approximately known parameters. The largest sources of uncertainty relate to the net radiative effects of the emissions of CFCs and to emissions sources of N_2O. Substantial uncertainty also attaches to estimates of CH_4 leakage from landfills, coal mines, oil production, and natural gas pipelines, CH_4 production from livestock manure and wild rice cultivation, nonCO_2 emissions from combustion, and CO_2 production associated with electricity imports. Emissions estimates for CO_2 from combustion are fairly certain. Future updates should be undertaken as better methods of estimation become available.

TABLE OF CONTENTS

Executive Summary i

List of Tables and Figures viii
Properties of Gases xi
Conversions Commonly Used in this Inventory xi

Part I. Introduction 1
Section I. Introduction 1

Part II. Emissions from In-State Fuels Uses 14
Section II. Carbon Dioxide from Fossil Fuel Consumption 15
Section III. Carbon Dioxide from Air Pollution Control at Power Plants 56
Section IV. NonCO_2 Greenhouse Gases from Fuel Use 57
Section V. Methane from Natural Gas Pipelines and Oil Refineries 70
Section VI. Carbon Dioxide from Nonfuel Uses of Fossil Fuels 74
Section VII. Emissions Summary 76

Part III. Emissions from Out-of-State Fossil Fuels Production, Processing and Transportation 79
Section VIII. Methane from Natural Gas Production, Processing and Transportation 80
Section IX. Methane from Coal Mining 82
Section X. Methane and Carbon Dioxide from Oil Production 84
Section XI. Carbon Dioxide from Finished Fuels Production, Processing and Transportation 89
Section XII. Carbon Dioxide from Net Electricity Imports 92
Section XIII. Emissions Summary 93

Part IV. Emissions from Industrial and Domestic Processes 96
Section XIV. Industrial Process Emissions 97
Section XV. Halogenated Compounds 102
Section XVI. Emissions Summary 107

Part V. Emissions from Landfill Leakage and Waste Incineration 109
Section XVII. Methane from Sanitary Landfill Leakage 111
Section XVIII. Greenhouse Gases from Incineration 122
Section XIX. Emissions Summary 127

Part VI. Emissions from Agricultural Practices 130
Section XX. Methane from Livestock 131
Section XXI. Methane from Livestock Manure 135
Section XXII. Methane from Wild Rice Cultivation 142
Section XXIII. Nitrous Oxide and Carbon Dioxide from Fertilizers and Agricultural Liming of Fields 144
Section XXIV. Emissions Summary 151

Part VII. Emissions from Land-Use Changes and Activities 154
Section XXV. Emissions from Land-Use Activities in Minnesota 154

Part VIII. Statewide Emissions Summary, Recommendations, and Conclusions 162
Section XXVI. Statewide Emissions Summary for All Emissions Sources 162
Section XXVII. Recommendations for Improving the Inventorying Process 175

Endnotes 181

Appendices

Appendix A. Energy Content of Fuels

Appendix B. Carbon Content of Solid Wastes

Appendix C. 1990 Minnesota Fossil Fuel Use (in MMBTU)

Appendix D. Sources of Fossil Fuels Use Data for Estimating CO_2 Emissions

Appendix E. Fossil Fuel Use in the Electrical Generation/Steam and Industrial Sectors

Table 1. Fossil Fuel Use in the Electrical Generation/Steam Sector
Table 2. Fossil Fuel Use in the Industrial Fossil Fuel Use Sector Reported in MPCA-EIS

Appendix F. Estimated Natural Gas Usage and CO_2 Emissions in the Commercial Energy Use Sector by SIC Code

Appendix G. Minnesota Highway Vehicle Fleet, Total Vehicle Miles Traveled, and Fuel Consumption

Table 1. Minnesota Passenger Car Fleet by Model Year and Vehicle Miles Traveled
Table 2. Minnesota Light-Duty Truck Fleet by Model Year and Vehicle Miles Traveled
Table 3. Minnesota Heavy-Duty Truck Fleet by Model Year and Vehicle Miles Traveled
Table 4. Gallons of Fuel Consumed by Gasoline-Powered Cars Calculated from Vehicle Miles Traveled
Table 5. Gallons of Fuel Consumed by Gasoline-Powered Light-Duty Trucks Calculated from Vehicle Miles Traveled
Table 6. Gallons of Fuel Consumed by Heavy-Duty Trucks Calculated from Vehicle Miles Traveled
Table 7. Gallons of Fuel Consumed by Diesel-Powered Light-Duty Vehicles Calculated from Vehicle Miles Traveled
Table 8. Gallons of Fuel Consumed by Buses and Motorcycles Calculated from Vehicle Miles Traveled
Table 9. Gallons of Fuel Consumed by Cars and Trucks by Model Year

Appendix H. Fuel Use and Carbon Dioxide Emissions for 1980, 1986, and 1988

Table 1. Statewide Fuel Use for 1980
Table 2. Estimated Statewide Carbon Dioxide Emissions for 1980 by Fuel and Source
Table 3. Statewide Fuel Use for 1986
Table 4. Estimated Statewide Carbon Dioxide Emissions for 1986 by Fuel and Source
Table 5. Statewide Fuel Use for 1988
Table 6. Estimated Statewide Carbon Dioxide Emissions for 1988 by Fuel and Source

Appendix I. CH_4 and N_2O Emissions from Stationary Sources: MPCA-EIS Component

Table 1. CH_4 Emissions from Stationary Sources in the Electrical Generation/Steam Sector: MPCA-EIS Component
Table 2. CH_4 Emissions from Stationary Sources in the Industrial Sector: MPCA-EIS Component
Table 3. CH_4 Emissions from Stationary Sources in the Commercial Sector: MPCA-EIS Component
Table 4. CH_4 Emissions from Stationary Sources in the Transportation Sector: MPCA-EIS Component
Table 5. N_2O Emissions from Combustion: MPCA-EIS Component

Appendix J. NO_X, CO, N_2O, and CH_4 Emissions from Fossil Fuel Use Not Accounted for by MPCA-EIS.

Table 1. Statewide NO_X Emissions from Fuel Use Not Accounted for by MPCA-EIS by Sector and Fuel
Table 2. Statewide CO Emissions from Fuel Use Not Accounted for by MPCA-EIS by Sector and Fuel
Table 3. Statewide N_2O Emissions from Fuel Use Not Accounted for by MPCA-EIS by Sector and Fuel
Table 4. Statewide CH_4 Emissions from Fuel Use Not Accounted for by MPCA-EIS by Sector and Fuel

Appendix K. 1990 Decay of CH_4 to CO_2 from Prior Year Landfill Emissions by Year of Emission

Table 1. Annual Methane Generation from the Increment of Waste Added Annually to Landfills
Table 2. 1990 Decay of CH_4 to CO_2 from Prior Year Landfill Emissions by Year of Emission

Appendix L. Fertilizer Consumption, Total Nitrogen in Consumed Fertilizer, and N_2O Emissions

Table 1. 1989 to 1991
Table 2. 1988 to 1990

Appendix M. Minnesota Production of Nitrogen through Animal Manure Production

Appendix N. CO_2-Equivalent Emissions by Emissions Case and Source for 1990

List of Tables

Table 1. Estimated 1990 In-State Emissions of Greenhouse Gases by Source and Gas
Table 2. Estimated 1990 CO_2-Equivalent Emissions of Greenhouse Gases by Source and Gas
Table 3. Global Warming Potential for the Principal Greenhouse Gases
Table 4. Estimated 1990 Greenhouse Gas Emissions from In-State Fossil Fuel Uses
Table 5. Estimated 1990 Minnesota Carbon Dioxide Emissions from Fossil Fuel Combustion
Table 6. Approximate Average Carbon Contents of Fossil Fuels and Wood
Table 7. Carbon Dioxide Emission Coefficients for Commercially-Used Fossil Fuels
Table 8. Assumed Efficiencies of Combustion
Table 9. Carbon Content of Wastes Burned to Produce Energy
Table 10. Carbon Dioxide Coefficients for Other Fuels Not Listed in Tables 7 through 9
Table 11. 1990 Minnesota Fossil Fuel Use (in physical units)
Table 12. Estimated 1990 Statewide Production of Carbon Dioxide from Fossil Fuel Combustion
Table 13. Estimated CO_2 Emissions from the Electrical Generation/Steam Sector by Utility
Table 14. Other Emissions Estimates for the Electric Utilities Sector
Table 15. Estimated CO_2 Emission Per Kilowatt Hour of Electrical Generation for Major Minnesota Electrical Utilities
Table 16. Estimated CO_2 Emissions from the Industrial Fuel Use Sector by Major Industrial Group
Table 17. CO_2 Emissions from In-State Petroleum Refining
Table 18. Fossil Fuel Use in the Commercial Sector by Major Industrial Group Reported in MPCA-EIS
Table 19. Estimated 1990 CO_2 Emissions from Fossil Fuel Combustion in the Commercial Fuel Use Sector
Table 20. Minnesota Transportation Fuel Use Apportioned to Vehicle and Transportation Type and Associated CO_2 Emissions
Table 21. Stationary Sources of CO_2 Emissions from the Transportation Sector
Table 22. CO_2 Emissions from Fossil Fuel Combustion for 1980, 1986, 1988, and 1990 by Fuel Use Sector
Table 23. CO_2 Emissions from Fossil Fuel Combustion for 1980, 1986, 1988, and 1990 by Major Fuel Type
Table 24. Electricity Consumption in Minnesota in 1990
Table 25. Inventory Estimates of Minnesota CO_2 Production from Fossil Fuel Combustion
Table 26. Biomass, Biogas, and Ethanol Fuel Use in Minnesota in 1990
Table 27. CO_2 Emissions from Wood-based Biomass Fuels
Table 28. 1990 NonCO_2 Emissions from Stationary Fuel Use Sources Given in MPCA-EIS
Table 29. Statewide 1990 Fuel Use Not Accounted for in MPCA-EIS for which Emissions Factors Exist for CO, CH_4, N_2O, and NO_x
Table 30. Emission Factors Assumed for the Non-MPCA-EIS Component of Fuel Use
Table 31. NonCO_2 Greenhouse Gas Emissions from Stationary Sources Not Accounted for in MPCA-EIS
Table 32. NonCO_2 Emissions from Highway Mobile Sources
Table 33. Fuel Use and Emission Factors for Mobile Transportation Sources by Pollution Control Technology
Table 34. Fuel Use and Emission Factors for Nonhighway Mobile Combustion Sources

Table 35. NonCO_2 Emissions from Nonhighway Mobile Sources
Table 36. NonCO_2 Greenhouse Gases from Combustion in 1990
Table 37. Emission Factors for Leakage from Natural Gas Pipelines and Estimated Emissions
Table 38. 1990 Emissions from Natural Gas Leakage by Gas
Table 39. Nonfuel Uses of Fossil Fuels In Minnesota
Table 40. Estimated 1990 Emissions from In-State Fuel Consumption, Processing, and Transportation
Table 41. Estimated 1990 Greenhouse Gas Emissions from Out-of-State Fossil Fuels Production
Table 42. CH_4 Leakage from the U.S. Natural Gas System by Component
Table 43. Receipts of Coal at Electric Power Plants in 1990 by State of Origin
Table 44. Methane Emissions from Out-of-State Mining of Coal Used in Minnesota Electric Power Plants
Table 45. Estimated 1990 U.S. Emissions from Domestic Oil Production
Table 46. Estimated Emissions from Out-of-State Oil Production
Table 47. 1990 U.S. Oil Imports by Exporting Nation and Rates of Flaring/Venting by Exporter
Table 48. Primary Energy Inputs for the Production and Delivery of Fuels in the United States as a Percentage of the Energy Content of the Finished Fuels
Table 49. Primary Energy Inputs to Finished Fossil Fuels Assumed in this Study
Table 50. Out-of-State Energy Inputs to Finished Fuels for 1990 Fossil Fuel Use in Minnesota
Table 51. Estimated CO_2 Production from Energy Inputs to Finished Fuels Used in Minnesota
Table 52. Estimated Out-of-State Emissions Associated with In-State Fossil Fuel Usage
Table 53. Estimated 1990 CO_2-Equivalent Process Emissions from Minnesota
Table 54. Other Mining, Manufacturing and Processing Activities in Minnesota Resulting in the Direct Noncombustion Release of Greenhouse Gases or their Precursors
Table 55. Processes Resulting in the Noncombustion Release of NMVOCs in Minnesota
Table 56. Industrial Process CO_2 Emissions from Minnesota
Table 57. Estimated 1990 Minnesota Emissions from the Use of Infrared-Absorbing Halogenated Substances
Table 58. Global Warming Potentials (GWPs) of Short-term Chemical Substitutes for Hard CFCs Normalized to CFC-11
Table 59. Other Long-Term CFC Substitutes Under Consideration
Table 60. Summary of 1990 Process Emissions from Minnesota
Table 61. Disposition of Minnesota's Wastes, 1990
Table 62. Estimated 1990 Greenhouse Gas Emissions from Waste Disposal Activities
Table 63. Emission Factors for Landfill Leakage
Table 64. Reported and Calculated Amounts of Landfilled Wastes in Minnesota, 1960-1990
Table 65. 1990 Generation of Methane from Minnesota Sanitary Landfills
Table 66. 1990 CO_2 from CH_4 Decay from Prior Years' Emissions
Table 67. 1990 Waste Incineration in Minnesota by Waste Type
Table 68. Carbon Content of Incineration Wastes
Table 69. 1990 Carbon Emissions from Incineration
Table 70. Emission Factors and 1990 Emissions from Incineration for Methane, Carbon Monoxide, and Nitrogen Oxides
Table 71. Petrochemical/Fossil Component of Estimated 1990 CO Emissions: Incineration
Table 72. Summary of Emissions from Landfill Leakage and Incineration
Table 73. Estimated 1990 Greenhouse Gas Emissions from Agricultural Activities
Table 74. Emissions from Ruminant and Nonruminant Livestock
Table 75. Ruminant and Nonruminant Livestock and Emissions from Minnesota, 1990
Table 76. Emission Factors and 1990 Methane Emission from Minnesota Cattle: Alternative Calculation
Table 77. Maximum Methane Producing Capacity of U.S. Livestock Manure
Table 78. 1990 Livestock and Generation of Volatile Solids in Manure
Table 79. Maximum Potential CH_4 Emissions from Livestock Manure
Table 80. Manure Management Systems in Use in Minnesota
Table 81. Estimated 1990 Minnesota Methane Emissions from Livestock Manure
Table 82. Emission Factors for Commercial Nitrogen Fertilizers
Table 83. Minnesota Commercial Fertilizer Use

Table 84. Estimated 1990 Minnesota Nitrous Oxide Emission from Commercial Fertilizer Usage
Table 85. Minnesota Production of Nitrogen through Animal Manure
Table 86. Summary of Emissions from Agriculture
Table 87. Estimated 1990 Carbon Storage in Minnesota Forests
Table 88. Carbon Removed from Minnesota Forests in 1990 Through Fuel Use and Forest Products Uses
Table 89. Acres of Prescribed Burning in Minnesota: 1990
Table 90. Organic Carbon Pools in Minnesota
Table 91. Total Estimated Statewide Emissions by Greenhouse Gas or Precursor Gas and Source
Table 92. Statewide CO_2-Equivalent Emissions by Emissions Source and Case: Emissions with Long-Term Effects
Table 93. Statewide CO_2-Equivalent Emissions by Emissions Source and Case: Emissions with Long-Term and Short-Term Effects
Table 94. CO_2-Equivalent Emissions Cases
Table 95. Emission Sources Not Treated in this Inventory

List of Figures

Figure 1. Energy Use In Minnesota by Energy Source, 1990
Figure 2. 1990 Minnesota Fossil Fuel Use by Sector
Figure 3. Estimated CO_2 Production from Fossil Fuel Combustion by Fuel Type
Figure 4. Estimated CO_2 Production from Fossil Fuel Combustion by Major Fuel Type
Figure 5. Estimated 1990 CO_2 Emissions from Fossil Fuel Combustion by Fuel Use Sector
Figure 6. Estimated CO_2 Emissions from Mobil Sources in the Transportation Sector
Figure 7. Carbon Dioxide Emissions from Secondary Energy Use by Sector
Figure 8. CO_2 Emissions from Wood-Based Biomass Fuels by Fuel Use Sector
Figure 9. CO_2-Equivalent Emissions from In-State Fuel Consumption, Processing and Transportation
Figure 10. Out-of-State CO_2-Equivalent Emissions Associated with In-State Fossil Fuel Usage
Figure 11. CO_2-Equivalent Emissions of Greenhouse Gases from Landfilling and Incineration
Figure 12. Estimated 1990 Emissions from Livestock Manure
Figure 13. CO_2-Equivalent Emissions from Agriculture
Figure 14. Long-Term In-State CO_2-Equivalent Emissions by Emissions Source: Case A, Zero CFC Effect
Figure 15. Long-Term In-State CO_2-Equivalent Emissions by Emissions Source: Case B
Figure 16. Long-Term In-State CO_2-Equivalent Emissions by Emissions Source: Case A.
Figure 17. In-State CO_2-Equivalent Emissions by Emissions Source: Case E
Figure 18. Long-Term In-State CO_2-Equivalent Emissions from Minnesota: High CFC Case

Properties of Gases

Natural Gas	
Energy Content (US average)	1,030 BTU/cf
Density	0.0419 lb/cf
% Carbon by weight	70.6
Methane (CH_4)	
Energy Content	1,012 BTU/cf
Density	0.04235 lb/cf
% Carbon by weight	74.87
Ethane (C_2H_6)	
Energy Content	1,784 BTU/cf
Density	0.0799 lb/cf
% Carbon by weight	79.88
Propane (C_3H_8)	
Energy Content	2,518 BTU/cf
Density	0.1183 lb/cf
% Carbon by weight	81.71
Carbon Dioxide (CO_2)	
Density	0.1154 lb/cf
% Carbon by weight	27.29
Nitrous Oxide (N_2O)	
Density	0.1172 lb/cf
% Carbon by weight	63.65

Conversions Commonly Used in this Inventory

To convert from tons or lbs. of:	Multiply by:
Nitrogen to Nitrous oxide	1.57111
Carbon to Carbon dioxide	3.66428
Carbon to Carbon monoxide	2.33214
Carbon to Methane	1.33569

PART I. INTRODUCTION

Anthropogenic or manmade emissions of various industrially produced gases are thought likely to substantially alter global climate and the global environment over the next one-hundred years. These gases, known as greenhouse gases, are infrared-absorbing gases that act to increase the opacity of the atmosphere to escaping long-wave radiation and to increase mean planetary surface temperature.[1]

These gases absorb in the infrared wavelengths. Once present in the atmosphere, they absorb a part of the heat that the earth radiates to space, and reflect it back down to the surface of the planet, thus effectively trapping it in the lower levels of the atmosphere.

Many of these gases occur naturally in the atmosphere. Their presence contributes to what is known as the background or natural greenhouse effect. The gases principally contributing to this background greenhouse effect include carbon dioxide (CO_2) and water vapor, and to a lesser extent, methane (CH_4), nitrous oxide (N_2O), ozone and other trace components. This background greenhouse effect is estimated to add roughly 35 degrees Celsius to average annual global surface temperature.[2]

The atmospheric accumulation of infrared-absorbing gases as a result of human activities results in an intensification of this background greenhouse effect, leading to increased surface heating and possibly to widespread and persistent environmental disruption. The principal infrared-active or greenhouse gases of concern in this regard are carbon dioxide, methane, nitrous oxide, the chlorofluorocarbons (CFCs) and their substitutes, and, possibly, tropospheric ozone.

Carbon dioxide results principally from the combustion of fossil fuels and other fossil fuel uses. It is directly emitted to the atmosphere upon combustion. It is also produced upon the oxidation of carbon monoxide (CO), methane, and nonmethane volatile organic compounds (NMVOCs). Its presence in the atmosphere at higher than background levels is largely a consequence of the large-scale reliance of society on fossil fuel combustion as its principal energy source.

Emissions of methane derive from a wide variety of sources, including rice cultivation, animal husbandry, sanitary landfill leakage, leakage from coal mines and natural gas systems, and from combustion. In the industrialized world, emissions tend to originate principally in landfill leakage and from energy production and consumption activities, whereas in the industrializing world, emissions are more agricultural in nature.[2]

In general, trends in methane emissions and in atmospheric concentrations have tended to closely mimic trends in global population.

The sources of nitrous oxide are poorly understood.[2] However, it is likely that a majority of anthropogenic emissions derive from the application of chemical fertilizers to agricultural fields. Emissions of chlorofluorocarbons and their substitutes result from a variety industrial processes, as well as from refrigeration and cooling activities.

In contrast to carbon dioxide and the other greenhouse gases, tropospheric ozone is not emitted directly to the atmosphere but is produced in the lower levels of the atmosphere as a result of the emission of NMVOCs, which in the presence of nitrogen oxides (NO_X) and sunlight lead to the *in situ* formation of ozone.[3]

The precursors of tropospheric ozone, nonmethane hydrocarbons and nitrogen oxides, result from combustion activities.[4-6] Nitrogen oxides are formed during high temperature combustion, particularly of coal.

One of the central characteristics of the greenhouse gases is their relatively long atmospheric lifetimes or residence times. Long atmospheric lifetimes allow these gases to accumulate in the atmosphere in significant concentrations. The long-term persistence of these gases in the atmosphere in significant concentrations is one measure of their climatic importance. Of the principal greenhouse gases, methane has a relatively short atmospheric lifetime, about ten to fifteen years, while carbon dioxide, nitrous oxide, and the 'hard' CFCs, which include CFC-11, CFC-12, CFC-113, CFC-114, and CFC-115, typically persist in the atmosphere for on the order of fifty to two-hundred years, depending on the particular compound in question.

Carbon dioxide is a case in point. Once emitted, carbon dioxide is only slowly removed from the atmosphere. The deep oceans probably constitute the main final repository of carbon dioxide that is emitted to the atmosphere and then removed through natural processes. At present rates of emission of carbon dioxide, the time-scales for the decay of a concentration of CO_2 are estimated to be about 120 years.[2] However, roughly 15 percent of an emission of CO_2 remains in the atmosphere for periods of several thousand to tens of thousands of years, after which it is removed through the dissolution of marine carbonate sediments and weathering of silicate rock. This means that, once emitted, a release of carbon dioxide can be expected to influence climate for periods well in excess of one-hundred years, and probably for centuries.[7-9]

Atmospheric levels of carbon dioxide were fairly stable until about 150 to 200 years ago and the beginnings of industrialization and the fossil fuel era. Atmospheric CO_2 levels are now roughly one-quarter to one-third higher than they were in the preindustrial era.[2] In the future, the rate at which in the future CO_2 will be removed from the atmosphere could be substantially more or substantially less than at present, depending on the scale of future emissions. In general, the greater and more intense the long-term emission of CO_2 to the atmosphere, the less will be the ability of the oceans to remove excess emissions, and the more rapid will be the rate of atmospheric accumulation of CO_2.[10,11]

The atmospheric chemistry and fate of nitrous oxide and the hard CFCs are different from that of carbon dioxide. Nitrous oxide and the CFCs are removed almost exclusively through photolysis high up in the atmosphere, and then only after very long atmospheric lifetimes of 50 to 150 years.

Most of the other greenhouse gases beside CO_2, N_2O and the hard CFCs are shorter- and intermediate-lived greenhouse gases or their precursors, gases like CH_4, or HCFC-22, HFC-134a, or HCFC-142b, which are substitutes for the hard CFCs. These compounds are chemically quite reactive. Once emitted to the atmosphere, these gases are removed from the atmosphere through photochemical reactions involving oxidants like the hydroxyl radical (OH).[12,13] Atmospheric lifetimes for the most radiatively important of these shorter-lived gases tend to be on the order of ten to twenty years, although all estimates of atmospheric lifetimes for highly reactive gases tend to be somewhat uncertain.[14-16]

It might be noted that the chemical and chemical-climate interactions of these gases are quite complex, especially for the shorter-lived greenhouse gases. The reactions leading to the oxidation of CH_4 or the HCFCs or HFCs depend critically on the water vapor content of the atmosphere and on the availability of OH.[17,18] As the climate warms, the amount of water vapor in the atmosphere will necessarily change, resulting in different amounts of OH available to oxidize these compounds and changing rates of atmospheric accumulation of these gases.[19]

Likewise, as some anthropogenic emissions increase, the capacity of the atmosphere to remove additional emissions of some of the shorter-lived and intermediate-lived greenhouse gases is reduced, with the result that these gases, once emitted, remain in the atmosphere longer and accumulate there more rapidly.[20-24] Carbon monoxide (CO) is important in this regard. CO competes with methane, as well as various CFC substitutes like HCFC-22, HFC-134a, and HCFC-142b, for OH. Increasing emissions of CO act to reduce the oxidizing capacity of the atmosphere and to accelerate the atmospheric accumulation of CH_4 and the HCFCs and HFCs.

By contrast, emissions of NO_x tend to increase the atmospheric reservoir of OH, leading to reduced atmospheric lifetimes of CH_4 and related species. Thus predicting future atmospheric lifetimes and rates of atmospheric accumulation of these gases depends critically on a proper understanding of very complex atmospheric chemistry.

In general, emissions of CO, CH_4, NMVOCs and the hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) substitutes for the hard CFCs tend to result in a reduced long-term oxidizing capacity of the atmosphere and more rapid accumulation of these gases.[17,25] If sufficient NO_x is available, they also result in elevated ozone levels in the troposphere.[26] High levels of emission of NO_x lead to the production of ozone in the troposphere, but tend to increase the rate at which CH_4 is removed from the atmosphere. The oxidation of CO leads to the production of long-lived CO_2, and the oxidation of CH_4 leads to the production of CO_2 and water vapor, which in the stratosphere is a very powerful infrared-absorber.[24]

Some greenhouse gases are more powerful infrared-absorbers than others. The principal greenhouse gas, carbon dioxide, absorbs in some of the same infrared bands as water vapor. As a result, on a per molecule basis, it is a rather weak infrared-absorber. However, particularly large anthropogenic emissions, measured in many billions of tons, render CO_2 the principal greenhouse gas of concern as regards future climate change. If average global temperature rises, as virtually all of present scientific understanding suggests, it will do so principally as a result of emissions of carbon dioxide resulting from fossil fuel combustion.[2,27]

By contrast, man-made emissions of chlorofluorocarbons are much smaller. However, the infrared bands in which the chlorofluorocarbons and their substitutes like the HFCs and HCFCs absorb are largely unsaturated. As a result, on a per molecule basis these compounds are roughly 21,000 times more effective in absorbing infrared radiation than CO_2.[2]

The CFCs and most of their substitutes are, it might also be noted, ozone-depleting compounds. In addition to acting as infrared-absorbing gases, chlorofluorocarbons or CFCs act to catalytically destroy large amounts of ozone in the stratosphere. Ozone is itself an infrared-absorbing gas. Thus stratospheric ozone depletion could result in a cooling of the lower atmosphere, thereby partially or wholly offsetting the surface heating effects of emissions of CFCs.[2,23,28-30] The processes are complex and poorly understood at present.

Other greenhouse gases also play a role in influencing the intensity of the ozone-depleting effects of the CFCs. In elevated concentrations, CO_2 acts to cool the stratosphere, thus slowing the chemical reactions

leading to ozone depletion.[31] This tends to temper the offsetting cooling effect of ozone depletion. Water vapor introduced into the stratosphere through the oxidation of CH_4 tends to accelerate ozone depletion, whereas hydrogen chloride, also formed as a result of CH_4 oxidation, acts to interrupt the catalytic cycles leading to the destruction of ozone.[32] N_2O acts to accelerate ozone depletion through its role in the formation of polar stratospheric clouds and through gas phase chemistry. Again, the processes are very complex.

Ozone depletion can also influence the atmospheric accumulation of greenhouse gases or their precursors. As a result of stratospheric ozone depletion, increased amounts of ultraviolet radiation (UVB) are allowed to penetrate the troposphere, leading to increased production of ozone and OH in the troposphere. Increased abundances of OH act to shorten the atmospheric lifetimes of CH_4, CO, and the HCFCs and related chlorinated and fluorinated species.[33]

Of the other principal greenhouse gases, nitrous oxide and methane are infrared-absorbers of intermediate strength, somewhere between CO_2 and the CFCs in this regard. On a per molecule basis, CH_4, the more important of the two, is roughly twenty times more powerful an absorber of infrared radiation than is CO_2.[2]

Atmospheric concentrations of the principal greenhouse gases have been increasing, for CO_2 and N_2O, for about one-hundred and fifty years to two-hundred years, for CH_4 for about four hundred years, and for the chlorofluorocarbons, which are synthesized compounds unknown in nature, for between thirty and sixty years.[2]

The future consequences of emissions of greenhouse gases depend on trends in emissions and rates of atmospheric buildup of these gases, and these depend on relationships between human activities and emissions. Based on projections of trends in human activities, it is projected that if no substantial action is taken in the next few decades, average annual surface temperatures of earth will rise between 1.5 and 6 degrees Celsius over the next fifty to one-hundred years.[2,17,27,34-36] It is generally thought that this represents an environmental change substantially larger than any other experienced by society over periods as short as a century. Although the effects of this are somewhat uncertain, it is the general consensus that such global change is likely to involve widespread and persistent environmental disruption, the particulars of much of which it will not be possible to predict with certainty beforehand.[2,36-38]

It is on the basis of this reasoning that most industrialized countries, including the United States, in 1990 entered into the United Nations Framework Convention on Climate Change, in which they committed themselves to stabilizing emissions of greenhouse gases with the aim of returning to 1990 levels.

At present, the extra radiative forcing on climate that results from each year's emissions is estimated to be roughly 0.015 to 0.05 degrees Celsius.[2,17] In simplest terms, this is the degree of increase in future mean surface temperature to which present-day human activities annually commit the planet.

In addition, if the climate modeling is correct, releases of greenhouse gases to 1990 have effectively committed the planet to a rise in mean global temperature of roughly 0.5 to 3 degrees Celsius.[1,2,17] At present, there is no obvious way to reverse the effects of prior emissions, either by removing them from the atmosphere or by offsetting them by some other means. This as of yet unrealized warming from past emissions is essentially inevitable.

The implications of this are clear: even if emissions of greenhouse gases are stabilized at 1990 levels, a significant increase in mean global surface temperature is likely. Or stated another way, if the basic modeling calculations are correct, much more than stabilization of emissions probably will be needed to meet the challenge of global warming. It is generally thought that something more nearly like the stabilization of atmospheric levels of greenhouse gases will be necessary, and this would require, for instance in the case of CO_2, the most important greenhouse gas, emissions reductions of probably 70 percent or more.[2] To the degree that past atmospheric accumulations of long-lived gases cannot be reversed, and to the degree that atmospheric accumulations of CO_2 and nonCO_2 greenhouse gases will continue while society makes the transition to a new nonCO_2-emitting commercial energy system, mean global temperature will still rise -- probably 2 to 3 degrees Celsius.[2,39] The amount of additional surface warming beyond 2 to 3 degrees Celsius that is finally experienced will depend on actions taken or not taken to realize that transition. In general, since industrial society is nearly 90 percent dependent on fossil fuels for commercial energy, the trajectory of atmospheric CO_2 accumulation from fossil fuel use will be a difficult one to rapidly alter.

It might be noted that the basic calculation that underlies the prediction of future global warming is based on computer models of the climate. These models could be in error and significantly overstate or understate the climatic response by omitting important processes or by describing them incorrectly. However, while unlikely to be complete in the sense of having incorporated every physical process at work in the atmosphere, these models have been reviewed dozens of times in the last decade and no basis has been found to challenge the basic calculation leading to the prediction of future global warming.[2,36,40-44] In general, these models predict a 1.5 to 4.5 degree Celsius average global surface warming with each doubling of the atmospheric CO_2 level.

The response time of the atmosphere with regard to CO_2 in general is well understood, and it is glacial -- once an emission of CO_2 is effected and CO_2 accumulates in the atmosphere, it will take hundreds of years for that accumulation to decay to initial levels. Thus, whatever the effects of global warming, they will persist far into the future, far beyond the period of emission, and far beyond the life of contemporary society. They represent a truly long-term effect. Most modeling suggests that over a one-hundred year period, the excess CO_2 added to the atmosphere from 1800 A.D. to the present would decline only about 40 percent.[2]

In this inventory, anthropogenic emissions of greenhouse gases and their precursors are estimated for the state of Minnesota for the year 1990. Emissions are estimated for six principal activities: in-state fossil fuel consumption and fuels processing and transportation; out-of-state production of finished fossil fuels consumed in Minnesota; industrial and domestic processes that emit greenhouse gases directly to the atmosphere; agricultural practices; the landfilling and incineration of wastes; and land-use practices.

Three considerations underlie the approach taken in assembling this inventory. First, emissions of infrared-active gases to the atmosphere are important in relation both to the infrared absorption strengths of individual gases and to the atmospheric residence times of the gases. The principal concern of this inventory is with emissions that have environmental effects on time-scales of 100 years or so. We are concerned with the effects of present-day emissions very far out into the future, where the bulk of projected climatic changes are concentrated. For this reason, special attention is paid to the longer-lived compounds among the principal greenhouse gases, especially carbon dioxide and nitrous oxide, both of which have atmospheric residence times in excess of 100 years.

Second, despite this very long-term focus, emissions of shorter-lived infrared-absorbing gases are important. Emissions and trends in atmospheric accumulations of some shorter-lived gases like methane relate closely to larger patterns of social, demographic, and economic development that will only slowly be affected by decisions to limit emissions.[2] While the climatic effects of present-day emissions will not persist far into the future, any efforts to slow the rate of emissions of these gases will yield fruit only over long periods of time. For this reason, the climatic effects of present-day emissions particularly of methane are treated as if in fact they do persist far into the future. Given the long-term forces driving methane emissions, decisions taken in the present to continue emissions in fact probably represent a long-term commitment to global warming on time-scales of fifty to one-hundred years.

Third, while the principal concern of this inventory is with emissions whose effects are important on time-scales of 100 years or so, the climatic consequences of emissions more proximate in time also matter.

Even with intervention these are unlikely to be small. For this reason, again, emissions of shorter-lived compounds are not ignored in this inventory.

One additional consideration is important. Some greenhouse gas emissions are natural, the result of large natural fluxes, principally of carbon in different forms, between the biosphere and the atmosphere. Carbon is continually moving back and forth from decomposing plant organic matter to the atmosphere and back to the biosphere through photosynthetic activity. Human uses of the forests and forest products that are reasonably consistent with the scale of those fluxes, and thus, over long periods of time allow for forest regrowth, do not result in the transfer of large amounts of carbon from the biosphere to the atmosphere. As a result, at least over such long time periods, these uses do not result in net emissions of CO_2 to the atmosphere.

Over periods substantially shorter than 100 years, over which there is not sufficient time for forest regrowth or harvesting, human management of forests can result in short-term emissions of CO_2 or short-term sequestration of carbon in standing plant biomass.

By contrast, the net effect of fossil fuel combustion is to add large amounts of carbon to the linked atmosphere-biosphere system from buried fossil sources far in excess of the ability of the entire system to absorb it over nearly any time-scale of interest. The effect is more or less to permanently elevate atmospheric CO_2 levels.[2]

Below we treat CO_2 emissions from Minnesota from fossil fuel use and other uses of fossil carbon, the amount of carbon annually withdrawn from the atmosphere and incorporated for the short-term in Minnesota's forests through forest growth, and all emissions of CH_4, N_2O, NO_x and NMVOCs for which a methodology exists for estimating emissions. Emissions are given in both tons of the pollutant in question and in CO_2-equivalent tons of greenhouse gases.

CO_2-equivalent emissions are calculated using the U.S. Environmental Protection Agency's recommended Global Warming Potentials that were originally developed by the Intergovernmental Panel on Climate Change (1990).[2] Global Warming Potentials (GWPs) are in essence a weighting of the various greenhouse gases to account for their relative infrared-absorption capabilities and different atmospheric residence times. This index has been subject to substantial criticism ever since it was first proposed.[18,23,24,45-47] The essence of the problem is that the calculation of CO_2-equivalent emissions depends critically on parameters that for particularly long-lived gases change with time and cannot be adequately forecast.

In calculating the GWPs, the Intergovernmental Panel on Climate Change implicitly assumed that the radiative forcing from a unit emission of any one greenhouse gas would remain constant through time, as would the residence times of these gases. This was a poor assumption. In fact, for a gas like CO_2, radiative forcing and surface temperature tend to vary logarithmically with concentration, with the result that as overall atmospheric concentrations rise, the effect of each individual molecule of CO_2 on radiative forcing declines. The same is true of N_2O and CH_4, for which radiative forcing varies near-logarithmically with atmospheric concentration, but not the CFCs or their substitutes, for which surface temperature and radiative forcing vary linearly with concentration.[18] The effect of this is that to calculate GWPs for the greenhouse gases, one must first specify rates of future atmospheric accumulation of these gases against which to estimate the long-term relative radiative consequences of a present-day emission of any one gas.[23,45,47,48]

In addition, there is some overlap in the absorption bands among the different greenhouse gases. In order to correctly estimate the effect of this overlap in absorption bands with respect to the long-term effects of a present-day emission of any one greenhouse gas, one must first know what the long-term future accumulations will be of other infrared-absorbing gases with absorption bands that overlap those of the greenhouse gas in question. This means that one must not only correctly specify the future atmospheric concentrations of the gas in question, but also correctly specify those of all other infrared-absorbing gases with overlapping absorption bands.[23,48]

To further complicate the matter, the atmospheric residence times of the greenhouses gases also will not remain constant over time. CO_2 is a case in point, and a particularly important one, since all other Global Warming Potentials are normalized to the integrated radiative effect of CO_2 over periods of 20 to 500 years. The integrated radiative effect of CO_2 depends on its atmospheric residence time. Virtually all of the modeling of the oceanic response to emissions suggests that at high long-term rates of emission of CO_2, the ability of the oceans to remove excess CO_2 would decline fairly precipitously as the upper layer of the oceans becomes chemically saturated with dissolved CO_2, whereas at low long-term rates it might increase.[10,11] Similarly, there has been substantial question about the response of the oceanic sink for CO_2 to climate change itself. It has long been speculated that as the planet warms as a result of emissions, the large-scale circulation of the oceans will slow, retarding the rate at which excess CO_2 is withdrawn from the atmosphere to the deep oceanic layers, and thus increasing the atmospheric residence time.[49,50]

The point is, it is unlikely that the atmospheric residence time of CO_2 will remain constant through time. Thus virtually any estimation of GWPs will necessarily be dependent on forecasts and scenarios of future emissions and attendant climatic changes and their effects.[23,45,48]

This is nowhere more true than with regard to the GWPs of shorter-lived gases that depend on the atmospheric OH reservoir. The atmospheric residence times of these gases will almost certainly change, but in an generally uncertain fashion, given the complex interactions of atmospheric chemistry and climate on concentrations.

To predict the atmospheric residence times of any one of these, one needs to know what is happening across time to the atmospheric concentrations of all other compounds linked to this complex atmospheric chemistry. The long-term atmospheric residence time of methane will depend on the trajectory of future emissions of CO, NMVOCs and NO_X, as well as on the changing temperature of the troposphere itself.[18,47] The effects of NO_X and CO on tropospheric ozone will depend on what is happening in the troposphere with regard to CH_4 and temperature, and these effects are uncertain.[21,24,32] Moreover, given the short atmospheric lifetimes of CO, NO_X and NMVOCs, it is critically important where these compounds are emitted. These compounds will not have the same effect on radiative forcing in one location as in another -- there will not be a single GWP for these compounds, but multiple GWPs.[23]

The net radiative effects of a present-day emission of the hard CFCs will depend on the differential effects of CO_2, CH_4, and N_2O on rates of future ozone depletion.[31] As the rate of atmospheric accumulation of these gases changes with changing policies, these net radiative effects will necessarily change. In order to estimate the long-term radiative consequences of present-day emissions, all of these changes must be modeled.

Finally, the present-day net radiative effect of the emission of CFCs is quite uncertain, and is now probably beyond the ability of science to forecast.[51] Given the poor understanding of anthropogenic and natural sources of N_2O, the estimated atmospheric residence time of this compound is uncertain.[23,52] And, there is the generic problem that the radiative forcings associated with increased atmospheric levels of CO_2 and the nonCO_2 greenhouse gases are thought to produce different vertical distributions of temperature change in the atmosphere, and thus may not be properly additive or comparable at all.[53]

Thus the Global Warming Potentials recommended for use in inventorying state greenhouse gas emissions should be thought to provide only a gross representation of the differential effects of present day emissions of greenhouse gases. At best, these are incomplete. They are employed in this inventory in light of this understanding, and are shown in Table 3.

Finally, many of the emissions estimates given in this inventory are characterized by substantial amounts of uncertainty. This is endemic to the very exercise, in which many of the physical processes that are

Table 3. Global Warming Potential for the Principal Greenhouse Gases

Gas	Global Warming Potential[a]
CO_2	1
CH_4	11
N_2O	270
CFC-11	3,400
CFC-12	7,100
CFC-113	4,500
CFC-114	7,000
CFC-115	7,000
HCFC-22	1,600
CCl_4	1,300
CH_3CCl_3	100
CF_3Br	4,900
HFC-134a	1,200

Source: I. Isaksen, *et al.*, "Radiative Forcing of Climate" in Intergovernmental Panel on Climate Change, *Climate Change 1992: The Supplementary Report to the IPCC Assessment,* (Cambridge, UK: Cambridge University Press, 1992).

(a) Integrated over a 100-year time horizon.

involved are only imperfectly or approximately understood. Thus the estimates given in the following sections are presented in that light, **as a first attempt to estimate emissions that should be updated and revised as better estimates and procedures become available.**

The methodologies used to estimate emissions derive largely from U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-B-92-002 (1992).[54] In those cases where emission sources were not treated in the *State Workbook* or where the methodologies that were given were deemed to be inadequate, resort was made to other sources and calculative procedures. The preparation of this inventory was funded by a grant from the U.S. Environmental Protection Agency's Office of Policy, Planning and Evaluation, Climate Change Division.

Below we sequentially treat emissions from energy consumption, out-of-state fuels production, industrial processes, landfill leakage and incineration, and agricultural and land-use changes. To quickly summarize, in the state of Minnesota, the principal identified emissions sources for infrared-active gases or their precursors include the combustion, processing, and transportation of fossil fuels, sanitary landfills, the use of commercial fertilizers, animal husbandry, and ozone-depleting compounds (ODCs) used in domestic and industrial processes. Between 89,070,822 and 89,163,827 tons of CO_2 are estimated to have been emitted to the atmosphere in 1990 from in-state sources (see Part VIII, Section XXV below). Emissions of CH_4 from in-state sources are estimated to have totaled between 524,020 and 558,341 tons, while those of N_2O and ODCs are estimated in 1990 to have been 14,037 to 15,004 and 8,511 tons, respectively.

Estimated precursor emissions in 1990 include 138,728 tons of NMVOCs from in-state activities, 749,559 to 1,095,743 tons of CO, and 340,134 to 343,679 tons of NO_x.

In terms of CO_2-equivalent emissions, and again recognizing the problems associated with the GWP index used to calculate these, total long-term emissions from in-state activities are estimated in 1990 to have totaled 98,990,846 to 126,333,216 CO_2-equivalent tons (see Part VIII, Section XXVI, Table 91 through 94, below). These are dominated by emissions from in-state fossil fuel combustion, processing and transportation, which are estimated to have accounted for between 71 and 91 percent of estimated weighted emissions. Emissions from agricultural sources are estimated to have accounted for another 5 to 6 percent, emissions from waste disposal activities another 2 to 3 percent, and process emissions between 0 and 22 percent.

By gas, in-state emissions of CO_2 in 1990 are estimated to have accounted for between 71 and 90 percent of all 1990 weighted emissions, the CFCs and other ozone-depleting compounds, between 0 and 21.7 percent, N_2O between 3.1 and 3.9 percent, and CH_4 from 4.7 to 5.9 percent of all 1990 weighted emissions.

Out-of-state emissions of greenhouse gases associated with in-state activities are estimated in 1990 to have totaled 9,106,576 weighted tons. Most of this derived from fossil fuels consumed in the production of finished fuels later combusted in Minnesota or from electricity generated out-of-state but consumed in Minnesota.

Minnesota's forests are annually sequestering large amounts of carbon through forest regrowth. An estimated 2.6 million tons of carbon are now annually sequestered in the forests, offsetting in the short-term 9,647,161 tons of CO_2 emissions from fossil fuel use and production. However, this is only a short-

term palliative. At some point in the future, Minnesota forests will become net emitters of CO_2 to the atmosphere.

Total weighted or CO_2-equivalent emissions from Minnesota from both in-state and associated out-of-state activities are estimated in 1990 to have totaled between 108.1 and 135.4 million tons, excluding the short-term offsetting effects of carbon storage in Minnesota forests. This probably constitutes the best measure of emissions for the state.

PART II. GREENHOUSE GAS EMISSIONS FROM IN-STATE FUEL USES

Individuals and businesses in Minnesota annually consume some 1,301.5 trillion BTUs of energy. Fossil fuel use comprises about 84 percent of this. In Part II, we treat the emission of greenhouse gases from in-state fossil fuel combustion, processing and transportation. Carbon dioxide is emitted to the atmosphere as a result of the combustion of fossil fuels. It is also emitted in much smaller amounts from the leakage of natural gas from transmission pipelines and distribution mains and from air pollution control activities involving the removal of sulfur oxides from effluent streams.

Methane is emitted to the atmosphere as a result of natural gas leakage from transmission pipelines and distribution mains. A much smaller amount also derives from combustion and leakage from oil refineries. Nitrous oxide is produced during combustion, as are carbon monoxide and nitrogen oxides.

Table 4. Estimated 1990 Greenhouse Gas Emissions from In-State Fossil Fuel Uses

Source	Emission (in tons)		
	CO_2	CH_4	N_2O
Fossil Fuel Combustion	87,859,509	10,119 to 10,375	3,006
Fossil Fuel CO Oxidation	910,847 to 962,541	NA	NA
Natural Gas Leakage	1,129	37,293	NA
Refinery Leakage	NA[(a)]	124	NA
Pollution Control	3,744	NA	NA
Nonfuel Fossil Fuel Uses	766	NA	NA
TOTAL	**88,775,995 to 88,827,689**	**47,536 to 47,792**	**3,006**

Source: Table 40 below.
(a) Not applicable

All told, 88,775,995 to 88,827,689 tons of CO_2 are estimated to have been emitted to the atmosphere in 1990 from in-state fossil fuel-related activities, along with about 47,536 to 47,792 tons of CH_4 and 3,006 tons of N_2O (see Table 4). Emissions from fossil fuel combustion constitute 99.99 percent of all CO_2 emissions. Roughly three-quarters of CH_4 emissions are estimated to have resulted from natural gas pipeline leakage, and the rest to have resulted from combustion. All estimated N_2O emissions from in-state fossil fuel use activities are from combustion sources.

SECTION II. Carbon Dioxide from Fossil Fuel Combustion

Of all in-state fossil fuel use activities, fossil fuel combustion represents the single largest emission source of greenhouse gases. In 1990, 1099.1 trillion BTU of fossil fuels are estimated to have been combusted, leading to the direct emission to the atmosphere of 87,859,509.4 tons of carbon dioxide. Coal use and petroleum use accounted for about four-fifths of this (see Table 5). Uses in transportation and in electricity generation dominate fossil fuel use emissions of CO_2, in 1990 accounting for 69 percent of emissions. Overall, on a CO_2-equivalent basis, emissions of CO_2 from combustion in 1990 accounted for between 70 and 90 percent of all weighted greenhouse gas emissions statewide, and thus dominate emissions from the state.

Carbon Dioxide Production from Fuel Use

The principal fuels used in Minnesota are commercial fossil fuels. The complete combustion of any fossil fuel can be represented by the following reaction:

$$C_xH_y + (x + 1/4y)O_2 \rightarrow xCO_2 + 1/2y(H_2O) + \text{heat}$$

where C_xH_y is a generalized hydrocarbon fuel. During the combustion process, the carbon that is fixed in the fuel is oxidized to CO_2 and is released to the environment in tandem with water and heat, the principal byproducts of combustion.[55]

A lesser amount of biomass-based fuels like wood and ethanol are also combusted in Minnesota to produce energy. As in the case of the combustion of a fossil fuel, CO_2 results from combustion of biomass-based fuels.

Table 5. Estimated 1990 Minnesota Carbon Dioxide Emissions from Fossil Fuel Combustion (in tons of CO_2)

	Residential	Commercial	Industrial	Electrical Generation/ Steam	Agricultural	Transportation	TOTAL
Natural Gas	6,176,287.3	4,460,898.5	4,912,021.6	555,408.1		745,468.4	**16,850,083.9**
Propane-Air Gas	1,906.6	1,386.6	1,559.9				**4,853.1**
Refinery Gas			1,641,410.7				**1,641,410.7**
Bituminous Coal	13,422.1	70,327.1	678,476.7	612,082.9			**1,374,308.8**
Subbituminous Coal		305,972.3	1,601,840.3	30,596,361.8			**32,504,174.4**
Lignite			42,376.9	2,054.0			**44,430.9**
Coal Coke			113,461.3				**113,461.3**
Solid Resins			16.3				**16.3**
Refuse-Derived Fuel		18,362.0		302,016.3			**320,378.3**
MSW-Mass Burn		11,073.9		197,330.0			**208,403.9**
Liquid Transportation Fuels							
Motor Gasoline		20,425.5	80,421.8		353,378.0	18,933,484.8	**19,387,710.1**
Aviation Gasoline						80,130.6	**80,130.6**
Jet Fuel						3,635,280.0	**3,635,280.0**
Diesel Fuel Oil		181,504.6	457,542.2		1,359,194.8	3,696,206.6	**5,694,448.2**
Unspecified Distillate						742,207.9	**742,207.9**
Non-Transportation Liquid Fuels							
Distillate Fuel Oil	1,512,502.0	258,458.5	313,686.0	46,810.5	71,950.3	211.3	**2,203,618.6**
LPG	763,908.9	134,914.7	244,174.7		396,539.9	14,845.8	**1,554,384.0**
Kerosene	24,959.5	3,430.0	886.5		5,065.8		**34,341.8**
Waste Solvent			1,630.0				**1,630.0**
Residual Fuel Oil		66,629.1	717,417.8	28,233.5		3,670.0	**815,950.4**
Waste Oil			106,994.9	318.5		12.2	**107,325.6**
Petroleum Coke			53,406.6	487,554.0			**540,960.6**
TOTAL	**8,492,986.4**	**5,533,382.8**	**10,967,324.2**	**32,828,169.6**	**2,186,128.8**	**27,851,517.6**	**87,859,509.4**

Source: Calculated from Appendix C using Tables 7 and 8 below.

In this inventory, we are primarily concerned with emissions of CO_2 resulting from the combustion of fossil fuels. The reason for this is readily apparent: CO_2 resulting from the combustion of fossil fuels is composed of carbon that has long been sequestered in the earth's crust in buried reservoirs that are completely isolated from the atmosphere-biosphere system. The combustion of fossil fuels results in the introduction into the atmosphere-biosphere system of a new source of carbon that is only slowly removed from the atmosphere through natural processes.

By contrast, biogenic carbon is continually flowing back and forth between the earth's atmosphere and biosphere through biological processes of respiration and photosynthesis. Atmospheric carbon is fixed in organic plant matter through photosynthesis and is released through respiration. If through combustion carbon that was fixed in biomass is emitted to the atmosphere, over periods ranging from a few months to tens of years, an equivalent amount of carbon will be withdrawn from the atmosphere and refixed in living plants through processes of regrowth, resulting in no net release of carbon to the atmosphere -- at least for systems in which the vegetation-producing capacities of the soils or climate are not irreparably damaged as a result of land-clearing activities.[2]

This latter possibility is addressed in Part VII of this inventory. For now it is assumed that the background productivity of natural systems is essentially unaffected by combustion or land-use practices on forested lands.

In this inventory, we are chiefly concerned with climatic changes that might result from CO_2 emissions over a 100-year period. A time frame like this is at least as long or longer than the lifetimes of many long-lived tree species. Thus, it probably makes little sense to include emissions from the combustion of biomass-based fuels in emissions estimates.*

Following the recommended U.S. Environmental Protection Agency methodology given in the *State Workbook*, a long time frame is thus assumed. We estimate emissions of carbon dioxide from fossil fuel combustion, wood burning and the combustion of other fuels derived from forest products. However,

* It might be noted, however, that if one's concern were with climate change resulting from emissions on time-scales well short of the lifetimes of long-lived tree species, e.g., 25 years, one might wish to include in estimated emissions some part of those emissions resulting from wood combustion. Over such periods of time, only a part of that carbon released to the atmosphere during combustion is likely to be refixed in biomass through regrowth, resulting in a net emission of carbon to the atmosphere.

emissions from wood burning and related forest products combustion are not included in the final inventory estimates. In Part VII, we estimate the present-day annual rate of carbon storage in Minnesota's forests as a result of forest growth and of management decisions not to harvest. This value is then subtracted from the total atmospheric emission of carbon as carbon dioxide from fossil fuel combustion to derive net emissions of CO_2 to the atmosphere in the short-term from activities within the state. The amount of carbon released to the atmosphere as a result of wood burning as fuel is implicit in the estimated amount of carbon that is annually withdrawn from the atmosphere and stored in Minnesota's forests -- uses of wood as fuel act to reduce the amount of total annual carbon storage in those forests, presumably by an amount equal to the carbon content of the wood combusted, and thus to increase net short-term emissions of CO_2 from the state.

Regardless of whether emissions from the combustion of fossil fuels or wood are included in inventory totals, emissions themselves depend on fuel carbon content. Different commercial and noncommercial fuels have very different carbon contents and different rates of emission of carbon dioxide for each unit of useful energy realized upon combustion. The fossil fuels, the principal focus of this inventory, include coal and lignite, various liquid and gaseous petroleum products, and natural gas. Approximate values for the carbon contents of commercial fossil fuels are shown in Table 6. These range from a low of about 40 percent for lignite to between 86 and 92 percent for refined petroleum products. An estimate is also included in Table 6 for wood.

In the case of commercial fuels, the emission of CO_2 resulting from fuel use is typically calculated using a standardized measure of the energy content of the fuels, coefficients that describe the emission of carbon per unit of realized energy upon combustion, and some estimate of the combustion efficiency.[56]

The technical literature on fuel composition gives a range of emission coefficients or emission factors for CO_2 based on the carbon content of commercially-used fuels. These are shown in Table 7. Typically estimates of carbon emissions are given per million BTU (MMBTU), and are based on the underlying chemical composition of the fuels. In the case of a fuel like coal, the carbon content of the fuel, as well as its energy content, can vary widely from region to region and coal type to coal type. Thus, estimated emission coefficients for coal are usually specific to particular regions. The values given above in Table 7 are mainly for U.S. coals.

The emission factors for CO_2 release from fossil fuel combustion that are used in this study are also shown in Table 7. These are for commercial fuels. In large part, following the U.S. Environmental Protection Agency's recommended methodology, these are taken from Grubb (1989).[63] However, where

Table 6. Approximate Average Carbon Contents of Fossil Fuels and Wood

	% (by weight)
Natural Gas	70.6
Process Gas	70.6
Residual Fuel Oil	85.6
Distillate Fuel Oil	87.2
Motor Gasoline	85.7
Jet Fuel	86.1
Petroleum Coke	92.0
Liquid Petroleum Gas	82.0
Subbituminous Coal	50.0(a)
Lignite	40.0(b)
Wood	27.0

Sources: U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-92-002, (Washington, D.C.: 1992).

(a) Letter from M. Martens, Northern States Power Company, April 15, 1994.
(b) Personal communication with V. Menze, Otter Tail Power Co., February 20, 1994.

no emission factor was available from Grubb, these were taken from the U.S. Department of Energy's greenhouse gas inventory, *Emissions of Greenhouse Gases in the United States, 1985-1990*, DOE/EIA-0573 (1993), or from related sources.[51]

The assumed energy contents of commercially-used fossil fuels were taken principally from the U.S.

Table 7. Carbon Dioxide Emissions Coefficients for Commercially-Used Fossil Fuels

Fuel Type	Emissions Coefficients (in lbs C/MMBTU)	
	Range Given in Literature[a]	This Study[b]
Liquid Transportation Fuels		
Motor Gasoline	41.80 - 45.41	41.80
Diesel Fuel Oil	44.20 - 46.74	44.20
Jet Fuel	42.92	42.92[c]
Aviation Gasoline	42.81	42.81[c]
Non-Transportation Liquid Fuels		
Distillate Fuel Oil	42.55 - 46.74	42.55
Residual Fuel Oil	46.52 - 49.54	46.61
Waste Oil	46.25 - 46.76	46.76[c,d]
Kerosene	42.92 - 45.13	43.1
LPG	35.8 - 35.85	35.8
Petroleum Coke	60.21 - 64.79	64.79[c]
Gaseous Fuels		
Natural Gas	31.34 - 32.85	31.39
Propane	37.68 - 37.92	37.92
Flare Gas	33.53	33.53[c]
Solid Fuels		
Bituminous Coal	55.12 - 60.01	57.01
Subbituminous Coal	50.71 - 59.74	59.00
Lignite	49.54 - 63.49	61.00
Coke Coal	70.90	70.90[e]

(a) See Endnotes 51 and 54 through 75.
(b) M. Grubb, *On Coefficients for Determining Greenhouse Gas Emissions from Fossil Fuel Production and Consumption*, (London: Energy and Environmental Programme, Royal Institute of International Affairs, 1989).
(c) U.S. Department of Energy, *Emissions of Greenhouse Gases in the United States 1985-1990*, DOE/EIA-0573, (Washington, D.C.: 1993).
(d) Emission coefficient for lubricants.
(e) M. Steinberg and A. Albanese, "Environmental Control Technology for Atmospheric Carbon Dioxide," in W. Bach, *et al.*, (eds.), *Interactions of Energy and Climate*, (Dordrecht, Netherlands: D. Reidel Publishing Co., 1981).

Environmental Protection Agency' s *State Workbook* and the U.S. Department of Energy's *State Energy Data Report* (1992), and are given in Appendix A.[54,76]

Combustion efficiencies are shown in Table 8 for various fuels. Upon combustion, most of the underlying carbon contained in fuels is oxidized to the atmosphere in the form of carbon dioxide. Following the U.S. Environmental Protection Agency *State Workbook* methodology, we assume a combustion efficiency of 99 percent for all commercially sold fossil fuels.[54] It is assumed that the remaining one percent is either released to the atmosphere in the form of carbon monoxide (CO) or volatile organic compounds (VOCs) or takes the form of carbon left as soot or unburned hydrocarbons around the burner or in the stacks.[51]

In addition to commercial fossil fuels, various other fuels are also combusted in Minnesota to produce energy. These include wood, refuse-derived fuel, and municipal solid waste. In Minnesota, a substantial

Table 8. Assumed Efficiencies of Combustion

Fuel	Combustion Efficiency (in %)
Coal	99
Refined Petroleum Products	99
Natural Gas	99
Wood	90
MSW - Mass Burn	90
RDF	98.5(a)

Source: U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-92-002, (Washington, D.C.: 1992).

(a) Personal conversation with J. Brobjorg, October 10, 1990, as cited in P. Ciborowski and D. Burdette, "Carbon Dioxide Emissions in Minnesota," report to the Minnesota Pollution Control Agency, St. Paul, MN, January 1991.

part of the solid waste that is generated by residences and businesses is combusted as fuel. Minnesota is atypical in this. Refuse-derived fuel (RDF) is a form of municipal solid waste from which inorganic materials, such as glass or metal, have been removed, along with most food and yard wastes, which have a high moisture content, and most fines, like large appliances. In addition, to insure that the waste burns evenly, the waste is variously shredded or pelletted to one of several classes of RDF.[77]

By contrast, unprocessed municipal solid waste (MSW) is combusted in mass-feed energy-to-waste incinerators. In either case, the heat derived from combustion is used to generate steam that is either sold as is to industrial customers or is used to generate electricity for sale to electrical utilities.

Wood use takes many forms in Minnesota. Wood is sometimes combusted in pelletted form by out-state public institutions like school districts. Wood products and paper products industries combust sawdust, mill residues, wood chips and wood chunks to derive energy to drive industrial processes. Wood waste is sometimes combusted by electrical utilities in Minnesota in place of fossil fuels.[78]

Following the U.S. Environmental Protection Agency *State Workbook* methodology, emissions from these sources are estimated using fuel amounts (by weight), average carbon content of the fuels by weight, and a measure of the efficiency of combustion. Wood is a fairly straightforward case. Following the recommended U.S. Environmental Protection Agency methodology, it is assumed to have a carbon content of 27 percent, and it is assumed to be combusted at a combustion efficiency of 90 percent.[54] Consistent with the above discussion, emissions totals for wood combustion are kept separate from totals for fossil fuel combustion, and are not included in inventory CO_2 totals.

Estimating emissions from RDF and MSW combustion is more complex. Municipal solid waste is composed of a variety of materials and products, ranging from petrochemical-based plastics and resins to paper, wood wastes and organic yard and food wastes. In addition, it also includes large amounts of inorganic wastes like glass, metals and construction and demolition debris. In Table 9, the carbon contents of both MSW and RDF are shown based on the typical composition of solid waste in the state of Minnesota and the carbon content of different components of the waste. Some of the carbon contained in solid waste is of a petrochemical, and thus fossil fuel, origin. We treat this part of municipal solid waste the same as any other fossil fuel.

The majority of the carbon contained in solid waste is of a forest products origin (see Table 9). This part of MSW and RDF is treated in the same manner as wood used as a fuel: emissions of CO_2 are totaled

Table 9. Carbon Content of Wastes Burned to Produce Energy

	Carbon Content by Weight (in percent)
Municipal Solid Waste	
Petrochemical Component[a]	12
Forest Products/Wood Component	18
Food and Yard Waste Component	3
TOTAL	**33**
Refuse-Derived Fuel	
Petrochemical Component	15
Forest Products/Wood Component	24
Food and Yard Waste Component	2
TOTAL	**41**

Source: Appendix B.

(a) Petrochemical component would equal the percentage of plastics in Minnesota's MSW or RDF multiplied by the carbon content of various plastic types.

separately from those arising from fossil fuel combustion, and are not included in statewide CO_2 inventory totals. Finally, we ignore that part of the waste that is composed of carbon from yard and agricultural wastes. In the case of the oxidation of either yard or food waste, no net atmospheric emission of carbon dioxide results over nearly any period of time, as that CO_2 that is emitted upon combustion is quickly removed from the atmosphere and refixed photosynthetically in plant organic matter.

For the combustion of municipal solid waste, a combustion efficiency of 90 percent is assumed. This value is taken from the literature.[79] For refuse-derived fuel, a combustion efficiency of 98.5 percent is assumed (see Table 8).

Besides commercial fossil fuels, wood, and solid waste, other fuels are also used in Minnesota, although in lesser amounts. Table 10 shows emission factors for some of these. Landfill gas is of biogenic origin, and results from the anaerobic decay of organic matter in such wastes as paper, wood, and yard and food

wastes in sanitary landfills. The emission coefficient given in Table 10 assumes that one-half of landfill gas by volume is CO_2 and one-half is CH_4, that methane has an energy content of 1,012 MMBTU per million cubic foot (MMcf), and that 70 percent of landfill gas is derived from the anaerobic decomposition of forest products like paper and wood and 30 percent derives from the anaerobic decomposition of food and yard wastes.[80] Consistent with the above discussion, we ignore that part of landfill gas that derives from the anaerobic decomposition of food and yard wastes. The remaining emission is treated in the same manner as are emissions from wood burning. The ratio of 70 percent to 30 percent is based on composition of the municipal solid waste placed in Minnesota's landfills (see Appendix B).

Refinery gas is a fossil fuel with an energy content of 1,150 MMBTU per MMcf, and an emission coefficient of 33 lbs. of carbon per MMBTU. The former value is a reported value from the largest refinery in Minnesota.[81] Various miscellaneous gases are included in the 'other gas' category, and these are assumed to have characteristics similar to methane. Plastics resins are assumed to have the same carbon content by weight as plastics generally, and waste solvents are assumed to possess similar characteristics as special naphthas.

Table 10. Carbon Dioxide Coefficients for Other Fuels Not Listed in Tables 7 Through 9

	lbs Carbon/MMBTU
Landfill Gas	62.46(a)
Refinery Gas	32.70(b)
Propane - Air	37.92(c)
Other Gases	31.39
Waste Solvents	42.81(d)
	% Carbon by weight
Plastic Resins	75

(a) Evaluated at 506 MMBTU/MMcf of landfill gas, methane and carbon dioxide densities of 0.04235 lb./cf and 0.1154 lb./cf, respectively, landfill gas composition of 50% methane and 50% carbon dioxide, and carbon content by weight for methane and carbon dioxide of 74.9% and 27.2%, respectively.
(b) Evaluated at an energy content of 1,150 MMBTU/MMcf, a composition (by volume) of 84 to 86% methane, 10 to 14% ethane, and 2 to 4% propane, densities for methane, ethane and propane of 0.04235 lb./cf, 0.0799 lb./cf, and 0.01183 lb./cf, respectively, and carbon contents (by weight) for methane, ethane and propane of 74.9%, 79.9%, and 81.7%, respectively.
(c) Value for propane component only.
(d) Value for special naphtha.

The combustion efficiencies for the fuels listed in Table 10 are similar to the others discussed above: 99 percent for gaseous fuels and waste solvent, and 90 percent for solid resins.

Finally, no emission coefficients are given for either ethanol or crop residues, small amounts of which are combusted each year in Minnesota for energy production. In the case of agricultural crops, no net CO_2 emission is assumed, essentially for the same reason that emissions from the combustion of the food and yard waste component of municipal solid waste are assumed to be zero. Carbon is photosynthetically fixed in agricultural crops on an annual basis, after which it is oxidized and released back to the atmosphere, only to be refixed photosynthetically in plant organic material in the following year in the same amounts. On an interannual basis, no net emission of CO_2 occurs that leads to any rise in the atmospheric concentrations of the gas. This is true irrespective of whether the crop residue is left out in the field to oxidize or whether it is combusted to produce energy.

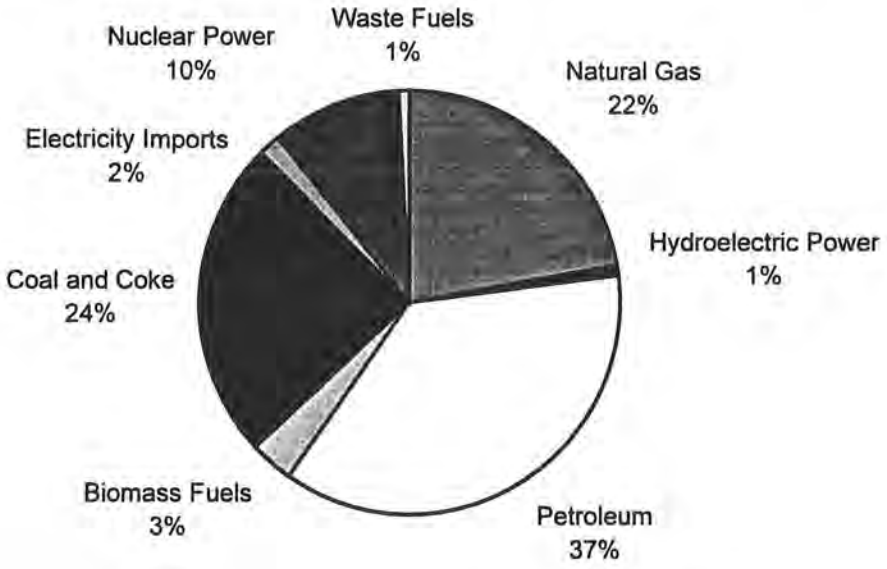
Energy and Fuel Use in Minnesota

In 1990, 1301.5 trillion BTUs of commercial energy are estimated to have been consumed in Minnesota. This is based on estimated 1990 fossil fuel and biomass use given immediately below, and on estimated amounts of energy derived in Minnesota in 1990 from civilian nuclear power, hydroelectrical generation and wind power (see Figure 1). This is in good agreement with other estimates of statewide energy consumption.[76,82,83]

The fossil fuel use component of Minnesota energy use is shown in Table 11 by fuel and by energy consuming sector. These are given in physical units and include energy production from MSW and RDF. These are presented in Appendix C converted to million BTU (MMBTU) energy equivalent. Roughly 1,099.1 trillion BTUs of fossil fuel energy was consumed in Minnesota in 1990. In terms of fuel use, coal use accounted for approximately 29 percent of fossil fuels combusted by energy content, petroleum fuels about 42 percent, and natural gas about 26 percent. The distribution of fossil fuel use among energy consuming sectors is shown in Figure 2 as a percent of the total energy content of the fossil fuels combusted in the state.

Total uses of MSW and RDF for energy production are also shown in Table 11 in tons of total waste combusted. As noted above, roughly 36 percent of the carbon contained in RDF and MSW is by weight of a petrochemical or other fossil fuel origin, while 57 percent by weight is carbon originally fixed in forest

Figure 1. Energy Use in Minnesota by Energy Source, 1990[a]



Source: Appendix C and Minnesota Department of Public Service, *Minnesota Energy Data Book*, (St. Paul, MN: 1990).

(a) Of a total of 1,305.1 trillion BTU.

products. The remainder originates in carbon from food and yard waste. In calculating CO_2 emissions, we include as a fossil fuel only the petrochemically-based part of MSW and RDF.

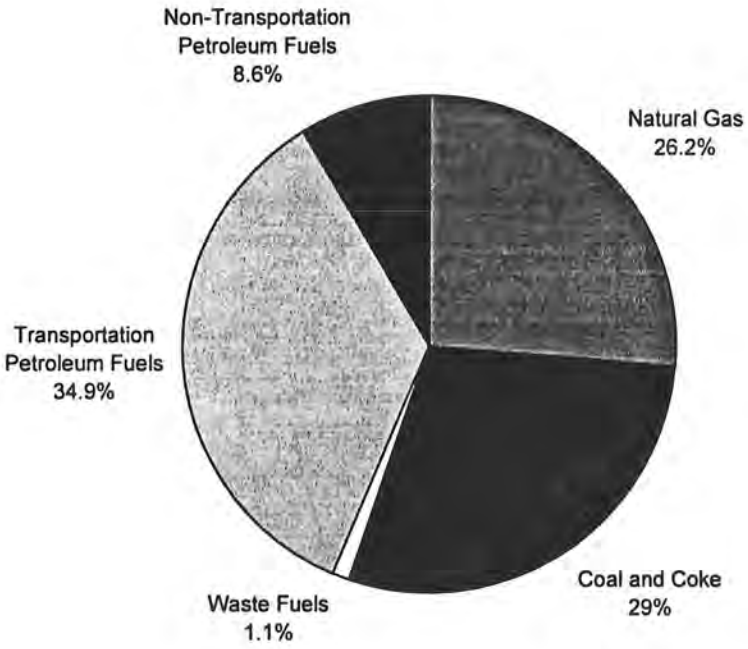
A number of different published sources were available from which to draw information on Minnesota's use of fossil fuels. These included: the Minnesota Pollution Control Agency's *Emission Inventory System* (1994),[84] the Minnesota Department of Public Service's *Minnesota Energy Data Book* (1990),[82] the Federal Highway Administration's *Highway Statistics 1990* (1990),[85] and the U.S. Department of Energy's *Natural Gas Annual* (1990),[86] *Quarterly Coal Report* (1990),[87] *Fuel Oil and Kerosene Sales Report*

Table 11. 1990 Minnesota Fossil Fuel Use (in physical units)

	Residential	Commercial	Industrial	Electrical Generation/ Steam	Agricultural	Transportation	TOTAL
Natural Gas (MMcf)	105,776	76,398	84,124	9,512		12,767	288,577
Propane-Air Gas (MMcf)	22	16	18				56
Refinery Gas MMcf			24,065				24,065
Bituminous Coal (tons)	5,900	30,914	298,241	269,056			604,111
Subbituminous Coal (tons)		168,185	880,490	16,818,025			17,866,700
Lignite (tons)			29,462	1,428			30,890
Coal Coke (tons)			32,921				32,921
Petroleum Coke (tons)			16,002	146,084			162,086
Solid Resins (tons)			6				6
Refuse-Derived Fuel (tons)		33,251		546,908			580,159
MSW-Mass Burn (tons)		28,313		504,519			532,832
Liquid Transportation Fuels (10^3 gallons)							
Motor Gasoline		2,154	8,481		37,266	1,996,659	2,044,560
Aviation Gasoline						8,586	8,586
Jet Fuel						345,900	345,900
Diesel Fuel Oil		16,324	41,150		122,242	332,426	512,142
Unspecified Distillate						66,752	66,752
Non-Transportation Liquid Fuels (10^3 gallons)							
Distillate Fuel Oil	136,030	23,245	28,212	4,210	6,471	19	198,187
LPG	123,186	21,756	39,375		63,945	2,394	250,656
Kerosene	2,365	325	84		480		3,254
Waste Solvent			168				168
Residual Fuel Oil		5,265	56,690	2,231		290	64,476
Waste Oil			8,736	26		1	8,763

Source: See Appendix D and text.

Figure 2. 1990 Minnesota Fossil Fuel Use by Sector[a]



(a) Of a total of 1,099.1 trillion BTU.

(1990),[88] *Electric Power Annual* (1990),[61] *Cost and Quality of Fuels For Electric Utility Plants* (1992),[89] and *State Energy Data Report* (1990).[76]

In the case of some fuels, the estimates given in these sources diverged markedly from one another. Choices among the data for each fuel type were based on several judgments:

- that in the case of industrial fuel uses in which use is restricted to a small

number of large users, firm-reported data are to be preferred to all other data;

- that where firm-reported data do not provide adequate coverage to much or most of fuel use for any one fuel, those survey data covering the widest possible range of sellers and purchasers of the relevant fuel are to be preferred;

- that data on actual fuel use consumption is to be preferred to data on sales;

- and, finally, that some estimates of fuel use can be judged to be implausible based on physical considerations like, in the case of residential energy use, total numbers of residences and average annual amounts of energy consumed in each household for space heating, lighting, water heating, and cooling.

The sources from which the data on 1990 Minnesota fuel uses were taken are summarized in Appendix D. The coal use totals for the electrical generation/steam and commercial sectors are from the Minnesota Pollution Control Agency's *Emission Inventory System* (MPCA-EIS). By state law, any firm emitting over 25 tons of a criteria pollutant is required to report fuel usage to the Minnesota Pollution Control Agency. The reported data on fuel use in the electrical generation/steam sector covers nearly every utility in Minnesota that is burning coal or any other fuel, and as such the accuracy of the data is high. As far as coal use in the commercial sector, the values reported to the MPCA are based on actual combustion rates. Total coal use reported by the MPCA-EIS in the commercial sector is larger than reported elsewhere.[91]

The total given for the statewide use of coal is taken from the U.S. Department of Energy's *Quarterly Coal Report*. These are reported data annually received from roughly 6,000 coal mining firms, 1,450 moderate-to-large coal purchasers or distributors, 1,050 manufacturers using coal, and all electric utilities.[87] Residential coal use is from the Minnesota Department of Public Service's *Minnesota Energy Data Book*, and is based on residential energy use modeling.[82] Coal use in the industrial sector is set to match the difference between total statewide use and the aggregate total for use in the electrical generation/steam, commercial, and residential sectors.

Liquid petroleum fuels are divided into two categories: liquid transportation fuels and other liquid fossil fuels, principally heating oils. With the exception of jet fuel, estimated 1990 Minnesota consumption of liquid transportation fuels is taken from the Federal Highway Administration's *Highway Statistics 1990.*[85] The fuel use data that appear in this publication are state-reported data. Virtually the same data, except for a few adjustments to account for the ethanol component of motor gasoline and for aviation gasoline, appear in the *Minnesota Energy Data Book*, from which the jet fuel use total for 1990 is taken.[82] Fuels that fall into the category of liquid transportation fuels include: motor gasoline, aviation gasoline, diesel fuel, other unspecified distillate, and jet fuel.

Other liquid petroleum fuels include #1 through #4 distillate fuel oils, liquid petroleum gas (LPG), residual oil (fuel oils #5 and #6), waste oil and kerosene. A minuscule amount of waste solvents is also combusted. 1990 usage totals for residual oil and waste oil are taken from the MPCA-EIS, which gives the most complete accounting available for either of these fuels by industry, firm, and facility. As firm-reported data, these are preferred to other sources. The residual oil uses given for refinery uses of these fuels are refinery-reported values. Total residual oil usage reported in the MPCA-EIS is close to Federal estimates of residual oil use in Minnesota.[92]

Usage totals for LPG and kerosene are taken from the U.S. Department of Energy's *State Energy Data Report.*[76,93] State totals for distillate fuel oil use are also from the *State Energy Data Report.* These data are based largely on the U.S. Department of Energy's *Fuel Oil and Kerosene Sales Report.*[88] Distillate usage totals in the electrical generation/steam sector and in the transportation sector are reported values from the MPCA-EIS. The percentage breakdown of distillate use among the remaining sectors is taken from the *Fuel Oil and Kerosene Sales Report.* The *Fuel Oil and Kerosene Sales Report* is based on responses from about 2,700 companies selling to end-users, including all refineries, companies with five percent or more of all sales in any one state, and companies doing business in four or more states.[88,94]

The natural gas total is a calculated total. Each year a certain amount of natural gas is estimated to leak from natural gas pipelines.[95] In Part II, Section V of this inventory, the amount of leakage of natural gas from within the state of Minnesota from transmission and distribution lines is calculated using an available U.S. Environmental Protection Agency methodology. Leakage in 1990 is estimated to have been 1,957 million cubic feet (MMcf). The total amount of natural gas combusted in 1990 in Minnesota equals the total amount of gas received at state borders less the amount of in-state leakage. The amount of gas received at state borders is taken from the U.S. Department of Energy's *Natural Gas Annual*, and equals some 290,587 MMcf.[86] The fuel use data given in the *Natural Gas Annual* are based on a mandatory reporting requirement on the part of 2,550 interstate and intrastate pipeline companies, gas distributors,

underground storage operators, and any field production facilities and processing plants that make direct deliveries to customers.

The estimates given for natural gas usage by natural gas pipelines are from the *Natural Gas Annual*, and those for other transportation uses and uses in the electrical generation/steam and industrial sectors are from the MPCA-EIS.[96,97] Natural gas usage totals for oil refineries located in Minnesota are either firm-reported totals or are from the MPCA-EIS. The remainder of use occurs in the residential and commercial use sectors, and it is distributed among these sectors according to the percentage breakdown of use among these sectors that is reported in the *Natural Gas Annual*.

Propane-air is a fuel temporarily used by natural gas utilities during system expansions. 1990 Minnesota consumption of this fuel is taken from the *Natural Gas Annual*.[86] Finally, petroleum coke and coal coke use totals are taken from the MPCA-EIS. Estimated fuel use totals for solid resins, solvent waste, RDF and MSW are also from the MPCA-EIS. Refinery gas consumption is a refinery-reported total.

Carbon Dioxide Production From Fossil Fuel Use in Minnesota, 1990

Total CO_2 emissions from Minnesota from the combustion of fossil fuels and related petrochemically-based waste fuels were shown above in Table 5 for 1990 (see page 16 above). These were computed from the emission coefficients and combustion efficiencies given in Tables 7 and 8, respectively, and the 1990 state fuel use totals given in Table 11 and Appendix C, where CO_2 emissions from the combustion of any one fuel equal:

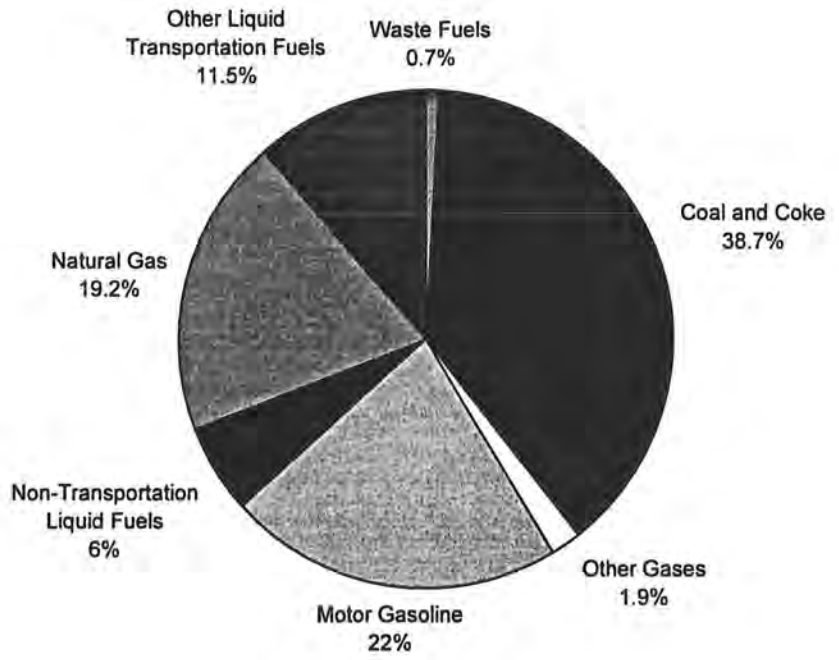
fuel use (in MMBTU) • emissions coefficient • combustion efficiency • 44.008/12.01

and where the fraction 44.008/12.01 converts carbon to CO_2.

For noncommercial fuels like RDF and MSW, emissions were estimated using the carbon content of the fuel, by weight (see Table 9 above), tons of fuel used, and a combustion efficiency of 90%. In general and in particulars, the calculation follows the discussion presented in pages 15 through 25 above.

In total, 87, 859,509.4 tons of carbon dioxide are estimated to have been emitted to the atmosphere in 1990 from Minnesota from the combustion of fossil fuels. Of this, coal combustion accounts for about 34 million tons, or roughly 39 percent, motor gasoline consumption 19 million tons, or 22 percent, and natural gas for about 17 million tons of carbon, or 19 percent (see Table 5 and Figure 3). The remainder is

Figure 3. Estimated CO_2 Production from Fossil Fuel Combustion by Fuel Type[a]



(a) Of a total emission of 87,859,509.4 tons of CO_2.

comprised of emissions from the combustion of other transportation fuels (12 percent), other gaseous fuels (2 percent), nontransportation liquid fuels (6 percent), and other solid and waste fuels (0.7 percent).

Emissions are shown in Table 12 and Figure 4 employing a slightly different breakdown. The combustion of all petroleum products accounts for roughly 41 percent of emissions, while emissions from coal and

Statewide emissions of CO_2 from fossil fuel combustion are estimated in 1990 to have totaled 87,859,509.4 tons.

coke combustion together comprise 39 percent of statewide emissions. All other gases and solids constitute the remaining 20 percent.

Table 12. Estimated 1990 Statewide Production of Carbon Dioxide from Fossil Fuel Combustion

Fuel Type	Emission (in tons of CO_2)
Solid Fuels	
Bituminous Coal	1,374,308.8
Subbituminous Coal	32,504,174.4
Lignite	44,430.9
Coal Coke	113,461.3
Waste Fuels	
Solid Resins	16.3
Refuse-Derived Fuel	320,378.3
Municipal Solid waste	208,403.9
Gaseous Fuels	
Natural Gas	16,850,083.9
Propane-Air Gas	4,853.1
Refinery Gas	1,641,410.7
Liquid Transportation Fuels	
Motor Gasoline	19,387,710.1
Aviation Gasoline	80,130.6
Jet Fuel	3,635,280.0
Diesel Fuel Oil	5,694,448.2
Unspecified Distillate	742,207.9
Nontransportation Liquid Fuels	
Distillate	2,203,618.6
LPG	1,554,384.0
Kerosene	34,341.8
Waste Solvent	1,630.0
Residual Fuel Oil	815,950.4
Waste Oil	107,325.6
Petroleum Coke	540,960.6
TOTAL	**87,859,509.4**

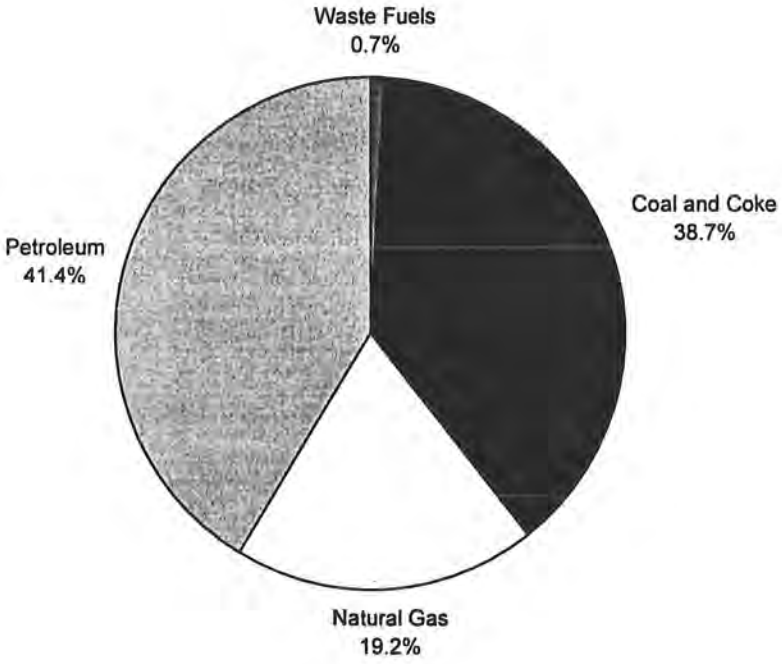
Source: Table 5.

Total U.S. emissions of CO_2 in 1990 from combustion are estimated to have been about 5,447 million tons.[51] Thus in 1990 CO_2 emissions from Minnesota from the combustion of fossil fuels equaled about 1.6 percent of total national emissions.

Carbon Dioxide Emissions by Fuel Use Sector

Carbon dioxide emissions from individual fossil fuel sectors are shown in Figure 5 by fuel use sector. The transportation and the electrical generation/steam sectors are estimated to have been the two largest

Figure 4. Estimated CO_2 Production from Fossil Fuel by Major Fuel Type

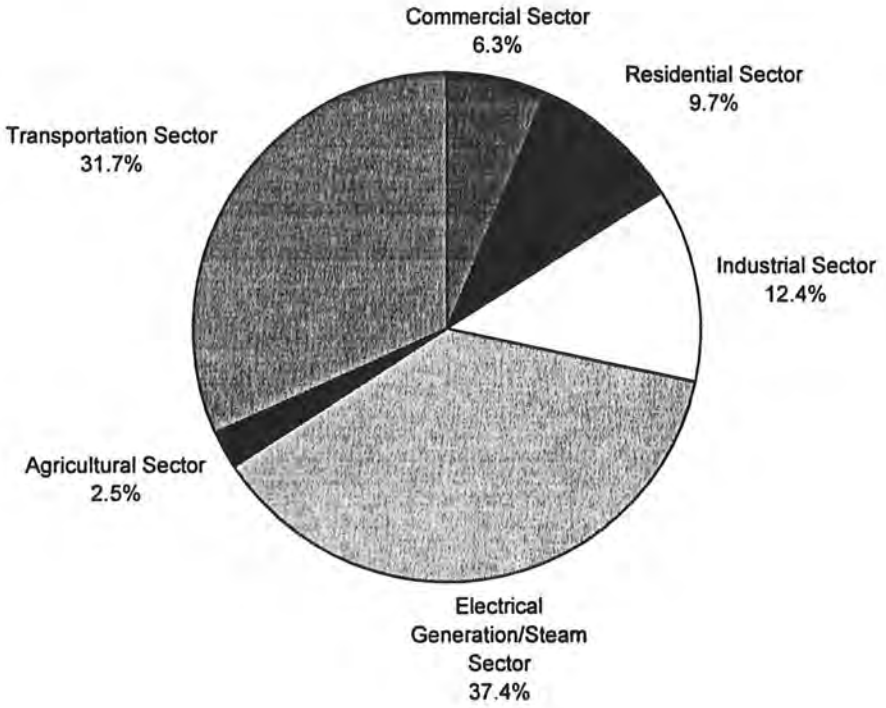


(a) Of a total emission of 87,859,509.4 tons of CO_2.

emitting sectors, together accounting for 69 percent of all emissions to the atmosphere. The industrial sector and residential sectors are estimated to have contributed an additional 12 and 10 percent, respectively. The rest are estimated to have resulted principally from emissions from the commercial sector.

Below, emissions from the electrical generation/steam, industrial, commercial and transportation sectors are treated in more detail.

Figure 5. Estimated 1990 CO_2 Emissions from Fossil Fuel Combustion by Fuel Use Sector[a]



(a) Of a total emission of 87,859,509.4 tons of CO_2.

Electrical Generation/Steam Sector

The electrical generation/steam sector is the second largest energy consuming sector in the state of Minnesota, but the largest CO_2 emitting primary energy use sector. The two largest emitting industrial concerns -- Northern States Power Co. and Minnesota Power and Light -- are also found in this use sector. In this inventory, the electrical generation/steam sector is assumed to be composed of firms or other public authorities falling into the Standard Industrial Classification codes (SIC) 4911, 4931, 4961 and, where waste is combusted to produce salable energy in the form of steam or electricity, SIC 4953.

Reported fuel usage for 1990 within the electrical generation/steam sector is presented in Appendix E (Table E-1) by firm, utility association or power cooperative. The heaviest fuels users are the state's two largest electrical utilities, Northern States Power and Minnesota Power and Light.

CO_2 emissions from fossil fuel combustion are shown in Table 13 by firm for the electrical

Table 13. Estimated CO_2 Emissions from the Electrical Generation/Steam Sector by Utility

Utility	Emission (in tons of CO_2)
Northern States Power Co.	21,139,172.0
Minnesota Power and Light	7,378,339.1
Ottertail Power Co.	323,928.7
SMMPA	2,431,368.9
Interstate Power and Light	221,612.9
Virginia Public Utilities Department	198,825.3
United Power Association	163,487.3
Hibbing Public Utilities Commission	143,695.6
Minneapolis Energy Center	136,495.2
Wilmar Municipal Utility Commission	104,719.5
Franklin Heating Station	93,630.7
New Ulm Public Utilities Commission	90,957.3
District Energy of St. Paul	82,532.0
Duluth Steam Cooperative	60,361.5
Waste-to-Energy Incinerators	206,780.8
All Other	52,262.8
TOTAL	**32,828,169.6**

Source: Calculated from Appendix E-1 using Appendix A and Tables 7 and 8.

generation/steam sector. The calculative procedure is identical to that described above. The total emission of CO_2 from fossil fuel combustion is estimated in 1990 to have been roughly 32.8 million tons. Of this, Northern States Power Co. is estimated to have emitted 21.1 million tons, or 64 percent, and Minnesota Power and Light, some 7.4 million tons or 22 percent. The other 35 firms or public utilities that reported fuel use to the MPCA are estimated to have emitted the remaining 4.3 million tons to the atmosphere.[98]

A number of Minnesota electrical utilities have in the past made an effort to estimate their emissions of CO_2 as a result of fossil fuel combustion. These are shown in Table 14. Other estimates are also shown. As will be noted, the estimates given in this inventory are in generally good agreement with those provided by the two principal emitting electrical utilities in Minnesota.

Finally, nationally, the typical emission of CO_2 from electrical generation per unit of electricity is about 1.45 lbs. of CO_2 per kilowatt hour.[99] Table 15 shows electrical generation and rates of emissions of CO_2 per

Table 14. Other Emissions Estimates for the Electric Utilities Sector

Author	Source of Emission	Year of Emission	Estimated Emission (10^6 tons of CO_2)
Northern States Power Co.	NSP - Minnesota Co.	1989	22.182(a)
Northern States Power Co.	NSP - Minnesota Co.	1988	20.572(a)
Ciborowski and Burdette	NSP - Minnesota Co.	1988	22.772
This Study	NSP - Minnesota Co.	1990	21.139
Minnesota Power and Light	MN Power	1989	7.640(a)
This Study	MN Power	1990	7.378
Electric Power Annual	Electrical generation sector	1990	33.847
This Study	Electrical generation sector	1990	32.828

Sources: J. Brobjorg, Northern States Power Co., "Internal Memorandum on NSP Carbon Dioxide Emissions," (Minneapolis, MN: May 7, 1990).
D. Niemi, Minnesota Power and Light, "Minnesota Power CO_2 Emissions Inventory," letter to P. Ciborowski, September 26, 1990.
U.S. Department of Energy, *Electric Power Annual*, DOE/EIA-0348 (90), (Washington, D.C.: 1991).
P. Ciborowski and D. Burdette, "Carbon Dioxide Emissions in Minnesota," report to the Minnesota Pollution Control Agency, January, 1991.

(a) Includes a small amount of CO_2 from wood.

kilowatt hour generated for 1990 for the five largest emitters of CO_2 in the electrical generation sector in Minnesota. Of the two utilities that dominate electrical production in Minnesota, Northern States Power Co. is close to the national average for lbs. of CO_2 generated per kilowatt hour, while Minnesota Power and Light is somewhat above it. In 1990, Northern States Power estimated its carbon dioxide generation per kilowatt hour for 1989 at 1.44 lbs. per kilowatt hour.[58]

Table 15. Estimated CO_2 Emission Per Kilowatt Hour of Electrical Generation for Major Minnesota Electrical Utilities

	1990 Electrical Generation (in 10^6 kWh)	lb. of CO_2 Emitted/kWh
Northern States Power Co.	33,312.2	1.269
Minnesota Power and Light	7,011.4	2.105
Ottertail Power	293.4	2.208
Interstate Power	215.2	2.060
SMMPA	2,066.1	2.354

Sources: Minnesota Department of Public Service, *Minnesota Utility Data Book,* (St. Paul, MN: 1991), and Table 13.

Industrial Sector

Estimated CO_2 emissions from industrial firms are shown in Table 16 by fuel and major SIC code. Total CO_2 emissions from the industrial sector in 1990 are estimated to have amounted to 10.97 million tons. The industrial sector is assumed to comprise all firms that fall within SIC codes 0 through 39. Four industrial classification codes -- corresponding to petroleum refining and related (SIC 29), metal mining

(SIC 10), food and kindred (SIC 20), and paper and allied products (SIC 26) -- are estimated to have accounted for at least 76 percent of this.

Fossil fuel use in the industrial sector is presented in Appendix E (Table E-2) in physical units by fuel and major SIC code. The fuel use data are from the MPCA-EIS.

Estimated emissions from the petroleum refining sector are shown in Table 17. Fuel use in this industry results in the largest emissions of any single industry in this sector.

Table 16. Estimated CO_2 Emissions from the Industrial Fuel Use Sector by Major Industrial Group

Industrial Group	CO_2 Emissions (in tons)
Petroleum Refining and Related	3,421,139.1
Metal Mining	2,286,629.6
Food and Kindred	1,716,114.8
Paper and Allied	929,821.2
Steel	287,016.3
Fabricated Metal Products	260,298.4
Stone, Clay, Glass, Concrete	206,339.1
Lumber and Wood	83,049.5
All Other	1,776,916.2
TOTAL	**10,967,324.2**

Source: Calculated from Appendix E-2 using Appendix A and Tables 7 and 8.

Table 17. CO_2 Emissions from In-State Petroleum Refining

Refinery Fuel	1990 Fuel Use	Estimated Emission (in tons CO_2)
Residual Oil	27,484.1 x 10^3 gallons	347,814.1
Propane	3,020.9 x 10^3 gallons	18,967.1
Natural gas	18,663.6 MMcf	1,069,001.8
Refinery Gas	24,064.5 MMcf[a]	1,641,423.5
TOTAL		**3,077,206.5**

Sources: Minnesota Pollution Control Agency, *Emission Inventory System,* (St. Paul, MN: 1994); Confidential correspondence from Ashland Petroleum to MPCA, May 6, 1994; Personal communication with S. David, Koch Refining, May 23, 1994.

(a) Evaluated at 1,150 MMBTU/MMcf.

Commercial Sector

Relatively few fuel uses in the commercial sector are reported by SIC code to governmental agencies. Those that are reported are shown in Table 18. In terms of the energy content of those fossil fuels consumed in this sector, this constitutes only about one-sixth of total estimated fossil fuel use in this sector.

Fuel use in the commercial sector is overwhelmingly dominated by natural gas use. Thus to estimate CO_2 emissions by SIC code, we develop an estimate of natural gas use by SIC code. To estimate natural gas use in Minnesota's commercial sector by SIC Code, it is assumed that usage in different commercial sector applications can be approximated by regional distributions of commercial sector natural gas usage.[100] The calculative procedure and results are given in Appendix F. The regional distribution of natural gas usage in commercial applications is determined from the regional intensity of natural gas use per square foot of commercial floor space and estimates published by the U.S. Department of Energy of total commercial floor space in use in 1989 in the West North Central census region (see Appendix F).

Table 18. Fossil Fuel Use in the Commercial Sector by Major Industrial Group Reported by MPCA-EIS (in physical units)

	SIC Code	Bituminous Coal (tons)	Subbituminous Coal (tons)	MSW (tons)	RDF (tons)	Distillate Fuel Oil (10^3 gal.)	Residual Fuel Oil (10^3 gal.)	LPG (10^3 gal.)	Natural Gas (MMcf)
Sanitary Services	49[a]			22,000	33,040	196			489
Wholesale Trade	50								15
Grain Storage	51							25	173
Personal Services	72							26	156
Misc. Business Services	73								655
Medical & Health Services	80	1,728			211	106	755		1,365
Educational Services	82	29,186	168,185	6,313		240	1,148		1,376
Social Services	83								133
Engineering, Accounting, & Research	87						3,362		1,389
State Government	92								2
Military	97					407		143	
TOTAL		**30,914**	**168,185**	**28,313**	**33,251**	**949**	**5,265**	**194**	**5,753**

Source: Minnesota Pollution Control Agency, *Emissions Inventory System*, (St. Paul, MN: 1994).

(a) Excludes utilities or firms in the electrical generation/steam sector.

Table 19 shows total CO_2 emissions summarized by major SIC code for the commercial sector. These include emissions associated with fuel uses reported to the Minnesota Pollution Control Agency's *Emission Inventory System* and emissions associated with natural gas use in the commercial sector. Roughly 89.5 percent of CO_2 emissions from fossil fuel combustion in the commercial sector are accounted for using this approach. SIC code 80, health care services, is the largest identifiable emitting

Table 19. Estimated 1990 CO_2 Emissions from Fossil Fuel Combustion in the Commercial Fuel Use Sector

Industrial Group	CO_2 Emission (in tons)		
	MPCA-EIS Component	Other Natural Gas Use[a]	Total
Educational Services	472,378.9	408,340.5	880,719.4
Food Sales		64,451.2	64,451.2
Food Services		253,396.2	253,396.2
Grain Storage	10,256.6		10,256.6
Health Services	94,483.5	1,054,819.9	1,149,303.4
Lodging		561,965.3	561,965.3
Mercantile/Services	10,046.8	961,202.8	971,249.6
National Defense	5,412.2		5,412.2
Office	161,896.1	362,270.6	524,166.7
Public Order/Safety	116.8	64,316.9	64,433.7
Sanitary Services	57,582.4		57,582.4
Social Services	7,765.9		7,765.9
Vacant Rental Space		32,225.6	32,225.6
Warehouses		361,990.4	361,990.4
Subtotal	819,939.2	4,124,979.4	4,944,918.6
Other Unspecified			588,464.2
Total			**5,533,382.8**

Sources: Table 18 using Appendices A and F and Tables 7 and 8.

(a) Calculated from the distribution of natural gas use by SIC code within the commercial sector of the West North Central census region of the nation. See Appendix F.

subsector, with 1990 emissions estimated to have been 1,149,303.4 tons, or equal to about 21 percent of emissions from the commercial fuel use sector, followed by retail trade and personal services with estimated emissions of 971,249.6 tons of CO_2 or 17.5 percent of sector emissions, and educational services, with emissions of 880,719.4 tons or 15.9 percent of sector emissions.

Transportation Sector

Carbon dioxide emissions from the transportation sector in 1990 are estimated to have been 27.85 million tons. Of this, 27.1 million tons are estimated to have derived from mobile sources and the rest from stationary sources.

Table 20 shows estimated 1990 CO_2 emissions from mobile transportation sources. These are based on estimated fuel uses for each vehicle category shown. CO_2 emissions from highway vehicles dominate, accounting for about four-fifths of all releases. The single largest emitting category is estimated to have been passenger cars, accounting for an estimated 42 percent of all emissions from mobile sources (see Figure 6).

The fuel uses shown in Table 20 are drawn from calculations presented in Appendix G for fuel use by highway vehicles. The calculative procedure is extended. Total fossil fuel use is estimated for each highway vehicle category from vehicle fuel efficiencies and estimated total vehicle miles traveled for each of nine classes of vehicles.

Rates of fuel efficiency for gasoline-powered passenger cars and light-duty trucks are derived from nationally averaged data on new car fuel efficiencies for each class of vehicles adjusted for the effects on fuel economy of vehicle age, highway speed, and the departure of ambient vehicle operating temperatures from new car fuel economy test conditions. The effects of vehicle age on fuel economy are estimated based on U.S. Environmental Protection Agency, *Passenger Car Fuel Economy* (1980).[101] The effects of highway speeds in excess of new car fuel economy test conditions are from Oak Ridge National Laboratory, *Transportation Energy Data Book* (1993),[102] while reported total highway vehicle miles traveled at speeds in excess of test conditions are from Federal Highway Administration, *Highway Statistics 1990* (1992).[85] The effects of ambient temperature per degree of departure of ambient operating temperature from those prevailing during testing are taken from OECD, *Automobile Fuel Consumption in Actual Traffic Conditions* (1982).[103] Long term climatic normals for Minneapolis/St. Paul are assumed to

Table 20. Minnesota Transportation Fuel Use Apportioned to Vehicle and Transportation Type and Associated CO_2 Emissions

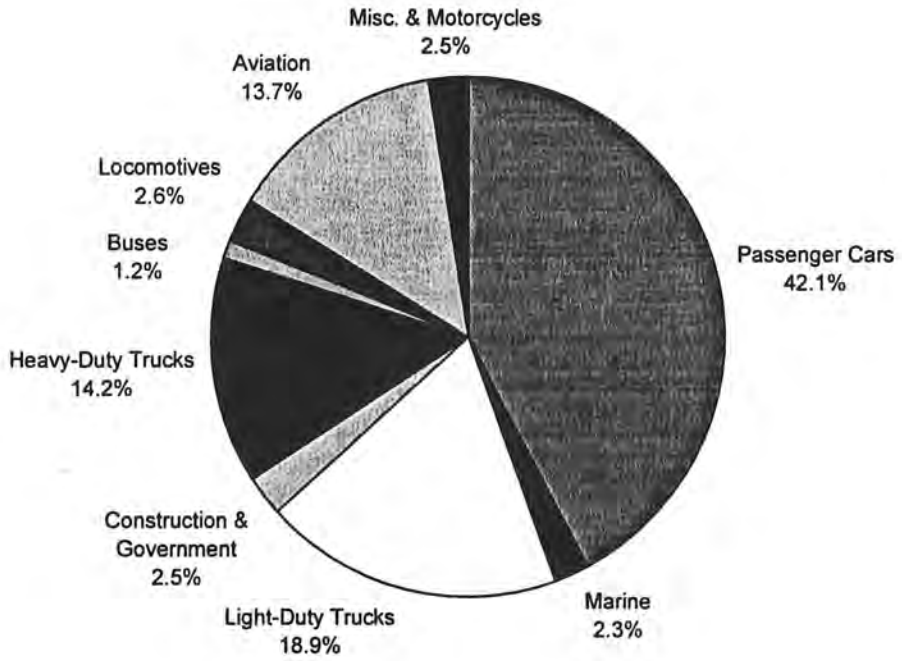
	Gallons Used	CO_2 Emissions (in Tons)
Passenger Cars		
Gasoline	1,196,737,653.0	11,348,163.7
Diesel	17,358,584.1	193,008.1
Subtotal	1,214,096,237.1	11,541,171.8
Light-Duty Trucks		
Gasoline	535,468,294.0	5,077,622.4
Diesel	11,258,948.1	125,186.9
Subtotal	546,727,242.1	5,202,809.3
Heavy-Duty Trucks		
Gasoline	111,729,244.1	1,059,481.8
Diesel	250,710,074.5	2,787,615.9
Subtotal	362,439,318.6	3,847,097.7
Buses		
Gasoline	8,625,570.8(a)	81,792.7
Diesel	22,455,115.6	249,675.8
Subtotal	31,080,686.4	331,468.5
Motorcycles	5,487,094.3	52,031.8
Locomotives	63,075,000.0	701,323.5
Marine	64,030,000.0	612,972.1
Construction	37,716,000.0	409,008.5
Government	27,627,885.8	261,983.7
Misc. Gasoline	67,266,000.0	637,855.4
Aviation		
Aviation Gasoline	8,586,000.0	80,130.6
Jet Fuel	345,900,000.0	3,635,280.0
Subtotal	67,266,000.0	3,715,410.6
TOTAL	**2,774,031,464.0**	**27,313,132.9**
Ethanol Use	24,434,000.0	231,697.4(b)
TOTAL Less Ethanol	**2,749,597,464.0**	**27,081,435.5**

Sources: For highway vehicles, Appendix G and Tables 7 and 8. For nonhighway vehicles, Federal highway Administration, *Highway Statistics 1990,* (Washington, D.C.: 1991) and U.S. Energy Information Agency, *Fuel Oil and Kerosene Sales Report*, DOE/EIA-0535, (Washington, D.C.: 1991).

(a) Reported gasoline usage given in Federal Highway Administration (1991) less estimated 1990 consumption of gasoline in publicly owned school buses, as calculated in Appendix G.

(b) Amount of fossil fuel CO_2 emissions from motor gasoline use displaced through the use if ethanol.

Figure 6. Estimated CO_2 Emissions from Mobil Sources in the Transportation Sector[a]



(a) Of an estimated 1990 emission of 27,087,309.5 tons of CO_2.

represent average conditions for the entire state. Fuel Efficiencies for heavy-duty trucks are based on 1988 survey data of heavy-duty trucks used in Minnesota.[104]

Total vehicle miles traveled are estimated for each vehicle class based on the 1990 makeup of the vehicle fleet in the state of Minnesota by vehicle type, fuel type, and age, and on average annual vehicle miles traveled per vehicle for each class of vehicle by model year (see Appendix G). Nationally-based estimates of average vehicle miles traveled per vehicle per year are employed in the case of passenger cars and light-duty trucks.[105,106] In the case of average annual vehicle miles traveled per vehicle in the heavy-duty truck category, survey data specific to heavy-duty trucks registered in Minnesota are used.[104] For

motorcycles and buses, national data are employed for both average annual vehicle miles traveled per vehicle and average fuel economy.[107]

The approximate makeup of the vehicle fleet, in the case of passenger cars and light-duty trucks, is determined for Minnesota from State of Minnesota vehicle registrations and estimates given at the national level for the age distribution of passenger cars and light-duty trucks and the distribution of vehicle types by fuel type.[85,102,105,106] For heavy-duty trucks, the make up of the fleet is estimated based on vehicle registrations and state-based survey data.[85,104] For buses and motorcycles, State of Minnesota vehicle registrations are employed.[85]

Using this method, 99.99 percent of all CO_2 emissions from mobile sources are accounted for. Overall, the method used accounts for an estimated 38,168.4 million total vehicle miles traveled in the state of Minnesota, which compares well with the estimate given by the Federal Highway Administration of 38,940 million vehicle miles traveled.[85]

In the transportation sector, stationary sources of carbon dioxide emission are dominated by fuel uses in oil and natural gas pipeline operations. These are shown in Table 21. Total CO_2 emissions from stationary sources in the transportation sector total 764,208 tons, and are small in comparison to emissions

Table 21. Stationary Sources of CO_2 Emissions from the Transportation Sector

Stationary Combustion Source	Fuel Use	CO_2 Emission (in tons)
	Natural Gas	
Natural Gas Pipeline Fuel Use	12,017 MMcf	700,280.7
Oil Pipeline Fuel Use	88 MMcf	5,128.1
	Distillate Fuel Oil	
Oil Pipeline Fuel Use	270,000 Gallons	3,002.1
Other	NA	55,797.1
TOTAL		**764,207.7**

Sources: U.S. Department of Energy, *Natural Gas Annual*, DOE/EIA-0131(90), (Washington, D.C.: 1991).
Minnesota Pollution Control Agency, *Emissions Inventory System,* (St. Paul, MN: 1994).

from mobile sources.

Trends in CO_2 Emissions by Sector and Fuel

Using the same calculative procedure and the same data sources as were used to estimate 1990 CO_2 emissions, CO_2 emissions from fossil fuel combustion were also calculated for the years 1980, 1986, and 1988. These are shown in Table 22 broken down by fuel use sector, along with emissions estimates for 1990. The fuel use data used to calculate these are given in Appendix H.

Total emissions of CO_2 from fossil fuel combustion in 1980 are estimated to have totaled 79.2 million tons,

Table 22. CO_2 Emissions from Fossil Fuel Combustion for 1980,1986, 1988 and 1990 by Fuel Use Sector

Fuel Use Sector	CO_2 Emission (in tons of CO_2)			
	1980	**1986**	**1988**	**1990**
Residential	9,617,077	8,631,632.1	9,207,115.4	8,492,986.4
Commercial	5,088,077.9	5,398,803.7	5,815,929.4	5,533,382.8
Industrial	10,171,682.4	9,119,759.9	9,309,798.7	10,967,324.2
Electrical Generation/Steam	25,968,840.8	19,811,493.1	31,584,842	32,828,169.6
Transportation	25,174,685.8	25,339,896.1	27,274,292.6	27,851,517.5
Agricultural	3,297,347.5	3,003,557.5	2,574,103.7	2,186,128.7
TOTAL	**79,237,711.4**	**71,305,142.4**	**85,766,081.8**	**87,859,509.4**

Source: Appendix H and Table 5.

falling initially in 1986 to 71.3 million tons and then growing by 1990 to 87.9 million tons. Emissions increased roughly 11 percent between 1980 and 1990.

Much of the growth in emissions from 1980 to 1990 resulted from increased emissions from combustion in the electrical generation/steam sector. Emissions from this fuel use sector increased by about 26 percent between 1980 and 1990, or some 6.9 million tons. The transportation sector saw a more minor increase in emissions from 1980 to 1990, about 2.7 million tons or 10.6 percent, while emissions from the industrial sector increased 0.8 million tons or 7.8 percent. Emissions from the commercial sector are estimated to have risen 0.45 million tons, or 8.8 percent, while those from the residential sector are estimated to have fallen by 1.1 million tons.

CO_2 emissions are shown in Table 23 by fuel type for the same years. Emissions are estimated to have

Table 23. CO_2 Emissions from Fossil Fuel Combustion for 1980,1986, 1988 and 1990 by Major Fuel Type

Major Fuel Type	CO_2 Emission (in tons of CO_2)			
	1980	**1986**	**1988**	**1990**
Coal and Coal Coke	26,542,569.7	21,400,242.1	32,539,021.8	34,036,375.4
Petroleum Liquid Fuels	34,464,929.5	34,049,909.2	34,191,066.5	34,797,987.8
Natural Gas	16,584,641.7	14,183,517.7	16,439,425.1	16,850,083.9
Other Gaseous Fuels	1,645,570.5	1,641,584.1	1,674,775.8	1,646,263.8
Waste Fuels	0	29,889.3	193,792.6	528,798.5
TOTAL	**79,237,711.4**	**71,305,142.4**	**85,766,081.8**	**87,859,509.4**

Source: Appendix H and Table 5.

been almost constant over this period for the combustion of all fuels except for coal, for which emissions increased 28 percent from 1980 to 1990. By contrast, emissions from the combustion of liquid petroleum fuels increased 1 percent from 1980 to 1990 and those from the combustion of natural gas 1.6 percent.

CO_2 Emissions From Energy End-Use Sectors

The electrical generation/steam sector is not a final energy consumer, but rather a provider of finished energy goods for residential, commercial, and industrial uses. It is possible in a general way to apportion CO_2 emissions from fossil fuel combustion in the electrical generation sector to final energy end-use sectors.

Electrical consumption in Minnesota is shown in Table 24 for 1990 by end-use sector, and as a percent of total generation. CO_2 emissions from in-state electricity production are apportioned to end-use sectors according to their share of electricity consumption in Minnesota. End-use emissions equal emissions resulting from primary energy consumption plus this extra emission associated with electricity consumption.

Table 24. Electricity Consumption in Minnesota in 1990

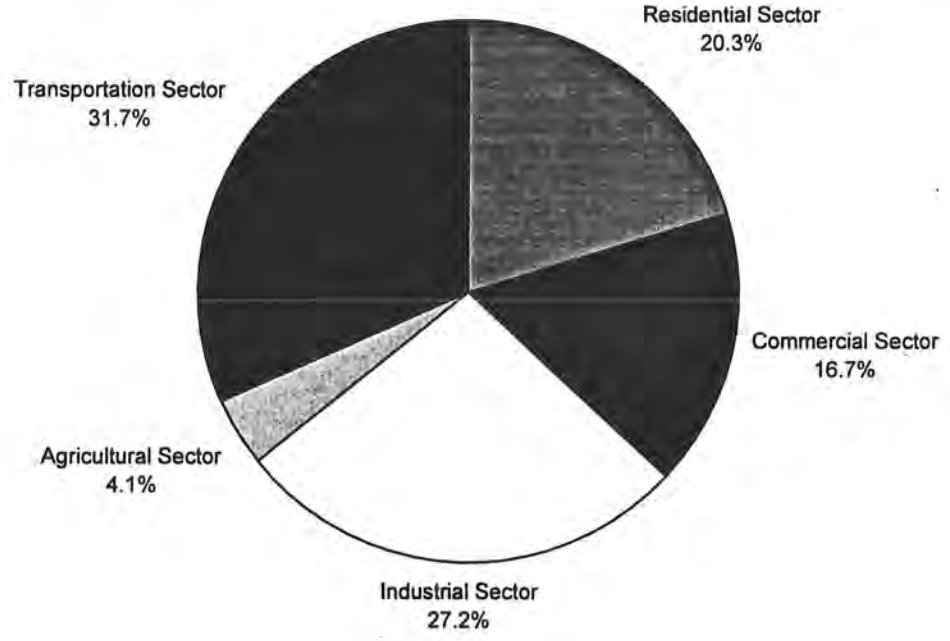
End-Use Sector	Electrical Use (in 10^6 kWh)	% of Total Use
Residential	13,269	28.5
Commercial	12,958	27.8
Industrial	18,335	39.3
Agricultural	2,066	4.4

Source: Minnesota Department of Public Service, *Minnesota Energy Data Book,* (St. Paul, MN: 1990).

Emissions from the secondary energy use sector are shown in Figure 7. The transportation sector remains the largest emitting sector. Due to the high rates of electricity consumption in Minnesota's industrial sector, this end-use sector accounts for about 27 percent of CO_2 emissions from fossil fuel combustion. The residential and commercial sectors account for 20 percent and 17 percent of emissions, respectively.

These estimates, it might be noted, are only approximations of probable general end-use emissions

Figure 7. Carbon Dioxide Emissions from Secondary Energy Use by Sector[a]



(a) Of a total of 87,859,509.4 tons of CO_2.

levels. In Minnesota, a part of the electricity that is generated in-state is sold to customers out-of-state, and, conversely, electricity generated out-of-state is imported into Minnesota and is consumed by Minnesota customers.[96] Emissions themselves depend on fuel type and plant thermal efficiency. These differ from one power plant to another, and from one electrical utility to another. Thus it is possible that electricity component of end-use emissions estimated above on the basis of in-state electricity production could understate or overstate emissions arising from in-state electricity consumption.*

Uncertainty and Other Inventory Results

A number of other CO_2 inventories have been assembled for Minnesota. The results from these are shown in Table 25 by year of estimate. These are in fairly good agreement with the estimates given in this inventory.

A certain amount of uncertainty attaches to the estimates given above for CO_2 emissions from fossil fuel combustion. At the state level, questions concerning fuel usage amounts constitute the principal source of uncertainty. It is often quite difficult to assess the accuracy of information on rates of fuel use. The estimates of statewide fossil fuel usage used in this inventory are generally lower than those given in Minnesota Department of Public Service, *Minnesota Energy Data Book* (1990).[91,92,97] Consequently, the emissions estimates given in this inventory tend to be at the lower end of those totals that might be calculated, given available information on the statewide combustion of fossil fuels.

The U.S. Department of Energy estimates that, at the national level, existing estimates of fossil fuel use are probably accurate to within 3 to 4 percent.[51] Overall, the U.S. Department of Energy considers that CO_2 emissions estimates at the national level are probably accurate to within 5 to 10 percent, and that they are substantially more reliable than estimates for emissions of greenhouse gases from any other source. Other sources of uncertainty that the U.S. Department of Energy has noted include: uncertainty in the standard energy conversion factors for commercial fossil fuels and uncertainty in carbon emission coefficients.

---

* In general, any effort to narrowly relate emissions to actual electricity consumption would more properly trace all electricity consumed in-state back to its original mode of generation regardless of location, and would account for fuel type, combustion efficiency, plant thermal efficiency and transmission losses.

Table 25. Inventory Estimates of Minnesota CO_2 Production from Fossil Fuel Combustion

Inventory	Year of Estimate	CO_2 Emission (in 10^6 tons of CO_2)
Renew America (1988)	1986	65.041
Ciborowski and Burdette (1990)	1988	86.685(a)
Ciborowski (1991)	1990	93.084(a)
Piccot and Saegar (1991)	1990	83.502
This Study	1986	71.305
This Study	1988	85.766
This Study	1990	87.860
DPS (1992)	1990	94.000(a)

Sources: Renew America, *Reducing the Rate of Global Warming: The States' Role*, (Washington, D.C.: 1988).
P. Ciborowski and D. Burdette, "Carbon Dioxide Emissions in Minnesota," report for the Minnesota Pollution Control Agency, January, 1991.
S. Piccot and M. Saeger, *National and State Level Emissions Estimates of Radiatively Important Trace Gas*, EPA/600/58-90/073, (Research Triangle Park, NC: 1991).
P. Ciborowski, "Update to Carbon Dioxide Inventory," report to the Minnesota Pollution Control Agency, (St. Paul, MN: 1992).
Minnesota Department of Public Service, *Transition into the 21st Century: 1992 Energy Policy and Conservation Report*, (St. Paul, MN: 1992).

(a) Studies based on data given in Minnesota Department of Public Service, *Minnesota Energy Data Book*, (St. Paul, MN: 1992).

Wood Use and Associated CO_2 Emissions

As discussed above, CO_2 emissions from the combustion of wood and related forest products are estimated in this inventory principally to demonstrate the effect of large-scale wood combustion on the ability of Minnesota's forest systems in the short-term to sequester excess CO_2 emitted from fossil fuel combustion.

Wood fuels uses are shown in Table 26 by fuel use sector in tons. Also shown in Table 26 are the amounts of solid waste combusted in 1990 in the state, again by fuel use sector, and amounts of landfill gas and other gas combusted in Minnesota in 1990.

Fuel use amounts are taken from four sources. Residential wood use is from the *Minnesota Energy Data Book* (1990).[82] Wood and sawdust use in the electrical generation/steam and transportation sectors, and

pulp gas use are from the MPCA-EIS.[84] Wood use in the industrial, commercial, and agricultural sectors is from two sources: MPCA-EIS and the Council of Great Lakes Governors, *Biomass Energy Facilities* (1989).[78] The amount of landfill gas combusted annually is taken from *Biomass Energy Facilities* (1989).

CO_2 emissions from the combustion of these fuels are shown in Table 27. These are calculated following the methods discussed earlier in Part II (see page 31 above). About 3.767 million tons of CO_2 are estimated to have been emitted to the atmosphere as a result of the combustion of wood, other forest products like paper, or landfill or pulp gas. This is equal to about 4 percent of CO_2 emissions from the combustion of fossil fuels in the state.

Figure 8 shows the distribution of CO_2 emission from the combustion of wood, wood-based wastes, and landfill and pulp gas by energy use sector. The residential sector is estimated to be the largest emitting sector, accounting for 40 percent of estimated emissions. The industrial and electrical generation/steam account for most of the remainder.

Summary

Carbon dioxide is produced as a result of the combustion of fossil fuels. 87,859,509.4 tons of CO_2 are estimated to have been emitted to the atmosphere in 1990 as a result of fossil fuel combustion activities in the state of Minnesota. The two largest emitting sectors are estimated to have been the transportation and electrical generation/steam sectors. In terms of fuels, the largest aggregate emissions are estimated to have resulted from the combustion of coal and motor gasoline.

The estimates given in this study for CO_2 production from fossil fuel combustion are in general agreement with estimates from other sources.

Table 26. Biomass, Biogas, and Ethanol Fuel Use in Minnesota in 1990 (in physical units)

	Residential	Commercial	Industrial	Electrical Generation/ Steam	Agricultural	Transportation	TOTAL
Landfill Gas (MMcf)				65.0			**65.0**
Biogas (MMcf)			11.3				**11.3**
Other Gas (MMcf)			128.0				**128.0**
Wood (tons)	1,695,000.0	61,349.0	1,348,848.0	133,279.0	4,760.0	6,637.0	**3,249,873.0**
Sawdust (tons)			2,954.0	22,790.0			**25,744.0**
Crop Residues (tons)		1,187.0			63.0		**1,250.0**
RDF		33,251.0		546,908.0			**580,159.0**
MSW		28,313.0		504,519.0			**532,832.0**
Ethanol (10^3 gallons)						24,434.0	**24,434.0**

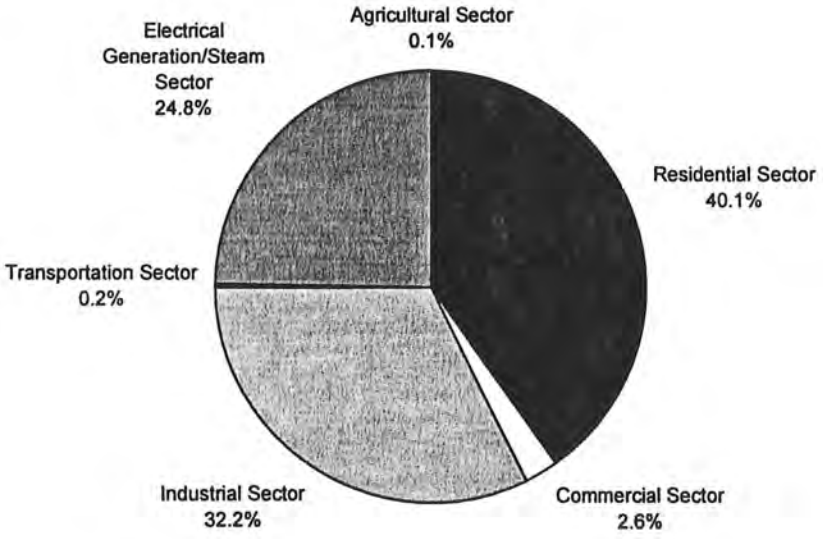
Sources: Minnesota Pollution Control Agency, *Emissions Inventory System*, (St. Paul, MN: 1994).
Council of Great Lakes Governors, *Biomass Energy Facilities: 1988 Directory of the Great Lakes Region*, (Chicago, IL: 1989).
Minnesota Department of Public Services, *Minnesota Energy Data Book*, (St. Paul, MN: 1990).

Table 27. CO_2 Emissions from Wood-Based Biomass Fuels

	CO_2 Emissions (in tons)
Landfill Gas	3,211.9
Other Gas	7,375.2
Wood	2,893,752.1
Sawdust	40,752.0
Refuse-Derived Fuel	502,345.1
MSW-Mass Burn	319,283.4
TOTAL	**3,766,719.7**

Source: Calculated from Table 26 using Tables 7 through 9.

Figure 8. CO_2 Emissions from Wood-Based Biomass Fuels by Fuel Use Sector[a]



(a) Of an estimated emission of 3.767 million tons.

SECTION III. Carbon Dioxide from Air Pollution Control at Power Plants

In addition to the carbon dioxide emitted to the atmosphere as a result of combustion, CO_2 is also emitted to the atmosphere as a result of flue gas desulphurization in some large coal-fired power plants and large industrial boilers. Sulfur oxides can be removed or 'scrubbed' from the flue gas emitted from the stacks of power plants or industrial boilers using either wet flue gas desulphurization (wet FGD) or dry flue gas desulphurization (dry FGD). In wet scrubbing or wet flue gas desulphurization systems, limestone is employed to remove sulfur from the pollutant streams. In this process, sulfur is exchanged for carbon in limestone, essentially on a one-for-one basis, and CO_2 is produced as a result and is subsequently vented to the atmosphere.[56]

In Minnesota in 1990, two electrical generation power plants used wet FGD to control sulfur dioxide emissions, resulting in SO_2 emissions reductions of a reported 4,443.5 tons.[108] An additional 1,000 tons of SO_2 are estimated to have resulted from the use of wet scrubbing in the industrial fuel use sector. The total amount of sulfur dioxide removed from the effluent streams of large combustion facilities through the use of wet flue gas desulphurization in 1990 in Minnesota was an estimated 5,443.5 tons of sulfur dioxide, or in terms of its sulfur content, 2,725 tons of elemental sulfur.

Thus, assuming a one-for-one exchange of sulfur for carbon in flue gas desulphurization, 1990 emissions of carbon dioxide would have equaled

$$2{,}725 \bullet 6/16 \bullet 3.66428 = 3{,}744 \text{ tons of } CO_2$$

where 6/16 denotes the ratio of the atomic weights of sulfur to carbon and 3.66428 converts tons of carbon to tons of CO_2.

Statewide emissions of CO_2 in 1990 from flue gas desulphurization are estimated to have totaled 3,744 tons.

SECTION IV. NonCO_2 Greenhouse Gases from Fuel Use

Carbon monoxide (CO), nitrogen oxides (NO_x), methane (CH_4), nitrous oxide (N_20) and nonmethane volatile organic compounds (NMVOCs) are formed during the combustion of fossil fuels and wood, and can be emitted in large amounts to the atmosphere.

Nitrogen oxides are formed during high temperature combustion, especially in electric power plants burning coal, and also in mobile transportation sources.[73] Carbon monoxide is formed as a result of the incomplete combustion of fossil fuels and wood-based fuels. Especially large emissions of carbon monoxide result from transportation fuel uses.

NMVOCs are also formed as a result of incomplete combustion. Methane is either present in the fuel and, going unburned, is vented to the atmosphere during combustion, or it is formed during combustion. Emissions may also occur during the start-up and shutdown of gas-fired turbines.[95] Nitrous oxide is formed during combustion, but many specifics of this are uncertain.[54]

Three combustion sources are treated in this section: mobile sources, large industrial stationary sources, and small stationary sources. Below, 339,832.3 to 343,337.2 tons of NO_x are estimated to have been emitted in 1990 from fuel uses, 749,039 to 1,095,151.1 tons of CO, 10,118.6 to 10,374.5 tons of CH_4, 3,006.2 tons of N_2O, and 134,818.8 tons of NMVOCs. The atmospheric decay of carbon monoxide is estimated to have resulted in an additional carbon dioxide emission in 1990 of 910,847 to 962,541 tons.

Emissions of nonCO_2 greenhouse gases or their precursors from fossil fuel combustion in Minnesota are estimated in 1990 to have totaled: 339,832.3 to 343,337.2 tons of NO_x, 749,039 to 1,095,151.1 tons of CO, 10,118.6 to 10,374.5 tons of CH_4, 3006.2 tons of N_2O, and 134,818.8 tons of NMVOCs.

Mobile sources, and particularly the passenger car, are estimated to have accounted for at least half and as much as two-thirds of the emissions of each of the compounds treated here.

Emissions from Stationary Sources

With the exception of a small part of emitted methane, most fossil fuel use emissions of carbon monoxide, CH_4, N_2O, NO_x and NMVOCs are formed during combustion. Carbon monoxide, methane, and NMVOCs are formed as a result of incomplete combustion. NO_x is formed in high temperature combustion, and emissions to some degree vary with the nitrogen content of the fuel, as well as with combustion temperatures. N_2O is formed in combustion at temperatures lower than required for the formation of NO_x.

The factors that influence the rate of formation and emission of these pollutants vary from pollutant to pollutant. NO_x emissions depend on the nitrogen content of the fuels, but even more importantly on the firing configuration of the combustion technology employed. High temperatures and excess air supply contribute to the formation of NO_x.[54] In general, coal-fired facilities have much higher emissions of NO_x than do oil-fired or gas-fired facilities, and smaller facilities tend to have lower emissions as a result of lower combustion temperatures.

Other factors that can influence the rate of NO_x formation from stationary sources include: facility usage rate and adjustments to burner technology such as limiting excess air in combustion or staging the combustion process.[54]

Nitrous oxide is formed during combustion at lower temperatures. As a result, these emissions tend to be larger with smaller facilities or with the use of fluidized bed technologies for coal combustion.[109] However, the factors that influence the rate of N_2O formation from stationary sources are poorly understood. Some N_2O may be formed in exhaust plumes through mechanisms involving NO_x.[110]

Emissions of CO, CH_4, and NMVOCs depend critically on the maintenance and operation of combustion facilities, as well as on facility size, fuel, type, and age. In general, rates of emission of these compounds tend to be larger with smaller, older, and less well maintained or poorly operated facilities.[54] Since emission rates for these compounds correlate closely with the efficiency of combustion, emission rates associated with small-scale wood combustion, especially in the residential sector, are relatively higher than for any other fuel.

NonCO_2 Emissions from Fossil Fuel Use in Stationary Combustion Sources

Stationary combustion sources of nonCO_2 emissions derive from two principal categories: large permitted stationary sources and small stationary sources, which are principally located in the residential and

commercial sectors. Calculated emissions of CO, NO_x and total volatile organic compounds (VOCs) are reported to the Minnesota Pollution Control Agency annually by all permitted facilities within the state of Minnesota. These are shown in Table 28 for 1990. Reported emissions from incineration activities at large permitted facilities have been removed from these totals. Emissions from all statewide incineration sources are treated separately in Part V, Section XVIII.

Also shown in Table 28 for 1990 are estimated CH_4 and N_2O emissions for large stationary combustion facilities. These were calculated using the emission factors given in Appendix I along with fuel uses reported to the Minnesota Pollution Control Agency by all permitted facilities by source classification code (see Appendix I). The latter provide specific information on boiler types, internal combustion engine types, incineration types and in-process fuel use combustion. Relatively few emission sources and emission factors have been identified for N_2O production from combustion.

In total, in 1990 large stationary combustion sources are estimated to have emitted to the atmosphere 148,271 tons of NO_x, 81,430 tons of carbon monoxide, 3,192 tons of methane, 48,900 tons of NMVOCs, and 550.5 tons of nitrous oxide (see Table 28).

Table 28. 1990 NonCO_2 Emissions from Stationary Fuel Use Sources Given in MPCA-EIS

Gas	Emission (in tons)
CO	81,430.0[a]
NO_x	148,271.0[a]
NMVOCs	48,900.0[a,b]
CH_4	3,192.0[c]
N_2O	550.5[c]

Source: Minnesota Pollution Control Agency, *Emissions Inventory System,* (St. Paul, MN: 1994).

(a) MPCA-EIS total less incineration emissions
(b) Total VOC emissions of 52,092 tons less 3,192 tons of CH_4.
(c) Calculated totals. See Appendix I.

Fuel uses in smaller stationary combustion sources are given in Table 29, and emission factors for smaller stationary combustion sources are shown in Table 30. The fuel amounts given in Table 29 represent the difference for fuel categories for which emission factors were available between total nontransportation fuel usage in Minnesota in 1990 (see Table 11) and the amount given in the MPCA-EIS for large stationary sources. Emission factors were unavailable for NMVOCs for this category of combustion, and were generally unavailable for N_2O. Emissions from smaller stationary combustion sources are shown in Table 31.

In total, emissions of nonCO_2 greenhouse gases from small stationary combustion sources are estimated in 1990 to have been 16,168.6 to 19,673.5 tons for NO_x, 149,843.1 to 450,955.2 tons for CO, 2,163.4 to 2,419.3 tons for CH_4, and 11.7 tons for N_2O (see Table 31).

Table 29. Statewide 1990 Fuel Use Not Accounted for in MPCA-EIS for which Emission Factors Exist for CO, CH_4, N_2O, and NO_x

	Sector				
Fuel Type	**Residential**	**Commercial**	**Industrial**	**Transportation**	**Electric Utility**
Coal (Tons)	5,900	0	360,993	0	0
Natural Gas (MMcf)	106,033	70,832	0	390	229
Propane-Air (MMcf)	22	16	18	0	0
Distillate Fuel Oil (10^3 Gals)	136,030	22,041	24,361	0	0
LPG (10^3 Gals)	126,186	21,562	10,574	2,394	0
Wood (Tons)	1,695,000	52,821	128,839	0	0

Source: Table 11 and Minnesota Pollution Control Agency, *Emissions Inventory System,* (St. Paul, MN: 1994).

Table 30. Emission Factors Assumed for Non-MPCA-EIS Component of Fuel Use

Sector	Emission Factors (in lbs/ MMBTU)			
	CH_4	N_2O	CO	NO_x
Residential				
Coal	0.0221	0.131	0.431	0.522
Natural Gas	0.0021	NE[h]	0.021	0.098
Propane-Air	0.0024	NE	0.022	0.104
Distillate	0.011	NE	0.029	0.113
LPG	0.0024	NE	0.022	0.104
Wood[a]	0.164[b]	NE	13.26-40.95	0.256-0.442
Commercial				
Natural gas[c]	0.0021-0.0025	NE	0.02-0.021	0.098-0.1
LPG[d]	0.0024	NE	0.022	0.104
Distillate[c]	0.0013-0.011	NE	0.029-0.035	0.113-0.141
Wood	0.0331	0.0095	0.44	0.073
Industrial				
Coal[e]	0.0022-0.0053	NE	0.206-0.396	0.5-0.73
LPG[c]	0.0028	NE	0.022-0.032	0.104-0.13
Distillate[f]	0.013	NE	0.035	0.36
Wood	0.0331	NE	3.32	0.25
Electric Utility				
Natural Gas Boilers	0.0002	NE	0.04	0.559
Transportation				
LPG	0.0024	NE	0.019-0.022	0.092-0.104
Natural Gas[g]	0.0198-1.124	NE	0.119-0.427	0.298-3.38

Sources: U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-B-92-002, (Washington, D.C.: 1992).
U.S. Environmental Protection Agency, *Compilation of Air Pollution Emission Factors, Vol. 2, Stationary Point and Area Sources*, 4th ed., and supplement, (Triangle Research Park, NC: 1985).
U.S. Environmental Protection Agency, *Air Facility System Source Classification Codes and Emission Factor Listing for Criteria Air Pollutants*, EPA450/4-90-003, (Research Triangle Park, NC: 1990).

(a) For wood stoves (lower) and fireplaces (higher).
(b) For wood stoves only.
(c) Emission factor for commercial boilers and residential furnaces.
(d) Emission factor for residential LPG furnaces.
(e) Emission factor for coal-fired industrial boilers and dryers.
(f) Emission factor for commercial distillate boilers.
(g) Emission factors for reciprocating and turbine engines used in the pipeline transmission of natural gas. See Table I-4, Appendix I.
(h) No emission factor available

Table 31. NonCO$_2$ Greenhouse Gas Emissions from Stationary Sources Not Accounted for in MPCA-EIS

	Emission (in tons)
CH_4	2,163.4 to 2,419.3
N_2O	11.7
CO	149,843.1 to 450,955.2
NO_x	16,168.6 to 19,673.5

Source: Calculated from Tables 29 and 30. See Appendix J.

NonCO$_2$ Greenhouse Gas Production from Mobile Sources

Emissions of nonCO$_2$ greenhouse gases from mobile sources result from the incomplete combustion of motor fuels. Carbon monoxide, methane and NMVOC emissions correlate with combustion efficiency and vehicle emission controls. Emissions of these pollutants are highest when air-fuel mixtures allow less oxygen than is required for complete combustion. This usually occurs at low speeds or during idling.[54]

Emissions of NO_x from mobile sources are also closely related to air-fuel mixtures and available pollution control technology. As in stationary source combustion, combustion temperatures are also a factor.

In general, emissions of nonCO$_2$ greenhouse gases from mobile combustion sources vary from vehicle to vehicle, depending on: the type of vehicle, the amount of fuel consumed, emissions control, operating characteristics, and proper maintenance.[54] Lack of proper maintenance can result in high emissions of carbon monoxide, methane, and NMVOCs, although in practice it is hard to account for this factor.

NonCO$_2$ Greenhouse Gas Emissions in 1990 From Mobile Sources

Estimated nonCO$_2$ emissions from mobile combustion sources are shown in Table 32 for 1990. These were derived from two sources: emission factors in lbs. of pollutant per gallon of fuel consumed for each

vehicle class and pollution control technology type; and estimated fuel usage in each of these vehicle categories.

The emission factors for each highway vehicle type and type of pollution control technology are shown in Table 33. All except those for N_2O derive from the U.S. Environmental Protection Agency's Mobile-4 mobile sources computer program. They are based on assumed 'typical' environmental and driving conditions in the United States, including 75 degrees Fahrenheit ambient daily temperatures, a diurnal range of 60 to 85 degrees F, average driving speeds of 19.5 miles per hour, and average U.S. values for fuel volatility. In general, VOC evaporative emissions tend to increase with increasing temperature and fuel volatility, while exhaust emissions tend to increase at lower temperatures.[54]

Emission factors for N_2O were taken from the U.S. Environmental Protection Agency's *State Workbook*, and were derived from a limited set of published estimates. Most nitrous oxide produced by motor vehicles

Table 32. NonCO_2 Emissions from Highway Mobile Sources

Source	Emission (in tons)				
	CH_4	N_2O	CO	NO_x	NMVOCs
Passenger Cars					
Gasoline	2,206.4	1,560.0	248,904.8	33,458.9	42,155.9
Diesel	5.8	4.8	534.0	453.9	198.0
Light-Duty Trucks					
Gasoline	1,112.1	680.3	151,406.7	17,542.0	21,571.9
Diesel	2.3	3.1	325.6	278.5	150.6
Heavy-Duty Trucks					
Gasoline	188.00	7.0	69,143.5	4,625.8	5,979.5
Diesel	301.5	69.5	21,383.8	27,064.7	4,934.5
Diesel Buses	25.7	6.2	1,978.4	2,202.6	395.5
Gasoline Buses	11.9	0.5	4,100.6	345.8	214.7
Motorcycles	53.2	0.7	4,473.8	181.9	735.3
TOTAL	**3,906.9**	**2,332.1**	**502,251.2**	**86,154.1**	**78,117.9**

Source: Calculated from Table 33.

Table 33. Fuel Use and Emission Factors for Mobile Transportation Sources by Pollution Control Technology

			Emission Factors (in lb./MMBTU)				
	Model Years	Fuel Use (in MMBTU)	CH_4	N_2O	CO	NO_X	NMVOCs
Passenger Cars- Gasoline							
Advanced 3-way catalyst	1989-90	20,941,610.3	0.016	0.015	2.497	0.398	0.53
Early 3-way catalyst	1981-88	82,535,064.4	0.025	0.029	1.945	0.331	0.42
Oxidation catalyst	1975-80	35,559,768.4	0.036	0.011	5.171	0.641	0.707
Non-catalyst control	1974 & earlier	10,640,731.9	0.069	0.002	9.502	0.796	1.26
Passenger Cars - Diesel							
Advanced control	1985-90	1,174,955.6	0.007	0.004	0.552	0.42	0.186
Moderate control	1982-4	499,780.4	0.004	0.004	0.354	0.376	0.119
Uncontrolled	1974-81	732,726.0	0.002	0.004	0.331	0.309	0.161
Light-Duty Trucks - Gasoline							
Advanced 3-way catalyst	1989-90	10,881,540.9	0.025	0.015	2.939	0.42	0.464
Early 3-way catalyst	1981-88	35,424,636.5	0.032	0.029	4.199	0.464	0.53
Oxidation catalyst	1975-80	14,309,625.3	0.031	0.011	4.154	0.552	0.663
Non-catalyst control	1974 & earlier	6,355,752.3	0.059	0.002	9.856	0.972	1.547
Light-Duty Trucks - Diesel							
Advanced control	1985-90	708,213.6	0.005	0.004	0.464	0.354	0.199
Moderate control	1982-4	322,349.2	0.003	0.004	0.309	0.331	0.133
Uncontrolled	1974-1981	530,940.7	0	0.004	0.42	0.376	0.221
Heavy-Duty Trucks - Gasoline							
3-way catalyst	1990	882,909.4	0.022	0.001	1.613	0.508	0.309
Non-catalyst control	1979-89	9,973,232.1	0.022	0.001	7.602	0.641	0.398
Uncontrolled	1978 & earlier	3,117,946.8	0.044	0.001	19.579	0.773	2.475
Heavy-Duty trucks - Diesel							
Advanced control	1985-90	14,721,968.8	0.011	0.004	1.149	0.84	0.221
Moderate control	1979-84	12,289,695.7	0.022	0.004	1.392	1.989	0.287
Uncontrolled	1978 & earlier	7,759,315.7	0.022	0.004	1.127	2.232	0.398
Diesel Buses							
Advanced control	NA	1,557,150.0	0.011	0.004	1.149	0.84	0.221
Moderate control	NA	1,557,150.0	0.022	0.004	1.392	1.989	0.287
Gasoline Buses	All	1,078,808.8	0.022	0.001	7.602	0.641	0.398
Motorcycles	All	686,276.4	0.155	0.002	13.038	0.53	2.143

Sources: U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-B-92-002, (Washington, D.C.: 1992) and Appendix G.

is produced by chemical reactions occurring in catalytic converters.

Estimated 1990 fuel usage for each vehicle type, fuel use type, and pollution control technology is taken from Appendix G.

For gasoline-fueled passenger cars and light duty trucks, model years 1989-90, 1981-1988, 1975-1980, and 1974 and earlier are assumed to represent advanced 3-way catalyst, early 3-way catalyst, oxidation catalyst, and noncatalyst pollution control technologies, respectively. For diesel-fueled passenger cars and light-duty trucks, model years 1985-90, 1982-84, and 1974 and earlier to 1981 were assumed to represent advanced, moderate and noncontrol cases, respectively.

For heavy-duty diesel-fueled trucks, model years 1985-1990, 1979-1984 and 1978 and earlier were assumed to represent advanced, moderate, and noncontrol cases, and for gasoline-fueled heavy-duty trucks, model year 1990 was assumed to represent 3-way catalyst control, and model years 1979-89 were assumed to represent noncatalyst controls.

These particular assignments of various model years to classes of pollution control technology were taken from the Wisconsin Department of Natural Resources' greenhouse gas inventory, *Wisconsin Greenhouse Gas Emissions* (1993).[111]

Nonhighway emissions were estimated using the emission factors given in Table 34 and the breakdown of transportation fuels uses given in the U.S. Department of Energy's *Fuel Oil and Kerosene Sales Report* (1991),[88] and the Federal Highway Administration's *Highway Statistics 1990* (1991),[85] and jet fuel use from Minnesota Department of Public Service, *Minnesota Energy Data Book* (1990)[82] (see Table 34).

Total emissions from mobile sources are estimated in 1990 to have totaled 4,763.2 tons of CH_4, 2,443.8 tons of N_2O, 562,765.9 tons of CO, 175,392.7 tons of NO_x, and 85,918.8 tons of NMVOC (see Tables 32 and 35)

NonCO$_2$ Emissions from All Combustion Sources

Total nonCO$_2$ emissions from all combustion sources in Minnesota are shown in Table 35. These are taken from Tables 28 through 34 above, and are estimated in 1990 to have totaled 10,118.6 to 10,374.5 tons of CH_4, 749,039 to 1,095,151.1 tons of CO, 339,832.3 to 343,337.2 tons of NO_x, 3,006.2 tons of

Table 34. Fuel Use and Emission Factors for Nonhighway Mobile Combustion Sources

Source	Fuel Use (in MMBTU)	Emission Factors (in lbs/MMBTU)				
		CH_4	N_2O	CO	NO_X	NMVOCs
Marine						
Gasoline	7,564,794.4	0.011	0.0044	1.1	3.54	0.24
Diesel	491,794.7	0.011	0.0044	1.1	3.54	0.24
Locomotives	8,747,871.8	0.013	0.0044	1.35	3.98	0.29
Farm Equipment						
Gasoline	4,660,895.9	0.024	0.0044	1.33	3.31	0.51
Diesel	16,920,734.8	0.024	0.0044	1.33	3.31	0.51
Construction Equipment						
Gasoline	791,199.2	0.009	0.0044	0.84	2.65	0.2
Diesel	4,353,479.1	0.009	0.0044	0.84	2.65	0.2
Aviation						
Aviation Gasoline	1,031,951.3	0.133	0.002	53.03	0.18	1.19
Jet Fuel	46,696,500.0	0.0044	NE	0.27	0.64	0.04
Industrial/Commercial						
Gasoline	538,930.9	1.1106(a)	0.4936(a)	NE	NE	NE
Diesel	3,173,504.6	1.1106(a)	0.4936(a)	NE	NE	NE
Miscellaneous - Gasoline	8,413,025.9	8.5146(a)	0.2468(a)	NE	NE	NE
Other Off-Highway - Diesel	428,552.1	NE(b)	NE	NE	NE	NE

Sources: U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-B-92-002, (Washington, D.C.: 1992). U.S. Department of Energy, *Fuel Oil and Kerosene Sales Report*, DOE/EIA-0535 (91), (Washington, D.C.: 1991).

(a) lbs/10^3 gallons, from OEDC, *Estimation of Greenhouse Gas Emissions and Sinks*, (Paris: August, 1991).
(b) No emission factors available.

N_2O, and 134,818.8 tons of NMVOCs. In general, stationary sources dominate the emission of NO_x, while mobile sources dominate estimated emissions of N_2O. Emissions of the other gases are more evenly split between mobile and stationary sources.

Statewide nonCO_2 greenhouse gas emissions from combustion are estimated in 1990 to have included: 10,118.6 to 10,374.5 tons of CH_4, 749,039 to 1,095,151.1 tons of CO, 339,832.3 to 343,337.2 tons of NO_x, 3,006.2 tons of N_2O, and 134,818.8 tons for NMVOCs

Table 35. NonCO_2 Emissions from Nonhighway Mobile Sources

	Emissions (in tons)				
	CH_4	N_2O	CO	NO_x	NMVOCs
Marine	44.3	17.7	4,431.1	14,260.2	966.8
Locomotives	56.9	19.2	5,904.8	17,408.3	1,268.4
Farm Equipment	259.0	47.5	14,351.8	35,717.6	5,503.3
Construction Equipment	23.2	11.3	2,160.8	6,816.7	514.5
Aviation	171.4	1.0	33,666.2	15,035.8	1,547.9
Miscellaneous Gasoline	286.4	8.3	NE	NE	NE
Industrial/Commercial	15.1	6.7	NE	NE	NE
TOTAL	**856.3**	**111.7**	**60,514.7**	**89,238.6**	**9,800.9**

Source: Calculated from Table 34.

Carbon Dioxide from Atmospheric Carbon Monoxide Oxidation

Carbon monoxide is quite reactive in the atmosphere. Its atmospheric lifetime is relatively short, a few months, after which it is oxidized to CO_2.[2]

Table 36. NonCO$_2$ Greenhouse Gases from Combustion in 1990

	Emissions (in tons)				
	CH_4	N_2O	CO	NO_x	NMVOCs
Highway Mobile Sources	3,906.9	2,332.1	502,251.2	86,154.1	76,117.9
Non-highway Mobile Sources	856.3	111.7	60,514.7	89,238.6	9,800.9
Stationary Sources	5,355.4-5,611.3	562.4	231,273.1-532,385.2	164,439.6-167,944.5	48,900
TOTAL	**10,118.6-10,374.5**	**3,006.2**	**749,039-1,095,151.1**	**339,832.3-343,337.2**	**134,818.8**

Sources: Tables 28, 31, 32, and 35.

Total carbon monoxide emissions from fossil fuels sources in 1990 totaled an estimated 644,124.4 to 644,855.5 tons.[112] Carbon monoxide is 42.879 percent carbon by weight. Thus total 1990 statewide fossil CO emissions would have contained an estimated 276,194.1 to 276,507.6 tons of carbon that within a few months would have been oxidized to CO_2. In terms of CO_2, this equals 1,012,052.2 to 1,013,201 tons. Bakwin *et al.* (1994) report a carbon monoxide sink in northern hemispheric soils equal to 5 to 10 percent of anthropogenic emissions.[5] Subtracting this 5 to 10 percent yields net emissions from this source. These are estimated in 1990 to have totaled 910,847 to 962,541 tons of CO_2.

Sources of Uncertainty in Emissions Estimates

There is a substantial degree of uncertainty implicit in the above estimates. The emission factors employed to calculate the production of nonCO$_2$ gases are based on a wide variety of assumptions about average conditions that may not be narrowly applicable to Minnesota. In particular, the set of 'typical' annually averaged conditions for mobile highway sources include ambient temperatures of 75 degrees F, which on an annual basis are atypical of Minnesota climate. Since VOC evaporative losses tend to increase with ambient temperature, while exhaust emissions tend to decrease with rising ambient temperature, it is possible that the estimates given above for emissions of NMVOCs from mobile sources

overstate actual emissions, while exhaust emissions from mobile sources are potentially underestimated.[113]

Likewise, emissions from mobile sources are sensitive to assumptions made about vehicle maintenance and the larger makeup and age of the vehicle fleet in Minnesota. The makeup of the vehicle fleet assumed above is an approximation based on estimates of the national distribution of cars and trucks by model year, survey data for the Minnesota truck population, and state motor vehicle registrations (see Appendix G). Without a more exact accounting of the statewide vehicle population by model year, fuel efficiency, installed pollution control technology, and average miles traveled per year, it is possible that the above estimates could overstate or understate actual emissions.

With regard to small stationary combustion sources, as noted above, actual emissions are closely associated with operation and maintenance and the age of facilities. These small stationary sources are unregulated and most likely to be poorly operated and maintained.[54] In absence of firm information regarding the actual combustion technologies employed in some small stationary combustion, the emission factors used to estimate releases from these sources were chosen to bound the uncertainty. However, particularly in the case of wood combustion, this resulted in a fairly wide range of possible emission rates.

No emissions were evaluated for the agricultural sector, as emission factors for this sector were unavailable, and no N_2O emissions were estimated for the industrial sector or for the liquid and waste fuels employed in the electrical generation/steam sector, for the same reason. These omissions may bias downward the estimates given above.

Finally, emissions from aviation fuels were estimated for take-offs and landings only, whereas it is thought that a large part of emissions associated with the consumption of aviation fuels are likely to result during cruising.[54] Also, there is some evidence that the emission factors used to estimate N_2O releases from highway vehicles may understate actual rates of emission from these vehicles.[114]

Given all of these factors, the estimates given above for emissions of nonCO_2 greenhouse gases are probably conservative and may underestimate emissions. They should be understood to represent a first attempt to estimate emissions of these pollutants, one that should be refined as better methods and information become available.

Finally, emissions estimates for 1990 for CO, NO_X, and VOCs prepared by the Minnesota Department of Public Service using the REMI/Energy 2020 Model include an estimated 840,000 tons of CO, 250,000

tons of NO_x, and 235,000 tons of VOCs.[115] These are in general agreement with emissions estimates given in this study.

Summary

Fuel combustion in stationary and mobile sources results in the production and emission to the atmosphere of carbon monoxide, nitrogen oxides, methane, nitrous oxide and NMVOCs. In 1990, it is estimated to have resulted in the release to the atmosphere of 10,118.6 to 10,374.5 tons of methane, 749,039 to 1,095,151.1 tons of carbon monoxide, 3.006.2 tons of N_2O, 339,832.3 to 343,337.2 tons of NO_x, and 134,818.8 tons of NMVOCs.

The level of uncertainty in these estimates is substantial, although it seems probable that the estimates given in this section underestimate actual emissions.

SECTION V. Methane from Natural Gas Pipelines and Oil Refineries

Depending on its point of origin, between 85 and 99 percent of natural gas is comprised of CH_4.[116-119] For the United States, a typical value is about 90 percent. During the production, processing and transmission of natural gas, a small amount of natural gas leaks from the system to the atmosphere, leading to a net emission of CH_4 to the atmosphere.

In the United States, emissions derive principally from leaks, compressor exhaust, and emissions from pneumatic devices. Additional emissions result from routine maintenance and system upsets. Leakage typically results from the failure of seals or the development of various holes, cracks, or flaws in pipeline components.[95] Valves, flanges, instruments and compressor shafts all can develop leaks from flawed or worn seals. Pipelines can develop leaks through cracks or corrosion.

There are no natural gas production fields or processing plants in Minnesota. The only components of the natural gas system located in the state of Minnesota are transmission pipelines, compressor stations, gate stations, distribution mains and service lines and energy end-use technologies using natural gas. In Minnesota in 1990 there were 4,373 miles of transmission pipelines, 17,011 miles of distribution mains and service lines, and 426 gate stations.[120] A gate station is an exchange point where the pressure of gas coming off of a long-distance transmission line is reduced and the gas itself is fed into distribution lines for

delivery to customers. There are five transmission pipelines operating in Minnesota: Northern Natural Gas, Northern Border, Great Lakes Transmission Co., Central Lines of Minnesota, and Viking Gas Transmission.[121] Most of the gas coming into Minnesota for Minnesota use comes through the Northern Natural Gas system.

To estimate leakage from the transmission of natural gas in and through Minnesota and leakage from distribution mains and service lines, we employ a set of emission factors taken from the U.S. Environmental Protection Agency's national methane emissions inventory, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (1993).[95] These were developed from measurements of leakage rates from model facilities variously located around the nation, and extrapolated to the natural gas system as a whole. These are shown in Table 37 for those systems components actually present in the state of Minnesota.

Also shown in Table 37 are estimates for the number of gate stations, dehydrator vents and the number of

Table 37. Emission Factors for Leakage from Natural Gas Pipelines and Estimated Emissions

	Emission Factor	Number of Miles or Units in MN	Emission (in Mg of CH_4)[(a)]
Transmission Pipelines	3.59 mg CH_4/mile	4,373 miles	15,699.1
Distribution Mains	0.2335 mgCH_4/mile	17,011 miles	3,972.1
Gate Stations	32 mgCH_4/unit	426 units	13,632.0
Dehydrator Vents	5.57 mgCH_4/unit	95 units[(a)]	529.2
TOTAL			**33,832.3**

Sources: U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*, EPA-430-R-93-003, (Washington, D.C.: 1993).
American Gas Association, *Gas Facts, 1990 Data,* (Arlington, VA: 1991).

(a) 1 mg = 1 metric ton or 1.1 short tons.
(b) Estimated as a percent of the total number of dehydrators in the U.S. natural gas system based on statewide natural gas consumption as a percent of U.S. natural gas consumption.

miles of transmission and distribution lines running throughout state. There are 426 gate stations in Minnesota: 401 in the Northern Natural Gas system, 24 in the Viking Gas system, and 1 on the Central Lines of Minnesota system.[122]

Using this approach, 33,832.3 metric tons of CH_4 are estimated to have been released to the atmosphere in 1990 from the components of the natural gas system located in Minnesota, or 1761.2 MMcf of methane. We assume that 90 percent of natural gas, by volume, is CH_4. Thus total leakage of natural gas from the system, as distinct from simply the methane component of natural gas, would equal 1,957 MMcf.

Total emissions from natural gas leakage are shown in Table 38 by gas component. Methane is assumed to comprise 90 percent of natural gas by volume, carbon dioxide just 1 percent, and ethane another 5 percent. This a typical percentage partitioning of natural gas by constituent gases.[118] Emissions of CH_4 were estimated above as 33,832.3 metric tons or 37,293 short tons. Based on leakage of 1,957 MMcf of natural gas, total emissions of carbon dioxide would equal 19.6 MMcf, which at a density of 0.1154 lbs. of CO_2 per cubic foot of CO_2 would equal 1,129 tons of carbon dioxide.

Ethane (C_2H_6) is a weak greenhouse gas. Recent evidence suggests that long-term concentrations of

Table 38. 1990 Emissions from Natural Gas Leakage by Gas

Gas	Emission (in tons) [a]
Methane	37,293
Carbon Dioxide	1,129
Ethane	3,909
Other NMVOCs	Unknown[b]

(a) Rounded to the nearest ton.
(b) Estimated emission of 78.3 MMcf of unspecified gas including NMVOCs and nitrogen.

ethane may be increasing globally.[123] Emissions of ethane from natural gas leakage in Minnesota are estimated to have been 97.8 MMcf in 1990, or 3,909 tons.

In Minnesota, methane leakage from transmission and distribution lines is estimated to amount to 0.6 percent of total marketed natural gas consumption. Nationally the U.S. Environmental Protection Agency estimates that CH_4 leakage from transmission lines and distribution mains equals about 0.4 percent and 0.1 percent of marketed production, respectively.[95]

As with most of the estimates given in this inventory, a degree of uncertainty attaches to the estimates given in this section for methane leakage from natural gas pipelines. The U.S. Environmental Protection Agency recommends that a range of possible emissions equal to 0.33 to 3 times the median estimate be used in order to bound the uncertainty in this calculation.[95] This yields a range of possible CH_4 emissions from pipeline leakage for 1990 of 12,307 to 111,879 tons of methane. The use of a small number of model facilities and a limited set of observations at those facilities as the basis for the emission factors given above constitute the principal sources of uncertainty.

Methane Leakage from Oil Refineries

Of all the stages involved in petroleum production and processing, only petroleum refining is located in the state of Minnesota. No crude oil is produced in Minnesota. Two refineries were operating in Minnesota in 1990, with a total refinery capacity of roughly 97,491,500 barrels per year.[124] The total refining capacity of these two refineries is, on an annual basis, slightly larger than the total petroleum consumption in Minnesota.

CH_4 is directly leaked to the atmosphere during refinery operations. Emissions occur principally during the unloading of crude petroleum tanks, when vapor displacement from those tanks results in emissions of CH_4, and during the refining process itself when methane is separated from crude oil through atmospheric or vacuum distillation and is lost to the atmosphere through leaky refinery components.[95] Methane that is not destroyed through process flares is also emitted to the atmosphere. Fugitive emissions through leakage constitute the largest source.

CH_4 leakage from oil refineries in Minnesota is unlikely to be significant. Nationally, methane emissions through refinery leakage are estimated to account for only 0.3 percent of all methane emissions from all sources.[95] DGMK (1990) estimates fugitive emissions released during petroleum refining at about 0.001

percent of the total energy content of refinery output.[125] At a refinery capacity of 97.491 million barrels per year, the energy content of the total refined products produced annually at Minnesota refineries would be some 565.5 million MMBTU. At 0.001 percent, roughly 5,655 MMBTU equivalent of energy would be released to the atmosphere annually in the form of CH_4, or 5.5 MMcf of CH_4. This is equivalent to 124.4 tons of CH_4, which is minuscule in comparison to other emissions.

Summary

In Minnesota, methane is emitted to the atmosphere as a result of fugitive emissions from natural gas transmission and distribution systems and oil refining. Estimated in-state 1990 emissions of CH_4 from the natural gas system are estimated to have amounted to 37,293 tons, while those from petroleum refining are estimated to have been 124.4 tons, for a total in-state CH_4 emission from oil processing and gas transmission of 37,417.4 tons.

These two sources constitute a minor source of methane emissions, accounting for only about 7 percent of total estimated statewide emissions of methane. This is in good agreement with results of national methane inventories, in which gas production, processing, and transmission and oil refining account for an estimated 10 percent of anthropogenic methane emissions originating in the United States.[95]

Statewide emissions of CH_4 from natural gas transmission and distribution and petroleum refining are estimated in 1990 to have totaled 37,417.4 tons.

SECTION VI. Carbon Dioxide from Nonfuel Uses of Fossil Fuels

Annually in the United States a small amount of fossil fuels production is committed to nonfuel uses. Most of this is directed to the production of plastics and synthetic rubber, in which petroleum liquids and natural gas liquids are used as feedstocks, to the manufacture of commercial fertilizers, and to the production of asphalt or bitumen.

Asphalt manufacture is the only major nonfuel use for fossil fuels located in Minnesota. No petrochemicals production capacity is located in Minnesota.[124] Uses of natural gas in the manufacture of commercial fertilizers are small in Minnesota and are treated in Section XIV.

Those nonfuel uses of fossil fuels that it was possible to identify are shown in Table 39, along with an estimate of the amount of carbon tied up in each. The percentage of that carbon that might be expected to be oxidized over periods of 20 years or longer is also shown in Table 39. Based on these values, a relatively small amount of carbon could be expected to be oxidized from nonfuel uses of fossil fuels.

To estimate 1990 emissions from this source, it is assumed that carbon that is not permanently sequestered is oxidized over a period of twenty years, and that 1990 emissions would be equal to one-

Table 39. Nonfuel Uses of Fossil Fuels in Minnesota

Nonfuel Use	Consumption (in 10^3 gallons)	Carbon Content (in tons of carbon)	% Not Sequestered[a]	1990 Emission (in tons of CO_2)[b,c]
Special Naphtha	49	131	20	5
Other Petroleum Feedstocks	8,806	20,763	20	761
Waxes[d]	4,576	12,755	0	0
Misc. Special Petrol. Products	20,624	61,732	0	0
Bitumen	253,638	929,335	0	0
TOTAL	**287,693**	**1,024,716**		**766**

Sources: U.S. Department of Energy, *State Energy Data Report,* (Washington, D.C.: 1991).
Bureau of Census, *1987 Census of Wholesale Trade*, WC87-5-4, (Washington, D.C.: 1991).
DeGoyle and McNaughton, *Twentieth Century Petroleum Statistics,* (1990).
U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA 230-B-92-002, (Washington, D.C.: 1992).

(a) Percentage not sequestered over a 20-year period, as taken from U.S. Environmental Protection Agency, *State Workbook,* (1992).
(b) One-twentieth of total emission for the 20-year period involved.
(c) Rounded to the nearest ton.
(d) Estimated on the basis of U.S. per capita consumption of waxes.

twentieth of the total 20-year emission. Employing these assumptions, emissions from nonfuel uses are estimated for 1990 at 766 tons of CO_2.

Statewide emissions of CO_2 from nonfuel uses of fossil fuels are estimated in 1990 to have totaled 766 tons.

SECTION VII. Emissions Summary

Emissions from all in-state fossil fuels consumption, processing and transportation are summarized in Table 40. Total emissions of carbon dioxide from these activities are estimated in 1990 to have been 88,775,995 to 88,827,689 tons of CO_2. These are dominated by emissions from the combustion of fossil fuels. Emissions of carbon dioxide from wood combustion are smaller, about 3.8 million tons.

Emissions of CH_4 from these activities are estimated in 1990 to have totaled some 47,536 to 47,792 tons, while emissions of N_2O from combustion are estimated to have totaled 3,006 tons.

Finally, total CO_2-equivalent emissions from in-state fossil fuels activities are estimated to have totaled between 90.11 and 90.17 million tons. 98.5 percent of this is attributable to CO_2 emissions from fossil fuel combustion (see Figure 9).

Table 40. Estimated 1990 Emissions from In-State Fuel Consumption, Processing and Transportation

Gas		Emission (in tons) [a]	CO_2-Equivalent Emission (in tons)
CO_2			
	Fossil Fuel	87,859,509	87,859,509
	Fossil Fuel CO Oxidation	910,847 to 962,541	910,847 to 962,541
	Natural Gas Leakage	1,129	1,129
	Non-Fuel Uses of Fossil Fuels	766	766
	Pollution Control	3,744	3,744
	Subtotal	88,775,995 to 88,827,689	88,775,995 to 88,827,689
CH_4			
	Combustion	10,119 to 10,375	111,309 to 114,125
	Natural Gas Leakage	37,293	410,223
	Petroleum Refinery Leakage	124	1,364
	Subtotal	47,536 to 47,792	522,896 to 525,712
N_2O	Combustion	3,006	811,620
NO_x	Combustion	339,832 to 343,337	NA
CO	Combustion	749,039 to 1,095,151	NA
NMVOCs			
	Combustion	134,819	NA
	Natural Gas Leakage	3,909	NA
	Subtotal	138,728	NA
TOTAL[b]			**90,110,511 to 90,165,021**
CO_2 from Biomass Burning		3,766,720	3,766,720

(a) Rounded to the nearest ton.
(b) Excluding CO_2 from wood and other biomass burning.

Figure 9. CO_2-Equivalent Emissions from In-State Fuel Consumption, Processing and Transportation[a]



(a) Of a CO_2-equivalent emission of 90,110,511 to 90,165,021 tons.

PART III. EMISSIONS FROM OUT-OF-STATE FOSSIL FUELS PRODUCTION, PROCESSING AND TRANSPORTATION

Large amounts of energy are used to produce finished fossil fuels. Most of this is itself of a fossil fuel origin. Consequently, the out-of-state production of finished fuels for in-state Minnesota uses results in substantial emissions of carbon dioxide to the atmosphere. Direct leakage of methane from coal mining, natural gas systems, and oil production also results in emissions of radiatively-active gases to the atmosphere.

In 1990, Minnesotans consumed 1,099 trillion BTUs of energy produced from fossil fuel combustion (see Table 11 and Appendix C). With the exception of various petroleum products refined at the two refineries within Minnesota, virtually all commercial fossil fuels production and processing in 1990 was located out-of-state.

Below we treat sequentially out-of-state emissions from: natural gas production, processing, and transportation; coal mining; oil production; finished fossil fuels production; and electricity imports. In total, 6,842,338 to 6,959,342 tons of CO_2 are estimated to have been released to the atmosphere in 1990 as a result of the production of imported electricity, the out-of-state production of finished fuels, and leakage from out-of-state transmission pipelines and gas processing plants ultimately serving Minnesota gas consumers (see Table 41). Methane leakage from the out-of-state production, processing and transportation of coal, oil, and natural gas consumed in Minnesota is estimated to have been some 65,113 to 165,824 tons. CO_2-equivalent emissions from out-of-state fuels production, processing, and transportation are estimated to have totaled 7.6 to 8.8 million tons.

It is also likely that significant amounts of CO_2 are produced and emitted to the atmosphere as a result of fossil fuel energy inputs to out-of-state infrastructure used to either produce, process or transport finished fossil fuels ultimately consumed in Minnesota. However, it was not possible to treat these emissions in this inventory.

Table 41. Estimated 1990 Emissions from Out-of-State Fossil Fuels Production[a]

Source	Emission (in tons)	
	CO_2	CH_4
Coal Mining	NA[b]	7,016 to 69,471
Oil Production	595,908 to 712,912	10,361 to 48,617
Natural Gas Production & Transportation	1,351	47,736
Electricity Imports	1,107,608	NA
Energy Inputs to Finished Fuels	5,137,471	NA
TOTAL	**6,842,338 to 6,959,342**	**65,113 to 165,824**

Source: Table 52 below.

(a) Associated with in-state fossil fuel use.
(b) Not applicable

SECTION VIII. Methane Leakage from Out-of-State Natural Gas Production, Processing, and Transmission

As discussed above in Part II, Section V, CH_4 is released to the atmosphere as a result of natural gas pipeline leakage. In fact, natural gas is leaked to the atmosphere from the entire system, from gas production through gas processing and transmission.

Table 42 shows the rates of CH_4 leakage nationally estimated by the U.S. Environmental Protection Agency for 1990 from each of these systems components. These are shown as a percent of total marketed production in the United States. Emissions from all components of the system are estimated in

1990 to have totaled 0.86 percent of marketed production. Of this, the greatest leakage rates are estimated to have originated from gas transmission.

No natural gas is produced or processed in Minnesota. The transmissions lines connecting Minnesota consumers to gas-producing regions are long. The transmission pipelines delivering gas to Minnesota gas utilities originate in the southwest and western gas-producing regions.[86]

To estimate out-of-state CH_4 emissions, it is assumed that the estimates given in Table 42 constitute an adequate representation of leakage rates for gas produced and processed out-of-state but used in Minnesota. Given the many movements of gas through the transmission system, it is not possible to trace any one cubic foot of natural gas back to the natural gas well from which it was produced or the processing plant where it was treated.

In the United States, 0.76 percent of marketed production of natural gas is estimated to be emitted to the atmosphere as CH_4 as a result of gas production, processing, and transmission. An additional 0.1 percent of marketed production is estimated to leak to the atmosphere from distribution mains and service lines. For the purposes of this calculation, we assume that 90 percent of the transmission lines

Table 42. CH_4 Leakage from the U.S. Natural Gas System by Component

System Component	CH_4 Leakage (as a % of marketed production)
Production	0.3
Processing	< 0.05
Transmission	0.3
Storage	< 0.01
Engine Exhaust	0.1
Distribution	0.1
TOTAL	**0.86**

Source: U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*, EPA-430-R-93-003, (Washington, D.C.: 1993).

that bring natural gas to Minnesota gas utilities are located out-of-state. The consumption of natural gas in Minnesota in 1990, as reported in the *Natural Gas Annual* (1990)[86] and adjusted for in-state leakage, totaled 288,577 MMcf. If out-of-state leakage were equal to 0.73 percent of marketed production (which accounts for the ten percent of total transmission line mileage that is assumed to be located in-state), total out-of-state leakage from gas production, processing, and transmission would be 2,106.6 MMcf. At 22.66 tons of CH_4 per MMcf, this implies an emission from this source in 1990 of 47,736 tons of CH_4. Associated CO_2 emissions would then be 1,351 tons, using the same calculative procedure as given in Part II, Section V above.

As in Part II, Section V, in order to bound the uncertainty in estimated rates of leakage from the natural gas system, a range of 0.33 percent to three times the above estimate is assumed, leading to a range for possible emissions of 15,753 to 143,208 tons.

SECTION IX. Methane from Out-of-State Coal Mining

Methane is present in the seams of most or all coal deposits. It is formed during the process of coalification or coal formation. The amount of CH_4 that is formed within coal seams depends on coal rank. The amount that remains stored in coal deposits until disturbed is controlled by the pressure and temperature of the coal seam. Upon disturbances experienced during coal mining, this CH_4 is released to the atmosphere.[95]

In general, due to the depth of most coal that is mined underground, underground mining releases substantially more CH_4 to the atmosphere than does the surface mining of coal.[126]

Finally, a portion of the CH_4 that is released to the atmosphere from coal mining derives from coal processing and transportation. In coal processing, the crushing and drying of coal increases the surface area of the coal resource, allowing more CH_4 to desorb from the coal.[127]

About 24 percent of Minnesota's total energy use derives from coal combustion (see Figure 1 above). There are no coal deposits in Minnesota. Virtually all of the coal consumed in Minnesota for purposes of energy production is brought into the state from outside Minnesota. In 1990, 92.4 percent of 1990 coal consumption in Minnesota originated in the electrical generation/steam sector.[89]

Table 43 shows the sources of all coal combusted in the electrical generation/ steam sector in 1990 by state of origin, along with the U.S. Environmental Protection Agency-recommended CH_4 emission factors

Table 43. Receipts of Coal at Electric Power Plants in 1990 by State of Origin

State of Origin	Coal Received (in tons)	% Surface Mined	Recommended Emissions Factor (in cubic ft. of CH_4/ ton of coal mined)
Montana	9,309	100%	15 - 150
Wyoming	7,116	100%	15 - 150
Indiana	69	100%	15 - 150
Illinois	51	0%	160 - 480
Kentucky	8	7%	220 - 780
Pennsylvania	3	0%	220 - 780
West Virginia	2	33%	220 - 780
North Dakota	1	100%	15 - 150

Sources: U.S. Department of Energy, *Cost and Quality of Fuels for Electric Utility Plants, 1990*, DOE/EIA-0191(90), (Washington, D.C.: 1991).
U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-B-92-002, (Washington, D.C.: 1992).

for each type of coal. Nearly all of the coal consumed in the generation of electricity in 1990 in Minnesota came from western surface mines.

Based on the information given in Table 43, it is possible to estimate CH_4 coal mining and processing emissions associated with in-state coal use in the electricity generation. These are shown in Table 44. All told, 309.6 to 3,065.8 MMcf of methane are estimated to have been emitted through coal mining activities resulting in coal consumption by Minnesota's electrical utilities. At 22.66 tons of CH_4 per MMcf, this equals 7,016 to 69,471 tons of CH_4.

Table 44. Methane Emission from Out-of-State Mining of Coal Used in Minnesota Electric Power Plants

	Mining Emission (in MMcf)	Post-Mining Emission (in MMcf)	Total Emission (in MMcf)
Surface-Mined Coal	247.4 to 2,474.4	49.5 to 494.9	269.9 to 2,969.3
Underground-Mined Coal	10.8 to 33.7	1.9 to 62.8	12.7 to 96.5
TOTAL	**258.2 to 2,508.1**	**51.4 to 557.7**	**309.6 to 3,065.8**

Source: Calculated from Table 43.

SECTION X. Methane and Carbon Dioxide from Out-of-State Oil Production

In 1990, Minnesotans consumed about 3,503.3 million gallons of refined petroleum products, plus 162,086 tons of petroleum coke and 24,065 MMcf of refinery gas. All of this was manufactured from crude oil produced out-of-state.[128]

Methane is often emitted during oil production. The principal sources of CH_4 emission during oil production include: fugitive emissions from production fields; emissions from crude oil storage; and emissions from the venting of natural gas.[95] Venting emissions are the largest source of CH_4 leakage. In the United States, most natural gas that is found associated with oil deposits is separated from the crude oil and sold as natural gas. However, a small amount is flared, equal nationally to about 0.7 percent of the energy content of the crude oil produced.[129] During flaring, CO_2 is produced and emitted to the atmosphere. Flaring is relatively inefficient in converting natural gas to carbon dioxide. Domestic flaring is estimated to be between 80 and 94 percent efficient in converting natural gas to CO_2.[130,131] That part of natural gas that is uncombusted is vented to the atmosphere, mostly as CH_4.

Outside of the United States, the amount of natural gas flared during oil production as a percentage of the energy content of the oil produced varies substantially. Among our major suppliers, the amount of gas

flared as a percent of the energy content of the produced oil ranges from a low of 0.7 percent for Mexico to a high of 16.5 percent for Nigeria.[129]

Harper and Goodner (1989) report that, in 1984, about 90 percent of all crude oil delivered to local Minnesota refineries originated from oil wells located in either Canada or North Dakota.[132] However, the two refineries located in Minnesota did not submit quantitative information for 1990 on the purchased sources of crude oil by oil producing region or country. Representatives of the dominant refiner operating in Minnesota reported that most of its crude oil purchases were made on the spot market, and that it was not possible for any given year to determine the point of origin of the crude oil it refined.[81]

Additionally, not all of the refined petroleum products consumed within the borders of Minnesota originate from local refineries. Each year a substantial quantity of refined petroleum products enters Minnesota via petroleum product pipelines.[133] These refined petroleum products would have originated from refineries located out-of-state, and have involved oil production with inherently uncertain points of origination.

Thus in order to estimate out-of-state CO_2 and CH_4 emissions from flaring and venting, it is assumed that the percentage breakdown of crudes received from domestic and foreign sources at either Minnesota refineries or out-of-state refineries serving Minnesota was the same in 1990 as it was nationally. Thus 54 percent of crude oil refined in 1990 at refineries located in or serving Minnesota is assumed to have been domestically produced, and 46 percent is assumed to have been imported from foreign sources.[129]

Estimated CH_4 emissions for the United States from domestic oil production are shown for 1990 in Table 45. These total 128,689.2 to 535,989 tons. In 1990, Minnesota's share of domestic oil consumption was 1.4208 percent.[76] Assuming that Minnesota's percentage share of methane emissions from domestic oil production is the same as its percentage share of domestic oil consumption, out-of-state CH_4 emissions associated with domestically-produced oil consumed in Minnesota in 1990 would have equaled 1,828 to 7,615 tons.

At the national level, that part of total methane emissions from domestic oil production that resulted in 1990 from the venting of natural gas is estimated to have equaled 101,962.75 to 509,262.6 tons of CH_4 or, at 0.04413 MMcf per ton of CH_4, 4,499.6 to 22,473.8 MMcf of CH_4. In estimating this, the U.S. Environmental Protection Agency assumed a combustion efficiency during flaring of 80 to 96 percent, with methane leakage equal to 4 to 20 percent of the total volume of natural gas both flared and vented.[95] Minnesota's share of this would have been 63.9 to 319.3 MMcf of CH_4.

Table 45. Estimated 1990 U.S. CH_4 Emission from Domestic Oil Production

Source	Emission (in tons)
Production Fields	
Fugitive Emissions	24,581.3
Routine Emissions	50.7
Crude Oil Storage	2,094.4
Venting and Flaring	101,962.8 to 509,262.6
TOTAL	**128,689.2 to 535,989.0**

Source: U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*, EPA-430-R-93-003, (Washington, D.C.: 1993).

Calculating backward from this emissions estimate, the total amount of natural gas actually flared during the domestic production of crude oil consumed in Minnesota would have equaled 1,454.6 to 1,711.1 MMcf, assuming a CH_4 content for vented and flared natural gas of 90 percent. Thus, at 1,030 MMBTU per MMcf and 33.54 lbs. of carbon per MMBTU, Minnesota's share of CO_2 emissions from domestic flaring in 1990 would have equaled 92,066.7 to 108,301.4 tons of CO_2.

Estimated out-of-state emissions of CH_4 and CO_2 from the production of foreign oil actually consumed in Minnesota are shown in Table 46 for 1990. Methane emissions from production fields and crude oil storage were set proportional to emissions from domestic production. CH_4 emissions from marine vessels were taken from the U.S. Environmental Protection Agency's national methane inventory and were set proportional to Minnesota's share of U.S. oil consumption.[95]

Emissions from venting and flaring were estimated separately based on the points of origin of U.S. imported crude oil and reported rates of flaring for each oil exporter. These are shown in Table 47. The total amount of gas flared in the production of imported foreign oil in 1990 equaled roughly 4.25 percent of the total energy content of all imports.

Table 46. Estimated Emissions from Out-of-State Oil Production

	Emission (in tons)	
	CH_4	CO_2
Domestically-Produced Oil	1,828 to 7,615	92,067 to 108,301[a,b]
Foreign Oil		
Production Fields		
Fugitive Emissions	294	
Maintenance	1	
Crude Oil Storage	25	
Marine Vessels	96	
Venting and Flaring	8,117 to 40,586	503,841 to 604,611
TOTAL	**10,361 to 48,617**	**595,908 to 712,912**

Source: See text.

(a) The amount of natural gas flared would be:

[63.9 MMcf CH_4/(0.04 • 0.9)] - 63.9 MMcf = 1,711.1 MMcf and

[319.3 MMcf CH_4/(0.2 • 0.9)] - 319.3 MMcf = 1,454.6 MMcf

where 0.04 and 0.2 are the percentages of CH_4 vented to the atmosphere and 0.9 is the CH_4 content of the gas by volume.

(b) The amount of CO_2 produced during flaring would equal: amount of gas flared (in MMcf) • 1030 MMBTU/MMcf • 33.54 lb C/MMBTU •3.664279 lb CO_2/lb C • 0.0005 tons per lb.

In 1990, U.S. oil imports totaled 2,926,395 thousand barrels of crude or 122,908,509 thousand gallons.[129] At 1.4208 percent of U.S. oil consumption, Minnesota's share of imported oil in 1990 would have been 1,746,284 thousand gallons with a total energy content of 241.2 trillion BTUs. At 4.25 percent, 10,249,006.3 MMBTUs of natural gas would have been flared and vented, or some 9,950.5 MMcf of natural gas, again assuming 1,030 MMBTU per MMcf. At combustion efficiencies of 80 to 96 percent, 398 to 1,990 MMcf of natural gas would have been vented, of which, assuming that 90 percent is methane, 358 to 1,791 MMcf would have been CH_4. At 22.66 tons of CH_4 per MMcf, this would equal 8,117 to 40,586 tons of CH_4.

Table 47. 1990 U.S. Oil Imports by Exporting Nation and Rates of Flaring/Venting by Exporter

	% of US Imports	Energy Content of Gas Vented & Flared as a % of Energy Content of Oil Production of Each Exporter
Saudi Arabia	20.27	0.9
West Africa	14.66	16.5
Mexico	11.69	0.7
Venezuela	11.28	2
Canada	10.91	2.1
Iraq	8.72	Unavailable
Indonesia/Malaysia	4.78	5.2
United Kingdom	2.63	2.1
Other Middle East	2.38	Unavailable
Norway	1.61	1.4
North Africa	1.51	8.1
Trinidad	1.39	37.2
Ecuador	0.64	Unavailable

Source: U.S. Department of Energy, *International Energy Annual 1990*, DOE/EIA-0219(90), (Washington, D.C.: 1992).

Extending this calculation, the amount of natural gas flared during the production of foreign oil that was consumed in 1990 in Minnesota would have been an estimated 7,960.4 to 9,552.5 MMcf (e.g., 80 to 94 percent of 9,950.5 MMcf of natural gas both vented and flared). At 1,030 MMBTU per MMcf, this would have equaled 8,199,212 to 9,839,075 MMBTU, which at 33.54 lbs. of carbon per MMBTU of flare gas would have yielded 137,500.8 to 165,001.3 tons of carbon or 503,841.2 to 604,610.7 tons of CO_2.

Total estimated emissions from out-of-state oil production are shown in Table 46. It is estimated that 10,361 to 48,617 tons of methane and 595,908 to 712,912 tons of CO_2 were emitted in 1990 as a result of oil production activities associated with the consumption of petroleum products in Minnesota.

SECTION XI. Carbon Dioxide from Finished Fuels Production, Processing and Transportation

Substantial amounts of energy are required to produce finished fossil fuels. Energy is required to produce, refine or process, and to transport oil and natural gas. Substantial energy inputs are also required for the mining, processing and transport of coal. With the exception of oil refined at two refineries located in Minnesota and transported in in-state gas and oil pipelines, the production, processing and transportation of all fossil fuels used in Minnesota are located out-of-state.

Table 48 shows various published estimates of energy inputs to finished fossil fuels in the United States. These estimates include only those fuels used to actually produce finished fossil fuels, and ignore the energy embedded in capital structures or in labor and training. They are given as a percent of the energy content of the finished fuels.

Table 49 shows the primary energy inputs to finished fuels that are assumed in this study. Again, these are given as a percent of the energy content of the finished fuels.

Table 50 shows fossil fuel use in Minnesota in 1990 by fuel, and the calculated amount of energy consumed in the out-of-state production and transportation of those fuels based on the estimates given in Tables 48 and 49. For natural gas, it is assumed that natural gas is the only fuel used in the production, processing and transportation of the finished fuel. In the case of refined petroleum products, to avoid any double counting of refinery emissions already treated in Part II, Section II above, energy inputs into oil production and transportation alone are considered.[128] It is assumed that petroleum is the only fuel used in these activities. In the case of coal, subbituminous coal with an energy content of 17 MMBTU per ton is assumed to be the fuel used in production and processing, and diesel fuel oil is assumed as the transportation fuel.

Table 51 shows CO_2 emissions associated with out-of -state energy inputs into fuel production and transport. Roughly 5.14 million tons of CO_2 are estimated to have been emitted during out-of-state fuels

Table 48. Primary Energy Inputs for the Production and Delivery of Fuels in The United States as a Percentage of the Energy Content of the Finished Fuels

Finished Fuel	Energy Input (as % of energy in finished fuel)	Source[a]
Coal		
Extraction & Processing	1 to 2	Marland (1983), Cleveland, *et al.* (1984), Calif. Energy Commission (CEC) (1990)
Transportation	2 to 3	Cleveland, *et al.* (1984), Grubb (1989), CEC (1990), American Gas Assn. (AGA) (1992)
Natural Gas		
Production & Processing	7	US EPA (1993)
Transmission	4	US EPA (1993)
Total	9 to 11	Grubb (1989), CEC (1990), AGA (1992), US EPA (1993), Cassler (1989), Sperling and DeLuchi (1989)
Petroleum		
Refining	7 to 10	IP Petroleum (1988), Cassler (1989), OTA (1993)
Production & Processing	10 to 14	Grubb (1989), CEC (1990)
Transportation	1 to 3	CEC (1990)
Total	14 to 17	Sperling & DeLuchi (1989), CEC (1990)
As Delivered to the Refinery	6	DeLuchi (1987)

(a) See Endnotes 56,59,65,95, and 134 through 140.

Table 49. Primary Energy Inputs to Finished Fossil Fuels Assumed in this Study

Fuel	Energy Input as a % of the Energy Content of the Finished Fuels
Coal	
Extraction & Processing	1.5
Transportation	2.5
Natural Gas	10.0
Petroleum	
As Delivered to the Refinery	6.0

Source: Table 48.

Table 50. Out-of-State Energy Inputs to Finished Fuels for 1990 Fossil Fuel Use in Minnesota

Fuel	Energy Content of Fuels Consumed in MN (in MMBTU)	Type of Input	Energy Input to Finished Fuels (in MMBTU)
Coal	318,308,195	Extraction & Processing	4,774,623
		Transportation	7,957,405
Natural Gas	290,308,462	Extraction, Processing & Transportation	29,030,846
Petroleum	478,879,887	Extraction, Transportation[a]	28,732,793

Sources: Appendix C and Table 49.

(a) As received at the refinery.

production, processing and transport. Inputs to refined petroleum products account for 45 percent of this, and inputs to natural gas and coal account for 33 and 22 percent, respectively.

Table 51. Estimated CO_2 Production from Energy Inputs to Finished Fuels Used in Minnesota

Fuel	Fuel Assumed to be Used	Emission (in tons CO_2)[a]
Coal		
Extraction & Processing	Coal	510,958
Transportation	Distillate fuel oil	637,975
Natural Gas		
Extraction, Processing & Transportation	Natural gas	1,685,008
Petroleum		
Extraction, Transportation	Distillate fuel	2,303,530
TOTAL		**5,137,471**

Source: Calculated from Table 50.

(a) Rounded to the nearest ton.

SECTION XII. Carbon Dioxide from Net Electricity Imports

Electricity generation in the United States is heavily dependent on coal as an energy source. In 1990, 46,627 million kilowatt hours of electricity were consumed by individuals and businesses living or located in Minnesota.[82] Most of the electricity that was consumed in Minnesota in 1990 was produced in-state. Net imports of electricity amounted to roughly 4 percent of the electricity consumed in 1990 in Minnesota, or 1,971 million kilowatt hours.[82]

The particular fuel amounts and types used to generate imported electricity are difficult to determine. A large amount of electricity is exchanged back and forth across the borders of Minnesota and its neighbors. In order to estimate CO_2 emissions from imports, it would be necessary to track each cross-border exchange back to the mode of generation employed and fuel used.[141]

In this inventory in absence of specific information, we treat only net imports. We conservatively assume that one-half of net electricity imports in 1990 were generated using subbituminous coal as a boiler fuel, and that the rest derived from nonfossil fuel sources. More than one-half of net imports are unlikely to have been generated using nonfossil fuel sources of power like nuclear power or hydroelectric power.

The typical efficiency of a conventional coal-fired power plant is 34 percent.[142] Additional energy derived from coal combustion is lost in transmission. If one-half of all net electricity imports were generated using coal, the total amount of energy consumed in the generation of the fossil fuel component of net electricity imports would have been 985.6 megawatt hours, with associated CO_2 emissions of 1,107,608 tons of CO_2.

It is not known whether these estimates reliably represent out-of-state emissions associated with electricity imports. The assumptions that were employed appear to be quite conservative, but given the lack of a really adequate basis for determining emissions, at best the estimates given above are only suggestive of the likely magnitude of emissions from this source.

SECTION XIII. Emissions Summary for Out-of-State Emissions Associated with Energy Production

Substantial emissions of greenhouse gases result from the out-of-state production, processing, and transportation of fuels and electricity consumed in Minnesota. The particular sources treated in this inventory included: energy inputs to finished fossil fuels; electricity imports; CO_2 from natural gas flaring in oil production; CH_4 and CO_2 leakage from natural gas production, processing, and transmission; and CH_4 leakage from coal mining.

Total estimated emissions from these activities are shown in Table 52 for 1990. The largest single out-of-state emission of CO_2 is estimated to have resulted from the production and processing of finished fossil fuels. Leakage from natural gas production, processing and transmission is estimated to have constituted the single largest source of CH_4 emission to the atmosphere from out-of-state activities. In total, 6,842,338 to 6,959,342 tons of CO_2 and 65,113 to 165,824 tons of CH_4 are estimated to have been

emitted to the atmosphere in 1990 as a result of out-of-state energy production activities associated with in-state energy consumption.

Out-of-state emissions of CO_2 associated with in-state fossil fuel uses are estimated in 1990 to have totaled 6,842,338 to 6,959,342 tons, and those of CH_4 to have totaled 65,113 to 165,824 tons.

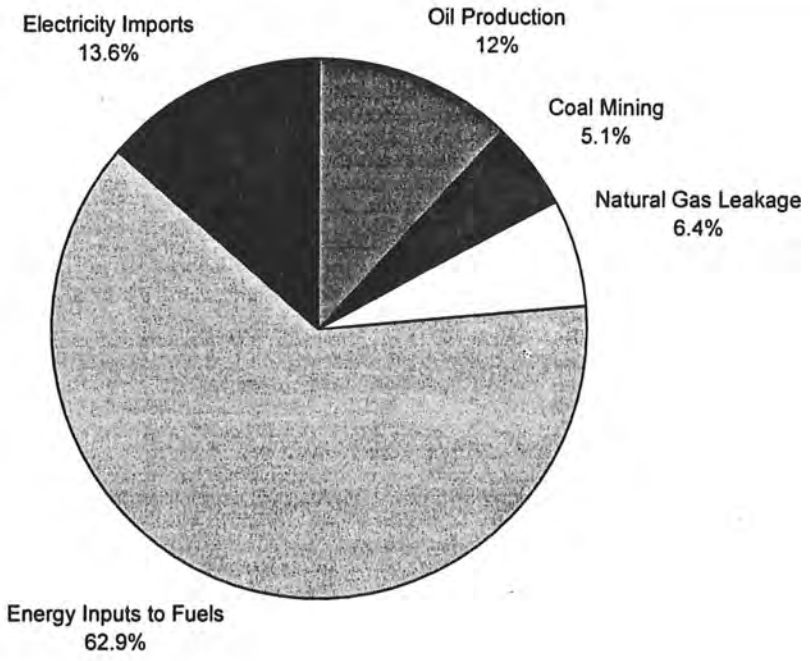
Finally, CO_2-equivalent emissions from these activities are estimated in 1990 to have totaled 7.6 to 8.8 million tons. Emissions from the out-of-state production of finished fossil fuels dominate this total, comprising between 58 and 68 percent of all CO_2-equivalent emissions (see Figure 10).

Table 52. Estimated Out-of-State Emission Associated with In-State Fossil Fuel Usage

Gas & Source	Emission (in tons)[a]	CO_2-Equivalent Emission (in tons)
CH_4		
Oil Production	10,361 to 48,617	113,971 to 534,787
Coal Mining	7,016 to 69,471	77,176 to 764,181
Natural Gas Production, Processing & Transmission	47,736	525,096
Subtotal	65,113 to 165,824	716,243 to 1,824,064
CO_2		
Oil Production	595,908 to 712,912	595,908 to 712,912
Energy Inputs to Finished Fuels	5,137,471	5,137,471
Natural Gas Production, Processing & Transmission	1,351	1,351
Electricity imports	1,107,608	1,107,608
Subtotal	6,842,338 to 6,959,342	6,842,338 to 6,959,342
TOTAL		**7,558,581 to 8,783,406**

Sources: Tables 44, 46, and 51 and text.
(a) Rounded to the nearest ton.

Figure 10. Out-of-State CO_2-Equivalent Emissions Associated with In-State Fossil Fuel Usage[a,b]



(a) Of a total of 8.2 million tons (average of the range given in Table 52).
(b) Using median emissions values for oil production and coal mining.

PART IV. EMISSIONS FROM INDUSTRIAL AND DOMESTIC PROCESSES

In addition to emissions from fuel uses, industrial concerns and households also directly release greenhouse gases to the atmosphere. Two classes of emissions are discussed in this section: process emissions resulting from the use or production of lime or limestone and process emissions that involve the emission of ozone-depleting compounds.

The principal ozone-depleting compounds of concern are CFC-11. CFC-12, CFC-113, CFC-114, and CFC-115, along with their substitutes. These are all greenhouse gases that absorb powerfully in infrared wavelengths. Through these direct radiative effects, they contribute to surface warming. However, present scientific understanding suggests that they may also contribute to a countervailing 'surface 'cooling' as a result of their ozone-depleting effects.

At present, it is not possible to estimate the net radiative effects of the emission of ozone-depleting compounds to the atmosphere. In this inventory we assume that they range from 0 to 100 percent of the direct radiative effects of these compounds without the countervailing effects of ozone depletion. Using this range of possible effect, in this section we estimate in-state CO_2-equivalent emissions from industrial and domestic processes to be between 2,418 and 27,344,788 tons, and in-state plus out-of-state CO_2-equivalent emissions to range from 938,000 to 28,280,370 tons (see Table 53).

Table 53. Estimated 1990 CO_2-Equivalent Process Emissions from Minnesota

Source of Emission	Emission (in tons) [a]
In-State Sources	2,418 to 27,344,788
Out-of-State Sources	935,582
Total	**938,000 to 28,280,370**

(a) Rounded to the nearest ton.
Source: Table 60 below.

Few methodologies for evaluating process emissions are available. Thus while a large number of potential emissions sources are identified in this part of this study, few emissions are actually treated. As methodologies become available, more and better developed estimates should be appended to those given here.

SECTION XIV. Industrial Process Emissions

The principal industrial sectors that directly emit greenhouse gases or their precursors to the atmosphere include: petrochemicals, fertilizers, coke manufacture, lime processing, and computer and electronics components manufacture.[51,54] Virtually all of the petrochemicals, coke, and lime, and most of the fertilizers, consumed within Minnesota are manufactured out-of-state. Emissions from the manufacture of electronics and computer components are treated in the following section on ozone-depleting compounds. Three possible minor sources of industrial process CO_2 emissions were identified in Minnesota: steel manufacture, CO_2 manufacture, and fertilizer manufacture.

Steel Manufacture

Limestone or calcium carbonate is used in steel manufacture as a flux to remove impurities from material streams.[143] CO_2 is formed as a result of the process. It results from the oxidation of carbon long sequestered in buried limestone.

There is one steel mill located in Minnesota. North Star Steel, the proprietor of the steel mill, reports the use in 1990 of 5,500 tons of dolomite or limestone.[144] Following the calculative procedure given in the U.S. Department of Energy's greenhouse gas inventory, *Emissions of Greenhouse Gases in the United States, 1985-1990* (1993), for processed and raw limestone used in iron smelting and steel making, 0.12 tons of carbon are assumed to be emitted for each ton of limestone used.[51] Thus for steel making within Minnesota, total carbon emissions in 1990 are estimated to have equaled 660 tons of carbon or 2,418 tons of carbon dioxide.

Statewide emissions of CO_2 from steel manufacture are estimated in 1990 to have totaled 2,418 tons.

CO_2 Manufacture

One CO_2 manufacturer is reported in Minnesota by SRI International 's *Directory of the Chemical Producers in the United States*, Koch Industries Inc.[145] According to the U.S. Department of Energy, nationally most manufactured CO_2 that is not dedicated to enhanced oil recovery is dedicated to products and processes which do not lead to the long-term sequestration of CO_2.[51] Ultimately it will be released to the atmosphere. However, no emission can be assumed on time-scales as short as one year for industrial CO_2 actually produced in 1990.

Koch Industries reports the Minnesota manufacture of 65,700 tons of CO_2 in 1990.[81] In absence of specific information as to its use, following the U.S. Department of Energy we assume that upon use one-third of this is sequestered for long periods and that two-thirds is committed to uses leading to future emissions from present day activities, or 43,800 tons.[51]

Fertilizer Manufacture

Nitrogen fertilizers are manufactured using natural gas as a feedstock. At high temperature, natural gas in the presence of a nickel catalyst is transformed to a process gas composed of hydrogen and carbon monoxide, which is reacted with steam to form hydrogen and CO_2. Nitrogen is then added to the hydrogen and the mixture is passed over another catalyst at high temperature to produce ammonia.[146] Byproduct CO_2 is either vented to the atmosphere or is captured and is committed to industrial processes or products that in general do not lead to long-term sequestration.

According to the Fertilizer Institute, 22 to 23 Mcf of natural gas are consumed for every ton of nitrogen fertilizer that is produced.[146] The *Oil and Gas Journal Data Book* reports an annual statewide production capacity for anhydrous ammonia of some 27,000 metric tons.[147] Based on a statewide production capacity of that size, 670 MMcf of natural gas would be consumed annually during the manufacture of anhydrous ammonia. At 1,000 MMBTU per MMcf and 32 lbs. of carbon per MMBTU, CO_2 production from fertilizer manufacture in the state annually would amount to some 39,260 tons of CO_2. Following the Department of Energy, two-thirds of this, or 26,174 tons, would be committed to uses that would not lead to long-term sequestration.[51]

Information was not requested from Minnesota fertilizer manufacturers regarding the fate of CO_2 produced during the manufacture of ammonia. In lieu of such information, we assume that the release of

most of the 26,174 tons of CO_2 estimated above takes place over a number of years. Thus, as in the case of CO_2 manufacture, this represents not a 1990 emission but a commitment to future emissions from present-day activities that, at least conceptually speaking, are only marginally different from an actual emission resulting in 1990 from activities taking place in 1990. It is not included in the inventory totals, but indicates a future emissions commitment from this activity.

Nationally, CO_2 emissions from nitrogen fertilizer manufacture are estimated to account for about 0.8 percent of all U.S. CO_2 emissions from fossil fuel sources.[148]

Other Probable Sources of Direct In-State Emission

In addition to carbon dioxide emissions from steel, fertilizer and CO_2 manufacture, other possible sources of direct process emissions of greenhouse gases have been identified. A listing for Minnesota is given in Table 54 for all gases except nonmethane VOCs, which are shown in Table 55. Methodologies and

Table 54. Other Mining, Manufacturing and Processing Activities in Minnesota Resulting in the Direct Noncombustion Release of Greenhouse Gases or Their Precursors

Activity	Gas	Number of Plants or Quarries
Acetylene Manufacture	CH_4, CO_2	2
Ammonia Manufacture	CH_4, NO_x,NMVOCs	1
Iron and Steel Casting (Foundries)	CO_2, CH_4	22
Lead Smelting	CO_2, NMVOCs	1
Limestone Production	CO_2	25
Leather Tanning	CO_2	4
Glass Manufacturing	CO_2	1
Electricity Transmission	SF_6	Unknown
Nitric Acid Production	N_2O	1
Peat Mining	CO_2, CH_4	9
Petroleum Storage and Transportation	CH_4, NMVOCs	Unknown
Steel Production	CH_4, CO, NO_x	1
Food Industry Waste Water	CH_4	Unknown

Source: See End notes 54,95,145,147,149-158.

Table 55. Processes Resulting in Noncombustion Release of NMVOCs in Minnesota

Manufacture of Electrical Components and Printed Circuit Boards
Metal Degreasing
Dry Cleaning
Other Solvent Use
Iron Ore Processing
Asphalt Paving and Roofing
Chipboard Production
Paper Pulp Manufacture
Paint Applications
Plastics/Rubber/Polymers Processing
Ink Processing
Printing
Wine/Spirits/Beer Production.

Source: U.S. Environmental Protection Agency,*State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA 230-B-92-002, (Washington, D.C.: 1992)

emission factors have yet to be developed for estimating the production and direct release of greenhouse gases from these industrial activities.

Out-of-State Emissions

Cement and lime manufacture constitute the principal sources of out-of-state CO_2 process emissions associated with in-state materials consumption in Minnesota.

The consumption of cement in Minnesota in 1990 totaled an estimated 1,675,000 tons.[159] All of this was manufactured out-of-state. Cement is manufactured using limestone, which is calcined or heated during the manufacturing process to form calcium oxide and CO_2. The lime eventually combines with silicates to form dicalcium or tricalcium silicates, a major component of powered cement or clinker.[160] Byproduct CO_2 is driven off and released to the atmosphere.

Following the recommended U.S. Environmental Protection Agency methodology, 0.4985 tons of CO_2 are assumed to be produced and emitted to the atmosphere for the manufacture of every one ton of cement.[54]

Using this emission factor, out-of-state emissions associated with in-state cement consumption in 1990 are estimated to have been 834,988 tons of CO_2.

In addition to its use in cement manufacture, lime or calcium oxide is also produced for a wide variety of other uses, including paper pulp manufacture, sugar refining, glass manufacture, water purification, sewage treatment, tanning, and nonferrous metals refining.

Four facilities in Minnesota calcine limestone for internal uses, but report no net emission of CO_2 from this activity. A closed system is reported to be in operation in which the CO_2 that is driven off of the heated limestone is captured, used in sugar refining activities, and then is recombined with calcium oxide to form various industrial calcium carbonate byproducts of varying degrees of purity.[143,161]

In 1990 in-state uses of lime totaled an estimated 262,000 tons.[158] Of this, 133,855 tons were used in activities in sugar refining that result in no net emission of CO_2 to the atmosphere.[161] The remaining 128,145 tons of lime consumed in the state were purchased from out-of-state manufacturers. An estimated 0.785 tons of CO_2 are emitted for each ton of lime that is produced.[111] Thus 100,594 tons of CO_2 would have been emitted to the atmosphere in 1990 as a result of the out-of-state manufacture of lime consumed in Minnesota.

128,145 tons of lime • 0.785 tons of CO_2/ton of lime = 100,594 tons of CO_2

Totaling CO_2 emissions from the out-of-state manufacture of cement and lime, we estimate that in 1990 935,582 tons of CO_2 would have been emitted to the atmosphere as a result of the out-of-state production of materials consumed within the state of Minnesota. This constitutes 99.7 percent of total in-state plus out-of-state industrial process emissions of CO_2 (see Table 56). Other large potential emissions of CO_2 that might result from in-state activities include those from fertilizer, coke, and petrochemicals manufacture.

Out-of-state CO_2 emissions associated with the manufacture of cement and lime that is consumed in Minnesota are estimated in 1990 to have totaled 935,582 tons.

Table 56. Industrial Process CO_2 Emissions from Minnesota

Source of Emission	Emission (in tons) [a]
In-State	
Steel Manufacture	2,418
Out-of-State	
Cement Manufacture	834,988
Lime Manufacture	100,594
Subtotal	**935,582**
TOTAL	**938,000**

(a) Rounded to the nearest ton.

SECTION XV. Halogenated Compounds

Industrial and domestic uses of halogenated compounds are large in Minnesota. These are compounds containing chlorine, fluorine, or bromine, and that are mostly of an anthropogenic origin. With the exception of a few compounds (e.g., methyl bromide), these compounds do not occur in nature.

The principal halogenated compounds of interest are the so-called 'hard' chlorofluorocarbons (CFCs) (CFC-11, CFC-12, CFC-113, CFC-114, CFC-115), Halon-1301, Halon 1211, various 'soft' CFCs or hydrofluorochlorocarbons (HCFCs) like HCFC-22 and HCFC-142b, and various other chlorinated substances like methyl chloroform, chloroform, carbon tetrachloride, methylene chloride, and methyl chloride.[2]

The hard CFCs are linked by a few shared characteristics: extreme chemical stability, low toxicity, low thermal conductivities, and good solvent cleaning capabilities. These compounds tend to be inert in the troposphere. The principal uses of CFC-11 and CFC-12 are in refrigeration and cooling and in the

manufacture of plastic foams. CFC-113 is used principally in solvent applications, especially in electronics manufacture. CFC-115 is used principally in cooling and refrigeration, while CFC-114 is used in the manufacture of foams and in chiller applications.[162]

Halons are used almost exclusively as fire extinguishing agents. These compounds are likewise quite chemically inert in the environment.

HCFC-22 is used principally in refrigeration, air conditioning, and in the manufacture of plastic insulating foams. Of the remaining halogenated compounds, methyl chloroform is the most important. It is principally used in solvent applications.

The chlorofluorocarbons and the HCFCs share one additional quality -- all are extremely powerful infrared-absorbers, with infrared absorption bands that do not overlap with the absorption bands of either CO_2 or water vapor, the two principal greenhouse gases in the earth's atmosphere.[17] As a consequence, on a per molecule basis, these compounds have infrared-absorption capacities roughly 21,000 times that of carbon dioxide.[2]

The hard CFCs and halons in particular have very long atmospheric lifetimes, typically ranging from 50 to 200 years.[2] They are removed from the atmosphere through photodissociation in the stratosphere in the presence of ultraviolet radiation. The decay products include chlorine, which in a free state recombines with ozone to form various chlorine compounds and diatomic oxygen. This acts to depress ozone concentrations in the stratosphere, which contains roughly 90 percent of all column ozone in the atmosphere.

The HCFCs or hydrofluorocarbons and the other remaining halogenated compounds are more chemically reactive. Much of the surface emission of these compounds is removed from the atmosphere through chemical reactions involving the OH radical. Relatively little of the chlorine that these compounds contain is ever released in a free state to the stratosphere.[163]

It is expected that, as a result of the use and release of these chemicals to the atmosphere, the protective ozone layer of the atmosphere will be substantially depleted in the coming decades. A 5-10 percent depletion has already been observed during some seasons in the middle latitudes.[164,165]

The response of global surface temperature to the ozone-depleting effects of the CFCs is highly uncertain. Ozone is an infrared-absorbing gas. The depletion of stratospheric ozone acts to reduce the opacity of the atmosphere to escaping long-wave radiation. This acts to cool the atmosphere and, to some

unknown degree, to offset the direct radiative heating effects of emitted CFCs.[28-30] The degree to which these direct radiative effects are offset depends critically on the altitude profile of ozone depletion. The surface cooling effects of ozone depletion tend to increase as ozone depletion moves to progressively lower altitudes.

Scientific understanding of the climatic response to ozone depletion is still evolving. Some analysts have suggested that it is now beyond the limits of scientific understanding to determine what the radiative effects of ozone depletion might be.[51] At present it seems possible that the net radiative effects of the CFCs, including the effects of ozone depletion, could range from zero to an amount equal to one-fifth of the total present-day radiative forcing resulting from emissions to the atmosphere of CO_2.[166]

Estimated 1990 emissions of the CFCs and other partially or fully halogenated substances are shown in Table 57. The emission estimates for CFC-113, methyl chloroform (1,1,1-trichloroethane) and carbon tetrachloride are taken from Minnesota Department of Public Safety, *Toxic Release Inventory* (1991).[167] Emissions of the remaining substances are based on U.S. *per capita* use rates for these compounds and 1990 Minnesota state population.[168] CO_2-equivalent emissions are also shown in Table 57, calculated from the Global Warming Potentials given in Table 3 of this study. These represent the upper end of the range of possible net radiative effects resulting from the emissions of CFCs to the atmosphere. The lower end is assumed to be near or at zero.

Thus, in total, emissions in 1990 of halogenated compounds from Minnesota are estimated to have been equal to 8,511tons, with a CO_2-equivalent effect of zero to 27,342,370 tons.

Statewide emissions of ozone-depleting compounds are estimated in 1990 to have totaled 8,511.4 tons, with a global warming potential of an estimated 0 to 27,342,370 CO_2-equivalent tons.

Due to the projected ozone-depleting effects of the CFCs, the Montreal Protocol on Substances that Deplete the Ozone Layer and the subsequent London and Copenhagen Agreements have committed the United States to a phase-out of the manufacture and use of fully halogenated CFCs by the end of 1995. In the Clean Air Act of 1990, a phase-out is required by 1995.[37]

Table 57. Estimated 1990 Minnesota Emission from the Use of Infrared-Absorbing Halogenated Substances

Compound	1990 Emission (in tons)[a]	CO_2-Equivalent Emission (in tons)
CFC-11	1,079.1	3,668,940
CFC-12	2,185.3	15,515,630
CFC-113	940.0	4,230,000
CFC-114	91.1	637,700
CFC-115	60.1	420,700
Chloroform	100.0	NA
Methylene chloride	746.0	NA
Carbon tetrachloride	2.9	3,770
Methylchloroform	1,571.0	157,100
HCFC-22	1,584.8	2,535,680
HCFC-141b	36.8	NA
HCFC-124	52.3	NA
HFC-134a	9.7	11,640
Halon-1211	19.4	NA
Halon-1301	32.9	161,210
TOTAL	**8,511.4**	**27,342,370**

(a) Except where otherwise noted, based on U.S. per capita usage and 1990 Minnesota population totals.
(b) Reported emissions from Minnesota Department of Public Safety, Emergency Response Commission, *Toxic Chemical Release Inventory,* (St. Paul, MN: 1991).
(c) No global warming potential is available to calculate this.

Given the impending 1995 phase-out of the use of the hard or fully halogenated CFCs, in the near future emissions resulting from the use of substitute chemicals will become an important component of Minnesota greenhouse gas emissions. In the short-term, the principal chemical substitutes for the hard CFCs like CFC-11 or CFC-113 are likely to be: HFC-134a, HCFC-142b, HCFC-123, HCFC-141b, HCFC-124, HFC-125 and HFC-143a.[54] These compounds either contain no chlorine, as is true for the hydrofluorocarbon (HFC) compounds, or are quite reactive in the troposphere, and thus have ozone depletion potentials that are from 0 to 5 percent of that of the fully halogenated or hard CFCs. With no or

relatively minor ozone-depleting capacities, the net radiative effects of these substitutes are likely to be strongly positive.[163]

Global Warming Potentials are shown in Table 58 for most of the principal short-term substitutes for CFC usage as a percent of the net surface warming that might be expected from an emission of CFC-11. In general, the integrated warming of these compounds over their atmospheric lifetimes ranges from 5 to 30 percent of that of CFC-11. Thus, were these compounds to replace the use of fully halogenated CFCs on a one-for-one basis, the CO_2-equivalent emission of substitutes in the middle 1990s would be on the order of 5 to 30 percent of estimated 1990 CO_2-equivalent emission of the fully halogenated CFCs, or on the order of 0.7 to 4 million tons. Other longer term potential substitute chemicals are shown in Table 59. The radiative absorption capacities of these have not yet been estimated.

Finally, in 1986 an estimated 3,645 tons of fully halogenated or hard CFCs were emitted to the atmosphere by individuals and businesses in Minnesota.[169] These are in unadjusted physical units. From Table 57 above, in 1990, 4,408 tons of fully halogenated CFCs are estimated to have emitted to the

Table 58. Global Warming Potentials (GWPs) of Short-term Chemical Substitutes for Hard CFCs Normalized to CFC-11

Compound	GWP[(a)(b)]
HCFC-123	0.019
HCFC-124	0.096
HCFC-141b	0.092
HCFC-142b	0.365
HFC-125	0.58
HFC-134a	0.27
HFC-143a	0.74
HFC-152a	0.030
Methyl chloroform[(c)]	0.023

Source: D. Fisher, *et al.*, "Model Calculations of the Relative Effects of CFCs and Their Replacements on Global Warming," *Nature*, 344, (1990): 513-516.
(a) Average of values given in Fisher, *et al.* (1990).
(b) CFC = 1.0
(c) Replacement for CFC-113 in solvent applications.

atmosphere by individuals and businesses living or located in Minnesota. A comparison of these values suggests a moderate increase in statewide consumption between 1986 and 1990, but given the coarseness of the estimation procedure, this cannot be concluded with certainty.

Table 59. Other Long-Term CFC Substitutes Under Consideration

HCFC-236ea	HCFC-133a
HCFC-236cb	HCFC-133b
HCFC-236fa	HCFC-131
HFCF-225cb	HCFC-134
HCFC-225ca	HCFC-245ca

Various hydrofluoroethers

Sources: D. Cooper, *et al.*, "Tropospheric Lifetimes of Potential CFC Replacements'" *Atmospheric Environment*, 26A, (1992): 1,331-1,334.
D. Cooper, *et al.*, "Potential CFC Replacements: Lifetimes of C_3 Hydrofluorocarbons and Hydrofluoroethers," *Atmospheric Environment*, 27A(1993): 117-119.
N. Garland, *et al.*, "Potential CFC Replacement: OH Reaction Rate Constants Between 250 and 315k and Infrared Absorption Spectra," *Journal of Geophysical Research*, 98(d) (1993): 23,107-23,111.
A. Newman, "Heading for Zero: Alternatives to CFCs and Halons," *Environmental Science and Technology*, 26 (1992): 2,347-92,349.

SECTION XVI. Emissions Summary

Total industrial and domestic process emissions from Minnesota are shown in Table 60 for 1990. In-state emissions of CO_2 are estimated to have totaled 2,418 tons, while in-state emissions of ozone-depleting compounds are estimated in 1990 to have amounted to 8,511 tons. Out-of-state emissions associated with the in-state consumption of cement and lime are substantially larger, totaling an estimated 935,582 tons of CO_2.

Estimated 1990 CO_2-equivalent emissions in-state range from 2,418 to 27,344,788 tons. Much of the uncertainty results from uncertainties over the response of the global climate to stratospheric ozone depletion. At this point, there is no way of effectively estimating where in this range the actual value might fall.

Table 60. Summary of 1990 Process Emissions from Minnesota

Source of Emission	Gas	Emission (in Tons) [a]	CO_2-Equivalent Emission (in Tons)
In-state:			
Steel Manufacture	CO_2	2,418	2,418
Ozone Depleting Compounds	ODCs	8,511	0 to 27,342,370
Subtotal			2,418 to 27,344,788
Out-of-state:			
Cement Manufacture	CO_2	834,988	834,988
Lime Manufacture	CO_2	100,594	100,594
Subtotal			935,582
TOTAL[b]			**938,000 to 28,280,370**

(a) Rounded to the nearest tenth.
(b) An additional future emission of approximately 70,000 tons CO_2 may also result from 1990 industrial production of CO_2 and anhydrous ammonia.

PART V. EMISSIONS FROM LANDFILL LEAKAGE AND WASTE INCINERATION

In the state of Minnesota, roughly 3.6 million tons of solid waste are landfilled, incinerated, or composted each year. The amount of solid waste generated in the state and its disposition are shown in Table 61. Greenhouse gas emissions from that part of municipal solid waste (MSW) that was combusted to produce commercially or industrially usable energy were treated above in Part II, Section II of this inventory. In this section, emissions from waste placed in sanitary landfills are treated, along with emissions arising from the on-site incineration of commercially- and industrially-produced wastes.

Table 61. Disposition of Minnesota's Wastes, 1990

	Tons of Waste
Mass Burn of MSW	532,832
Combustion of RDF	580,159
Medical/Pathological On-Site Incineration	17,356 to 44,785
Other On-Site Incineration	27,120 to 80,460
MSW Landfilled	1,823,779[a]
Industrial Waste Landfilled	226,426[b]
Demolition/Construction Waste Landfilled	238,823[b]
Sludge Incinerated	105,051
Composting	42,769[a]
Recycling	10,270[a]

Sources: Minnesota Pollution Control Agency, *Emissions Inventory System*, (St. Paul, MN: 1994).
Minnesota Pollution Control Agency, *Minnesota Solid Waste Management: Selected Economic and Financial Issues*, (St. Paul, MN: 1991).
Minnesota Pollution Control Agency, *Estimated Cost of Waste Disposal/Incineration Alternatives*, (St. Paul, MN: 1993).

(a) Estimated at 0.3 tons per cubic yard of uncompacted waste.
(b) Estimated at 0.375 tons per cubic yard of uncompacted waste.

The principal emissions of concern include CH_4 from landfills and CO_2 from incinerated wastes. In total, some 222,501 to 253,631 tons of CH_4 are estimated to have been emitted to the atmosphere in 1990 from waste disposal activities, nearly all of it produced in landfills through the anaerobic decay of organic wastes by methanogenic bacteria (see Table 62). Between 266,140 and 307,451 tons of CO_2 are estimated to have been emitted to the atmosphere as a result of the incineration of petrochemically-based plastics. NO_x and CO emissions are estimated at 302 to 342 and 520 to 592 tons, respectively.

A number of sources of potential greenhouse gas emissions from waste disposal are not treated in this section. These include, among others, wastewater treatment facilities, which are suspected to be large emitters of N_2O.[170] No well developed methodology exists to allow emissions estimates to be developed for this source. Likewise, no methodology exists for the estimation of CH_4 emissions from composting. In Minnesota, composting activities extend to yard wastes, municipal solid waste, and wastewater sludges.[171] As methodologies are developed, emissions from these sources should be estimated.

Table 62. Estimated 1990 Emissions from Waste Disposal Activities

Source	Emission (in tons)	
	CO_2[(a)]	CH_4
Landfill Leakage	NA[(b)]	222,237 to 253,367
Incineration	265,957 to 307,213	264
Decay of Incineration CO	183 to 238	NA
TOTAL	**266,140 to 307,451**	**222,501 to 253,631**

Source: Table 72 below.

(a) Fossil fuel-based CO_2
(b Not applicable

SECTION XVII. Methane from Sanitary Landfill Leakage

In 1990 in Minnesota, 6,079,262 cubic yards of municipal solid waste were placed in some 65 operational sanitary landfills. Roughly 888,087 cubic yards of solid industrial wastes were also placed in either industrial landfills or in industrial cells of sanitary landfills receiving mostly municipal solid waste.[172] At an estimated weight of 0.3 tons per cubic yard for uncompacted waste delivered to the landfill, the weight of municipal solid waste placed in sanitary landfills in 1990 is estimated to have amounted to some 1,823,779 tons.[173]

In the United States, methane emitted from landfills constitutes the single largest anthropogenic source of CH_4 emissions, accounting for an estimated 36 percent of all methane emissions. Of this, 90 to 95 percent is estimated to derive from sanitary landfills containing municipal solid waste, and 5 to 10 percent is estimated to derive from landfilled industrial wastes.[95]

Below methane emissions from landfills located in Minnesota are treated. Using emission factors derived from what is considered to be a representative sample of landfills around the nation, it is estimated that 223,674 to 254,840 tons of CH_4 were produced in Minnesota landfills in 1990. Of this, 1,473 tons were combusted to produce energy, for a net emission of 222,237 to 253,367 tons of CH_4.

Methane Production in Sanitary Landfills

Unless incinerated, recycled, or composted, municipal solid waste in Minnesota is landfilled. By weight, about 70 percent of MSW is organic material that, in the anaerobic conditions promoted in sanitary landfills, is decomposed by methane-producing bacteria known as methanogens. The end-products of the anaerobic decomposition of MSW include methane, carbon dioxide, and stabilized organic material. Once produced, methane migrates gradually through the landfill until it is eventually vented to the atmosphere. Of total methane produced in sanitary landfills, roughly 90 percent is estimated to eventually make its way to the atmosphere, while the remainder is thought to be oxidized to CO_2 in the upper soil layers of landfills.[95]

The particular qualities of a sanitary landfill that promote the anaerobic decomposition of solid waste and methane production include: the large quantity of organic matter placed in landfills, its depth and degree of compaction, and the high moisture and nutrient content of the waste.[95] Sanitary landfills are typically

divided into individual cells that, after filled, are closed and capped with clay and top soil. Once the landfill is covered, any oxygen contained within the landfill cell is quickly consumed, leading to the creation of an oxygen-free environment suitable for the production of methane.

Typically, methane production begins 1 to 2 years after waste is landfilled. It is estimated to last between 10 and 60 years. Evidence from specific landfill sites suggests that production of methane peaks in amount in about the thirtieth year after waste placement, after which it declines.[95]

Landfill gas vented from sanitary landfills is, by volume, roughly one-half methane and one-half carbon dioxide. Methane migrating through subsoil can seep into the basements of buildings, creating a safety hazard. To remedy this, landfill gas is sometimes collected and flared or used to produce commercially salable energy. The efficiency of combustion during the flaring of landfill gas is estimated to be 98 percent.[54]

Those factors controlling the rate of CH_4 generation in any single landfill include:

- waste organic content and nutrient availability
- refuse particle size and average refuse density
- MSW moisture content
- landfill temperature
- pH within the landfill.[174]

In general, methane production from landfilled waste increases with increased moisture, waste organic content, the degree of refuse compaction, landfill size, and decreasing refuse particle size.[95]

Finally, due to wide variation in waste composition, landfill moisture content, and landfill temperature, CH_4 production from landfilled waste may vary widely from landfill to landfill. There have been relatively few actual measurements of CH_4 emissions from landfills.[95] Most emissions estimates derive from calculated potential methane generation based on the amount of organic matter placed in landfills, or from measurements from landfills were landfill gas is collected for use in energy production.[175]

Methane Generation from Waste Landfilled in Minnesota in 1990

Methane production from landfilled waste typically begins 1 to 2 years after placement. Thus most or all methane generated from refuse placed in landfills in the state of Minnesota in 1990 will be generated only in the 20 to 50 year period after placement.

However, it is useful for policy makers to understand the total likely future emission of CH_4 resulting from the 1990 landfill disposal of waste. To estimate this, we follow the recommended U.S. Environmental Protection Agency methodology given in the *State Workbook*, in which:

methane emissions = amount of MSW landfilled • degradable organic content (DOC) of MSW • the percent of DOC dissimilated • 0.67 lb. of CH_4/ lb. of landfill waste

where the DOC is set at 22 percent and 77 percent of DOC is assumed to be dissimilated.[54]

The latter two values are representative values for waste in the United States, as taken from Bingemer and Crutzen (1987).[176] The value that they give for degradable carbon content is close to what is estimated in Appendix B.

An estimated 3,647,558,000 lbs. of MSW was landfilled in Minnesota in 1990.[172] Using the above calculative procedure, an estimated 413,990,538 lbs. of CH_4 will eventually be generated from the decomposition of wastes placed in landfills in Minnesota in 1990. Assuming that none of this is collected and flared or burned to produce energy, this would result in a release to the atmosphere over the next 2 to 5 decades of 206,995 tons of CH_4.

Between 1990 and 2040, an estimated 206,995 tons of CH_4 will be released from waste landfilled in Minnesota in 1990.

Emissions in 1990 from MSW Landfilled from 1960 to 1990

That CH_4 that was actually vented to the atmosphere in 1990 from landfills located in Minnesota resulted from the anaerobic decomposition of waste placed in those landfills between 1960 and 1989. To estimate landfill emissions actually occurring in 1990, emission factors are taken from the U.S. Environmental Protection Agency's national methane inventory, *Anthropogenic Methane Emissions in the United States: Estimates for 1990* (1993).[95] These were derived from an analysis of amounts of landfill gas collected from what were considered to be representative U.S. landfills for purposes of energy production. In that inventory, emission factors were given based on landfill size. These are shown in Table 63.

Based on reported amounts of solid waste actually landfilled in Minnesota from 1980 to 1990, it is evident that most or all of Minnesota's landfills fall into the smallest four classes shown in Table 63.[172] As of 1990, the state's largest landfill, the Pine Bend Sanitary Landfill, had approximately 4.5 million tons of waste in

Table 63. Emission Factors for Landfill Leakage

Landfill Size Class (10^6 tons in place)	Emission Factor (cubic feet CH_4/ lb. waste)
0.115	0.065
0.812	0.064
2.461	0.078
7.394	0.057
16.700	0.051
67.835	0.047

Source: U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*, EPA 430-R-93-003, (Washington, D.C.: 1993).

place.[177] As of 1990, there were about 65 landfills in the state still accepting waste. However, no single registry exists of the total amount of waste actually in place at these landfills. Likewise, no information was available on the total number of landfills and covered city dumps that had been closed in the preceding quarter century. In absence of such detailed information on the total amount of waste placed in each of the state's operating and closed landfills, we adopt the midpoint in the range of emission factors given by the U.S. Environmental Protection Agency for landfills of the general size of those found in Minnesota, or 0.065 cubic feet of CH_4 per ton of landfilled waste (see Table 63).

Sanitary landfilling began in Minnesota in 1970. Prior to that, most MSW was placed in open dumps, where it was often, though not always, burned.[178] No information is available regarding amounts of waste presently contained in such dumps. Information on the amounts of refuse placed in sanitary landfills is available only for the period 1980 to 1990.

The total amount of waste placed in landfills in Minnesota is thus estimated from two sources. The total amount of waste landfilled from 1980 to 1990 is taken from the Minnesota Pollution Agency, *Solid Waste Management: Selected Economic and Financial Issues* (1991).[172] These are reported values and are shown in Table 64. To estimate refuse amounts placed in landfills from 1960 to 1980, the annual rate of change in *per capita* waste generation for each year in this period is calculated from research on long-term trends in *per capita* waste generation presented in the California Energy Commission, *1988 Inventory California Greenhouse Gases* (1990).[138] These are also shown in Table 64. Using these, amounts of waste generated statewide are calculated backward for each year for the period 1960-1980. These are likewise shown in Table 64.

Some past estimates of waste generation are available to check the reasonableness of the schedule of waste generation given in Table 64. For instance, for 1970 the Minnesota Pollution Control Agency estimated that 2.2 million tons of solid waste were generated in the state, and for 1972 gave 3.1 million tons as its estimate of the amount of statewide waste generation.[179,180] In the mid1970s, Reid and Peterson (1975) likewise estimated state solid waste generation amounts at 3 million tons per year.[181] These are all in good agreement with the estimates of solid waste generation given in Table 64 .

Table 65 shows total amounts of MSW landfilled statewide between 1960 and 1990 by decadal increments. For the decade of the 1960s, it was assumed that 10 to 50 percent of the waste placed in open dumps was burned.

Table 64. Reported and Calculated Amounts of Landfilled Wastes in Minnesota, 1960 - 1990

Year	Reported Landfilled Waste (in cu. yds.) [a]	% Decline in per Capita Waste Generation from Preceding Year (In %) [b,c]	Calculated per Capita Waste Generation (in cu. yds.)	Minnesota Population (10^3) [e]	Reported & Calculated Waste Generation (In cu. yds.)	Waste Generation (In 10^6 tons)
1990	6,079,262				6,079,262	1.824
1989	7,864,662				7,864,662	2.359
1988	9,841,452				9,841,452	2.952
1987	9,800,797				9,800,797	2.94
1986	10,765,119				10,765,119	3.23
1985	10,477,007				10,477,007	3.143
1984	10,541,890				10,541,890	3.163
1983	10,274,589				10,274,589	3.082
1982	9,985,274				9,985,274	2.996
1981	10,392,006				10,392,006	3.118
1980	10,737,701		2.6344 [d]	4,076	10,737,814	3.221
1979		0.432	2.623	4,060	10,649,380	3.195
1978		0.434	2.6116	4,024	10,509,078	3.153
1977		0.436	2.6002	3,980	10,348,796	3.105
1976		0.438	2.5889	3,954	10,236,511	3.071
1975		0.444	2.5775	3,921	10,106,378	3.032
1974		0.442	2.5661	3,904	10,018,054	3.005
1973		0.444	2.5547	3,890	9,937,783	2.981
1972		0.446	2.5433	3,877	9,860,374	2.958
1971		0.448	2.5319	3,860	9,773,134	2.932
1970		0.45	2.5205	3,806	9,593,023	2.878
1969		0.452	2.5091	3,758	9,429,198	2.829
1968		0.454	2.4977	3,703	9,248,983	2.775
1967		0.456	2.4863	3,659	9,097,372	2.729
1966		0.458	2.4749	3,617	8,951,713	2.686
1965		0.46	2.4636	3,592	8,849,251	2.655
1964		0.462	2.4522	3,558	8,724,928	2.617
1963		0.464	2.4408	3,531	8,618,465	2.586
1962		0.466	2.4294	3,513	8,534,482	2.56
1961		0.469	2.418	3,470	8,390,460	2.517
1960		0.471	2.4066	3,414	8,216,324	2.465

(a) Minnesota Pollution Control Agency, *Minnesota Solid Waste Management: Selected Economic and Financial Issues* (St. Paul, MN: 1991).
(b) Moving backward in time from 1980.
(c) Derived from equation presented in California Energy Commission, *1988 Inventory of California Greenhouse Gases* (final draft), October, 1990.
(d) Calculated from total reported Minnesota landfilled waste and 1980 Minnesota population.
(e) Minnesota Department of Public Service, *Minnesota Energy Data Book*, (St. Paul, MN: 1990).

Table 65. 1990 Generation of Methane from Minnesota Sanitary Landfills

	Tons of Waste Landfilled	1990 Methane Emission (MMcf CH_4)
1960 - 1969	13,209,176.4 to 23,776,517.5	1,717.193 to 3,090.947
1970 - 1979	30,309,753.3	3,940.268
1980 - 1990	32,027,927.7	4,163.631
Total	75,546,857.4 to 86,114,198.5	9,821.092 to 11,194.846
Less Gas Collected		65
Net Emission		**9,756 to 11,130[a]**

Source: Tables 63 and 64.

(a) At 22.67 tons of CH_4/MMcf, equivalent to 221,073 to 252,202 tons of CH_4.

Table 65 also shows the corresponding amount of methane that would have been generated in 1990 from waste placed in landfills during each of the three prior decades, assuming a rate of production of 0.65 cubic feet per ton of waste landfilled. Based on all of the above assumptions, total CH_4 production for 1990 from landfills is estimated to have been some 9,821 to 11,195 MMcf.

In 1990, 65 MMcf of landfill gas were collected at the Anoka Sanitary Landfill and combusted for purposes of energy production (see Part II, Section II above). The flaring of landfill gas was not considered.[182] Thus the estimated net 1990 emission of CH_4 to the atmosphere from municipal landfill leakage would have been some 9,756 to 11,130 MMcf, which at 22.66 tons of CH_4 per MMcf yields a net emission of 221,073 to 252,202 tons of CH_4.

Methane Leakage from Industrial Landfills

In addition to municipal solid waste, industrial waste is also landfilled. Prior to 1982, industrial waste was landfilled in sanitary landfills. Thus we estimate emissions from industrial landfilled wastes only for those wastes placed in landfills from 1982 to 1990. Emissions from industrial wastes placed in sanitary landfills prior to 1982 are presumably accounted for in the above emissions estimate for sanitary landfills. From 1982 to 1990, 6,236,356 cubic yards of industrial waste were placed in industrial landfills.[172]

To estimate total CH_4 production from this waste, we follow the methodology outlined by the U.S. Environmental Protection Agency in the national methane inventory.[95] At 0.375 tons of waste per cubic yard of waste placed in industrial landfills, the amount of total industrial waste landfilled from 1982 to 1990 would equal 2,338,634 tons. This is converted to tons of organic matter using a recommended value of 11 percent organic waste matter as appropriate for industrial wastes. This yields some 257,250 tons of organic waste matter, which is converted to MSW-equivalents by dividing this total by the portion of organic matter in landfilled MSW, here specified as 65 percent. This yields 395,769 MSW-equivalent tons of industrial waste, which represents 1.54 percent of the total MSW placed in sanitary landfills between 1982 and 1990. In 1990, 3,339.6 MMcf of CH_4 or some 75,675 tons of CH_4 is calculated to have been generated and vented to the atmosphere from MSW placed in landfills over the prior thirty years. 1.54 percent of 75,675 tons is 1,165 tons, which represents the methane generated by and released from industrial landfills in 1990 from waste placed in those landfills from 1982 to 1990.

Landfill Methane Summary

Total estimated statewide emissions of CH_4 in 1990 from sanitary and industrial landfills are 222,237 to 253,367 tons of CH_4. Most of this derives from sanitary landfills.

1990 statewide emissions of CH_4 emissions from municipal and industrial landfills are estimated to have totaled 222,237 to 253,367 tons.

Overall, methane leakage from landfills constitutes 42 percent of total estimated in-state emission of CH_4 for the year 1990. This is in good agreement with the 36 percent estimated for the United States nationally in the national methane inventory, especially considering the absence from Minnesota of major emitting sectors like coal mining and gas production.[95] As a percent of in-state CH_4 emissions plus out-of-state emissions, which include CH_4 vented to the atmosphere from these fuels-producing activities, estimated emissions of CH_4 from landfills comprise between 35 and 38 percent of all methane emissions associated in some way with activities occurring in the state of Minnesota..

The amount of solid waste placed in Minnesota landfills declined dramatically from 1985 to 1990, by more than 40 percent. However, since methane emissions vary linearly or near-linearly with the total amount of landfill waste in place, any extra placement of waste in landfills, no matter how minor, implies a rising level of CH_4 emission from landfills. Based on the reconstructed history of the landfilling of solid waste in Minnesota, and assuming a linear relation between emissions and amounts of landfill waste in place, in the short-term one might reasonably expect emissions of methane from landfills to increase by perhaps 2 or 2.5 percent per year.

As is evident from the above discussion, a number of simplifying assumptions had to be made in the calculation of methane production in Minnesota landfills. These point to a degree of uncertainty in the calculation and estimates given above. One major source of uncertainty relates to the degree to which methane recovery data from landfills producing gas for energy production purposes can form an adequate surrogate for actual emissions measurements.[95] If in fact these landfills are not representative of Minnesota landfills, the estimates given in this inventory may diverge substantially from actual emissions.

Other sources of uncertainty include:

- assumptions made about the amount of MSW generated from 1960 to 1970 that was burned in open dumps. If more than 50 percent was burned, the emissions estimates given above would overstate actual emissions.
- choice of emission factors from the range given by the U.S. Environmental Protection Agency. Lacking any substantial basis for selecting any particular emission factor from the range given by the EPA for the size of landfills common to Minnesota, we chose the midpoint in the range. Thus even assuming that the EPA methodology and emission factors were fully applicable to Minnesota landfills, actual emissions of CH_4 from Minnesota landfills could be higher or lower than the estimates given here by 15 to 20 percent.

- the assumed time frame. A 30-year time horizon was assumed for emissions from landfills. If a time horizon longer than 30 years was to prove to be in order, actual statewide landfill emissions are likely to be substantially higher than given in this inventory.
- rate of methane oxidation. The emission factors employed in calculating emissions assume that 10 percent of all landfill-generated CH_4 is oxidized to carbon dioxide in the upper layers of landfill soils. This value is based on a limited number of measurements. If the amount oxidized were to be substantially higher, then the emissions estimates given above would significantly overstate actual emissions.[175]

Carbon Dioxide Emissions from Landfills

Along with CH_4, CO_2 is also emitted to the atmosphere from landfills, and in comparable amounts. Following the U.S. Environmental Protection Agency methodology, it is assumed that one-half of landfill gas, by volume, is CO_2. 222,237 to 253,367 tons of CH_4 are estimated above to have been emitted from Minnesota landfills in 1990. The associated CO_2 emissions would be:

$$222{,}237 \text{ to } 253{,}367 \bullet 44/16 = 611{,}152 \text{ to } 696{,}759 \text{ tons of } CO_2$$

where 44/16 is the ratio of the atomic weights of CO_2 and CH_4 respectively.[54] In this inventory we are concerned only with fossil fuel-derived CO_2 or that part of biogenic CO_2 that originates in biotic systems in which large amounts of carbon are stored for very long periods of time, e.g., forests and soils. Roughly 70 percent of the biogenic carbon held in MSW generated in Minnesota originates in forest products (see Appendix B). Thus the annual emission of biogenic-wood CO_2 from landfills would be some 427,806 to 487,731 tons of CO_2.

CO_2 from the Atmospheric Oxidation of Methane Emitted in Prior Years from Landfills

Methane has an atmospheric residence time of about 10 years. The final decay product of methane is carbon dioxide. Given an adequate history of past methane emissions, it is possible to estimate the amount of methane that in any one year decays to CO_2 from any one past emissions source. The decay of an atmospheric concentration of CH_4 can be described mathematically by the expression:

$$E = E_o \bullet e^{-t/c}$$

where E denotes the amount of the concentration, T is time, and C is the turnover or residence time of the gas, which for methane is about 10 years.[183]

From this equation, one can calculate how much of landfill CH_4 emitted in 1984, 1982, 1989 or whatever year would have decayed in 1990 to CO_2. This is done in Appendix K for all years going back to 1960. The results are shown in Table 66 for decadal results. From 1980 to 1989, roughly 5,172 to 6,040 MMcf of methane are estimated to have been oxidized in 1990 to carbon dioxide, from 1970 to 1979 roughly 971 to 1,301 MMcf are estimated to have been oxidized in 1990 to carbon dioxide, and from 1960 to 1969, 91 to 164 MMcf are estimated to have been oxidized in 1990, for a total of 6,234 to 7,505 MMcf. At 0.4235 lb. of methane per cubic foot, this equals some 132,005 to 158,918 tons of methane, which at 74.87 percent carbon by weight is equivalent to 98,832 to 118,982 tons of carbon. Converted to CO_2, this equals 362,148 to 435,983 tons of CO_2. If 70 percent of this derives from the decay of forest products, the net emission of carbon dioxide from long-lived biotic reservoirs from this source would have equaled 253,504 to 305,188 tons of CO_2.

In passing, it might be noted that, given an adequate history of past methane emissions from combustion, coal mining, the natural gas system, or whatever source, a similar calculation of carbon dioxide production from methane oxidation also could be performed.[184]

Table 66. 1990 CO_2 from CH_4 Decay from Prior Years' Emissions

	CH_4 Decaying to CO_2 in 1990 From Prior Years' Emissions (in MMcf)
1980 - 1989	5,171.9 to 6,040.3
1970 - 1979	970.8 to 1,301.1
1960 - 1969	91.1 to 164
TOTAL	**6,233.8 to 7,505.4[a]**

Source: Appendix K.
(a) Equivalent to 132,005 to 158,918 tons of CH_4.

SECTION XVIII. Greenhouse Gases from Incineration

In Minnesota, substantial amounts of solid waste are generated that are neither landfilled nor combusted to produce energy, but rather are incinerated on-site. These include pathological and general medical wastes, hazardous waste, sludge, commercial and industrial wastes, and rural wastes.

The amount of waste incinerated in 1990 in Minnesota is shown in Table 67 by type. Most of the data given in Table 67 are Minnesota Pollution Control Agency estimates. The amount of waste that is burned in the open in rural areas is estimated based on an average national rate of 0.45 tons of waste generated per rural resident per year, and a 1990 rural population in Minnesota of 1,318,625 persons.[185,186] The total amount of waste incinerated in 1990 is estimated to have been between 881,093 and 962,042 tons.

Table 67. 1990 Waste Incineration in Minnesota by Waste Type

Waste Type	1990 Tons of Waste
Industrial On-Site	9,545 to 62,885(a)
Waste Wood	3,773
Commercial On-Site	138,000
Sludge	119,218
General Medical Waste	13,793 to 37,287
Pathological Waste	3,383 to 7,498
Open Burning of Rural Waste	593,381(b)
Total	**881,093 to 962,042(c)**

Sources: For industrial on-site, commercial on-site, general medical and pathological waste, Minnesota Pollution Control Agency, *Estimated Cost of Waste Disposal/Incineration Alternatives,* (St. Paul, MN: 1993).
For waste wood, sludge and hazardous waste, Minnesota Pollution Control Agency, *Emissions Inventory System,* (St. Paul, MN: 1994).

(a) On-site industrial incineration wastes total 13,320 to 66,660 tons including waste wood.
(b) Estimated at a rate of 0.45 tons per rural resident per year and an estimated 1990 rural population of 1,318,625 persons.
(c) In addition, 550,000 MMBTU-equivalent of hazardous waste was also combusted in 1990.

The carbon content of each incinerated waste type is shown in Table 68 as a percent of the weight of the waste.

Carbon emissions from incineration are given in Table 69. A combustion efficiency of 75 percent was assumed for the open burning of rural waste, and 90 percent was assumed for all other incineration. The latter is a typical value for the incineration of these types of wastes.[79] Carbon emissions are arranged into two groupings: fossil fuel carbon, principally from petrochemicals underlying plastic wastes, and carbon from forest products. As in Section II, we are primarily interested in fossil fuel CO_2 emissions, and secondarily in emission of carbon dioxide from the combustion of wood derived from long-lived tree species and forest systems in which large amounts of carbon would be otherwise sequestered for periods of as long as 50 years or more.

Table 68. Carbon Content of Incineration Wastes

Incineration Waste Type	Carbon Content % By Weight	
	Petrochemical Component	Forest Products Component
On-Site Industrial Waste	12	19
Waste Wood	0	33
On-Site Commercial Waste	12	19
Sludge(a)	0	32
General Medical Waste	26	19
Pathological Waste	0	0
Open Burning of Rural Wastes(b)	12	18
Hazardous Waste	100	0

Source: Appendix B.

(a) For wood sludge only.
(b) Same as statewide municipal solid waste.

Total fossil fuel-based carbon emissions from incineration for 1990 total 72,581 to 83,840 tons of carbon, which in terms of CO_2 equals 265,957 to 307,213 tons of carbon dioxide. The 1990 forest products-related emission is estimated to have been 113,519 to 127,715 tons of carbon or 415,965 to 467,983 tons of CO_2.

Emission factors for methane, carbon monoxide, and NO_x for incineration for various types of waste are shown in Table 70, along with waste totals for each category of waste and associated emissions. Total

Table 69. Carbon Emissions from Incineration

	Tons of Carbon[a,b]
Petrochemical Component	
Industrial On-Site	1,031 to 6,791
Commercial On-Site	14,904
General Medical On-Site	3,227 to 8,726
Rural	53,405
Hazardous Waste	14[c]
Total	**72,581 to 83,840[d]**
Forest Products-Wood Component	
Industrial On-Site	1,634 to 10,755
Commercial On-Site	23,598
Waste Wood	1,121
General Medical On-Site	2,979 to 8,054
Rural	80,107
Sludge[e]	4,080
Total	**113,519 to 127,715[f]**

(a) At a combustion efficiency of 90% for all except for open burning of rural wastes for which a 75% combustion efficiency is applied, from H. Peavy, *et al.*, *Environmental Engineering*, (New York: McGraw-Hill, 1985).
(b) Rounded to the nearest ton.
(c) Estimated value from L. Chamberlain, Minnesota Pollution Control Agency, October, 1990 as reported in P. Ciborowski and D. Burdette, "Carbon Dioxide Emissions in Minnesota," report to the Minnesota Pollution Control Agency, January, 1991.
(d) In CO_2-equivalent tonnage, this equals 265,957 to 307,213 tons.
(e) Forest products component alone.
(f) In CO_2-equivalent tonnage, this equals 415,965 to 467,983 tons.

Table 70. Emission Factors and 1990 Emissions from Incineration for Methane, Carbon Monoxide and Nitrogen Oxides

Type of Waste	Tons of Waste	Emission Factors			Emissions (in Tons)		
		CH_4	CO	NO_X	CH_4	CO	NO_X
General Medical	13,793 to 37,287	NE[a]	5 lb./ton[b]	2.7 lb./ton[b]	NE	34.5 to 93.2	18.6 to 50.3
Pathological	3,383 to 7,498	Negligible[c]	Negligible[c]	3 lb./ton	Negligible	Negligible	5.1 to 11.2
On-Site Commercial	13,800 (1,338,600 MMBTU)	NE	0.011-0.022 lb./ MMBTU[d]	0.0022 to 0.0033 lb./ MMBTU[d]	NE	7.4 to 14.8	1.5 to 2.2
On-Site Industrial	13,320 to 66,660 (129,204 to 646,602 MMBTU)	NE	0.011-0.022 lb./ MMBTU[d]	0.0022 to 0.0033 lb./ MMBTU[d]	NE	0.7 to 7.1	0.1 to 1.1
Rural Waste	593,381 (5,755,796 MMBTU)	0.0144 lb./ MMBTU[d]	0.0928 lb./ MMBTU[d]	0.0066 lb./ MMBTU[d]	41.4	267.1	19.0
Sludge							
Multiple Hearth	90,190	4.6 lb./ton[c]	4 lb./ton[c]	5 lb./ton[c]	207.4	180.4	225.5
Fluid Bed	14,861	2 lb./ton[c]	4 lb./ton[c]	4.4 lb./ton[c]	14.9	29.7	32.7
TOTAL[d]					**264**	**520 to 592**	**302 to 342**

(a) No emission factor available.
(b) B. Walker and C. Cooper, "Air Pollution Emission Factors for Medical Waste Incinerators," *Journal of the Air and Waste Management Association*, 42 (1992): 784-791.
(c) U.S. Environmental Protection Agency, *Compilation of Air Pollution Emission Factors*, 4th edition plus *Supplements*, AP-42, (Washington, D.C.: 1985).
(d) Totals may not add due to rounding in the table.

methane emissions from incineration are estimated to have equaled 264 tons, CO emissions 520 to 592 tons, and NO_x emissions 302 to 342 tons. No emission factors were available for nitrous oxide.

Finally, as discussed in Part II, carbon monoxide has an atmospheric lifetime of several months, after which it is oxidized to carbon dioxide. Table 71 presents 1990 carbon monoxide emissions from incineration by source, as well as the appropriate percentages of the total carbon in each waste that is petrochemically-based and thus of a fossil fuel origin. Based on these percentages, the carbon in roughly 233,800 to 304,590 lbs. of carbon monoxide emissions is assumed to be of a fossil fuel origin, or 117 to 152 tons. Since by weight CO is 43 percent carbon, this equals 50 to 65 tons of carbon of fossil fuel provenance and, upon oxidation, 183 to 238 tons of carbon dioxide.

Statewide emissions from incineration are estimated in 1990 to have totaled 265,957 to 307,213 tons of fossil CO_2, 264 tons of CH_4, 520 to 592 tons of CO, 183 to 238 tons of CO_2 from fossil CO oxidation, and 302 to 342 tons of NO_x.

Table 71. Petrochemical Component of Estimated 1990 CO Emissions: Incineration

	CO Emission (in tons)	% Petrochemical/ Fossil[a]	Fossil CO Emission (in tons)
General Medical	34.5 to 93.2	52	17.9 to 48.5
Pathological	Negligible	0	0
On-Site Commercial	7.4 to 14.8	35	2.6 to 5.2
On-Site Industrial	0.7 to 7.1	35	0.2 to 2.5
Rural Waste	19.0	36	96.1
TOTAL	**520 to 592**		**116.9 to 152.3[b]**

(a) See Appendix B.
(b) Equivalent to 50 to 65 tons of carbon and, upon oxidation, to 183 to 238 tons of CO_2.

SECTION XIX. Emissions Summary for Waste Disposal

Estimated 1990 emissions of carbon dioxide, methane, carbon monoxide and NO_x are shown in Table 72 for landfill leakage and incineration. If we exclude carbon dioxide resulting from the combustion or oxidation of wood or wood products from the total, estimated 1990 carbon dioxide emissions from this sector total 266,140 to 307,451 tons. Methane emissions, 99.9 percent of which in this sector derive from landfill leakage, are estimated to have amounted to 222,501 to 253,631 tons. NO_x and carbon monoxide emissions are estimated to have been 302 to 342 tons and 520 to 592 tons, respectively.

Emissions of carbon dioxide resulting from the combustion or other oxidation of wood biomass are estimated to have totaled 1,097,275 to 1,260,902 tons.

Statewide emissions from waste disposal activities are estimated in 1990 to have totaled 266,140 to 307,451 tons of fossil CO_2, 222,501 to 253,631 tons of CH_4, 520 to 592 tons of CO, and 302 to 342 tons of NO_x.

CO_2-equivalent emissions from landfill leakage and incineration are also presented in Table 72. Excluding the biogenic-wood component of carbon dioxide emissions, the total CO_2-equivalent emission from this sector in 1990 is estimated to have been 2,713,651 to 3,097,392 tons, of which about 90 percent is estimated to have derived from CH_4 leakage from landfills. If the forest products component of carbon dioxide emissions is included in these estimates, total CO_2-equivalent emissions from this sector are estimated to have totaled 3,810,926 to 4,358,294 tons, of which 62 percent is estimated to have derived from methane leakage from landfills (see Figure 11).

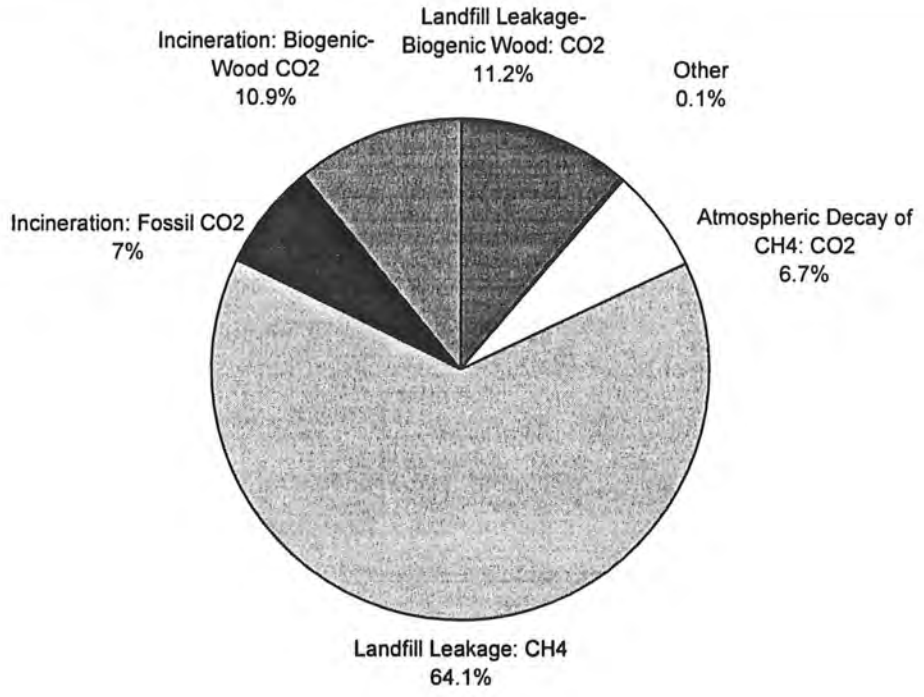
Table 72. Summary of Emissions from Landfill Leakage and Incineration

Source of Emission	Gas	Emission (in tons)[a]	CO_2-Equivalent Emission (in tons)
Landfill Leakage	CH_4	222,237 to 253,367	2,444,607 to 2,787,037
Incineration	CH_4	264	2,904
Subtotal	**CH_4**	**222,501 to 253,631**	**2,447,511 to 2,789,941**
Incineration	CO_2	265,957 to 307,213	265,957 to 307,213
Atmospheric Decay of CO	CO_2	183 to 238	183 to 238
Subtotal	**CO_2**	**266,140 to 307,451**	**266,140 to 307,451**
Incineration	NO_x	302 to 342	NA
Incineration	CO	520 to 592	NA
TOTAL			**2,713,651 to 3,097,392**
Biogenic- Wood CO_2 Component			
Landfill Leakage	CO_2	427,806 to 487,731	427,806 to 487,731
Incineration	CO_2	415,965 to 467,983	415,965 to 467,983
Atmospheric Decay of CH_4 Emitted from Landfills in Prior Years	CO_2	253,504 to 305,188	253,504 to 305,188
TOTAL			**1,097,275 to 1,260,902**

Sources: Tables 65 to 71 and text.

(a) Rounded to the nearest ton.

Figure 11. CO_2-Equivalent Emissions of Greenhouse Gases from Landfilling and Incineration



(a) Of an estimated emission of 3.8 million tons.

PART VI. EMISSIONS FROM AGRICULTURAL ACTIVITIES

Minnesota is one of the leading agricultural states in the nation, in 1990 placing 4th in the nation in both milk production and in the number of milk cows on farms, 6th in red meat production, 3rd in the marketed number of hogs and pigs, 2nd in turkey production, 4th in corn production, 3rd in soybean production, and 6th in wheat production.[187]

Greenhouse gases and their precursors are released to the atmosphere from a number of agricultural sources. CH_4 is produced through the anaerobic decay of organic matter in the digestive systems of livestock, particularly ruminant livestock like cattle. CH_4 is also produced anaerobically in the manure of livestock and in rice paddies. CO_2 is emitted to the atmosphere as a result of the agricultural liming of fields.

N_2O is produced naturally in soils during denitrification or nitrification activities of soil microbes. The use of commercial fertilizer or manure as fertilizer enhances this natural emission, leading to the accumulation of N_2O in the atmosphere above background levels.

Below we treat these emissions sources. In total, in 1990, 253,983 to 256,918 tons of CH_4 are estimated to have been emitted to the atmosphere from agricultural activities located in Minnesota, 11,031 to 11,998 tons of N_2O are estimated to have been produced from agricultural activities in Minnesota, and 26,269 tons of CO_2 are estimated to have been produced as a result of these activities (see Table 73). Total CO_2-equivalent emissions from agricultural activities are estimated to have been between 5.8 and 6.1 million CO_2-equivalent tons. These are dominated by emissions from livestock and from the use of commercial fertilizers, which together account for almost 80 percent of all weighted emissions from agricultural activities.

A number of possible sources of emissions from agricultural activities are not treated in this inventory. These include N_2O emissions from groundwater and surface waters resulting from the run-off of nitrogen fertilizers from agricultural fields, CH_4 leakage from the storage of agricultural commodities, and CO_2 from soil disturbances. In addition, we did not treat the possible increased storage of carbon in soils as a result of the usage of commercial fertilizers, or changes in the CO and CH_4 soil sink resulting from the conversion of cropland to less intensive uses. These sources may or may not be significant.

Table 73. Estimated 1990 Emissions from Agricultural Activities

Source	Emission (in tons)		
	CO_2	CH_4	N_2O
Commercial Fertilizer	NA[(a)]	NA	9,366 to 10,333
Manure Fertilizer	NA	NA	1,665
Livestock	NA	179,931	NA
Animal Manure	NA	72,595	NA
Wild Rice	NA	1,457 to 4,392	NA
Agricultural Liming	26,269	NA	NA
TOTAL	**26,269**	**253,983 to 256,918**	**11,031 to 11,998**

Source: Table 86 below.
(a) Not applicable

SECTION XX. Methane from Livestock

In 1990, excluding poultry, the number of domesticated animals kept on Minnesota farms and feedlots totaled an estimated 6,916,700 head.[187] Of these, roughly 2.36 million were ruminant animals, whose particular digestive physiology results in the production and emission to the atmosphere of large amounts of methane. Dairy and beef cattle comprise roughly 90 percent of the domesticated ruminant livestock population. These are the largest producers of methane per animal, with an average methane production per animal amounting to between 140 and 180 lbs. of methane per year.

Below the production of methane from ruminant and nonruminant livestock is estimated for 1990 based on a relatively mature discipline of animal nutrition and a relatively well developed characterization of the

physical and biological processes involved in ruminant digestion. Based on 1990 livestock populations on farms and feedlots in Minnesota, along with emission factors recommended in the U.S. Environmental Protection Agency's *State Workbook* methodology, 179,931 tons of methane are estimated to have been produced and released to the atmosphere in 1990 from livestock in the state.

Methane from Livestock

Methane is produced in the digestive tracts of livestock through enteric fermentation. In ruminant animals, this takes place in the rumen or fore-stomach, where microbial fermentation breaks down feed and other coarse plant material into soluble products that can be utilized as energy by the animal. Methane is produced as a byproduct of this fermentation process, and is exhaled or eructated (belched) by the animal as a waste product.

Among nonruminants, enteric fermentation takes place in the large intestines or cecum. However, relatively small amounts of methane are produced as a result of these processes in nonruminant animals.

Emissions of methane from livestock vary with animal type, caloric intake, and the quality of feed to be digested.

Following the recommended U.S. Environmental Protection Agency methodology, 1990 methane emissions from ruminant and nonruminant livestock grown and fed on Minnesota farms and feedlots are estimated using emission factors specific to each of several different livestock types. These are shown in Table 74. Methane production in both ruminant and nonruminant livestock is expressed as a percentage of the gross caloric intake of these animals. These range from a high of 4 to 9 percent for ruminants to 3 to 4 percent for horses and 1 percent for swine.[54] The emission coefficients given in Table 74 are based on these percentages and the typical caloric intake for each livestock animal type.

Estimated emissions from livestock grown and fed in 1990 in Minnesota are shown in Table 75. Estimated emissions total 359,862,200 lbs. of methane or 179,931 tons. Cattle constitute the source for 94 percent of this. This is similar to the situation in the nation as a whole, in which beef and dairy cattle constitute the source of 95 percent of emissions from livestock herds.[95]

These estimates are based on a mature science of animal nutrition and over 30 years of observations relating animal diet to methane production.[95] However, it is possible that these estimates are sensitive to

Table 74. Emissions from Ruminant and Nonruminant Livestock

Livestock Type	Lbs. of CH_4 Per Head of Livestock Per Year
Dairy Cattle	184.0
Beef Cattle	142.0
Hogs and Pigs	3.3
Sheep and Lambs	18.0
Horses	40.0
Mules and Asses	22.0
Goats	11.0

Source: U.S. EPA, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA 230-B-92-002, (Washington, D.C.: 1992)

regional differences in diet and animal husbandry. To check the sensitivity of the above estimates to region-specific emission factors, methane emissions from cattle were also calculated using an alternative calculative procedure taken from the national methane inventory assembled under the auspices of the U.S. Environmental Protection Agency.[95] This alternative calculative procedure is based on a mechanistic model of rumen digestion and a variety of regional diets and management practices. These emission factors are shown in Table 76 for the North Central region of the United States.

Table 76 also shows estimated emissions from dairy and beef cattle using the alternative emission factors. Using this alternative approach, estimated emissions from cattle are somewhat larger than those given in Table 74, but are generally of the same order as those given in Table 74 and are largely consistent. This suggests that regional variability in diet is not a major factor influencing CH_4 emissions from ruminant livestock.

Statewide emissions of CH_4 from livestock are estimated in 1990 to have totaled 179,931 tons.

Table 75. Ruminant and Nonruminant Livestock and Emissions from Minnesota, 1990

	Thousand Head of Livestock	Methane Emission (10^3 lb. CH_4)[c]
Dairy Cattle		
Milk Cows	715.0	131,560.0
Heifers (Milk Replacement)	325.0	59,800.0
Subtotal	**1,040.0**	**191,360.0**
Beef Cattle[a]		
Beef Cows	350.0	49,700.0
Heifers (Beef Replacement)	65.0	9,230.0
Steers	390.0	55,380.0
Bulls	40.0	5,680.0
Other	185.0	26,270.0
Subtotal	**1,030.0**	**146,260.0**
Hogs and Pigs	4,500.0	14,850.0
Sheep and Lambs	285.0	5,130.0
Horses	54.3[b]	2,172.0
Mules and Asses	0.8[b]	17.6
Goats	6.6[b]	72.6
TOTAL		**359,862.2**

Sources: Minnesota Department of Agriculture, *Minnesota Agriculture Statistics, 1991*, (St. Paul, MN: 1991).
Bureau of the Census, *1987 Census of Agriculture: State and County Data: Minnesota*, Part 23, AC-87-A-23, (Washington, D.C.: 1989).

(a) Excluding calves.
(b) 1987 value.
(c) Calculated using emission factors given in Table 74.

Since 1975, the number of head of cattle grown and fed in Minnesota has declined by about 40 percent, and about 25 percent from 1985 to 1990.[187] It is reasonable to expect that methane emissions from livestock populations declined a similar or nearly similar amount over the same period. The long-term trend is clearly toward reduced ruminant livestock populations. This suggests that the trend toward lower Minnesota emissions from ruminant populations will persist into the foreseeable future. Economic

Table 76. Emission Factors and 1990 Methane Emission from Minnesota Cattle: Alternative Calculation

	Emission Factor (lb. CH_4/head of livestock)	CH_4 Emission (10^3 lb. CH_4)
Dairy Cattle	241.18	172,443.7
Dairy Replacement	126.54[a]	41,125.5
Beef Cows	131.17	45,909.5
Beef Replacement	134.04[b]	60,988.5
Bulls	220.46	8,818.4
Calves	49.8 to 103.6	25,764.9 to 53,571.5
TOTAL		**355,050.5 to 382,857.1**[b]

Sources: U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*, EPA 430-12-93-003, (Washington, D.C.: April, 1993) and Table 75.

(a) Upper end of the range of emission factors for dairy and beef replacement aged 0 to 24 months. The values for dairy and beef replacement cattle (heifers) reported in Minnesota Department of Agriculture, *Agricultural Statistics, 1991* (St. Paul, MN: 1991) are for heifers weighing more than 500 lbs., which is near the threshold of 600 lbs. assumed by the higher emissions factor for these animals, and also steers, which are larger than heifers but nearer to the weight of heifers than to that of bulls or beef cows.
(b) 177,525 to 191,299 tons CH_4.

modeling suggests that nationwide ruminant livestock populations will remain fairly stable or slightly decline over the next decade or so.[95]

SECTION XXI. Methane from Livestock Manure

In addition to the direct release of methane from the digestive tracts of livestock, methane is also produced through the anaerobic decomposition of organic matter in the manure of livestock. The rate of methane generation is critically dependent on manure management practices. Below the emission of

methane from animal manure produced in Minnesota is treated. 72,595 tons of methane are estimated to have been produced and emitted to the atmosphere in 1990 from Minnesota from livestock manure.

Methane Generation from Manure

Methane is produced in animal manure through the decay of organic matter in anaerobic environments. Livestock manure is principally composed of organic matter and water. Under anaerobic conditions, the organic matter in manure is decomposed by anaerobic bacteria or methanogens. The end-products of the anaerobic decay of manure organic matter are methane, carbon dioxide, and stabilized manure solids.

The methane-producing capacity of manure depends on a number of factors, including the energy content and digestibility of the feed consumed by the animal in question, the prevalence of anaerobic conditions, water content, manure pH and temperature.[54] In general, the production of methane rises with increasing temperature, moisture content, and the digestibility and energy content of animal feed. The storage of manure in liquid form in particular promotes the oxygen-free environment necessary for methanogenesis.

By contrast, the presence of oxygen acts to inhibit methanogenesis. Under aerobic conditions, in which manure is in contact with oxygen, the methane-producing capacity of manure is zero.[95]

The methane-producing capacity of manure is typically expressed in terms of the amount of methane produced per unit of volatile solids (VS) in the manure. Volatile solids are defined as the organic fraction of the total solids in manure that will oxidize and volatilize at a temperature of 600 degrees F.[95] The amount of volatile solids produced by livestock varies by animal type and size. Values for the methane-producing potential of livestock are shown in Table 77. The methane-producing potential of manure represents the maximum amount of methane production possible under optimal conditions.

Actual methane production is typically estimated by adjusting the estimated maximum methane-producing capacity of manure to account for environmental limitations to methanogenesis. These limitations are typically expressed in terms of the percentage of estimated maximum potential emissions that might actually be realized for each manure management system. In the United States, manure management systems include: anaerobic lagoon, liquid slurry, pit storage, pasture, range, paddock, dry-lot, solid storage, and daily spread. The percentage of maximum potential emissions that might actually be realized range from 90 percent for anaerobic lagoon to 1 percent for daily spread, with liquid/slurry and pit storage at about 10 percent, pasture, range, paddock, and solid storage at 1 to 2 percent and dry-lot at 1 to 5 percent.[95]

Table 77. Maximum Methane Producing Capacity of U.S. Livestock Manure

Livestock Type	Maximum Potential Emission (cu. ft. CH_4/lb. of volatile solids)
Dairy Cattle	3.84
Beef Cattle in Feedlots	5.29
Other Beef Cattle	2.72
Market Swine	7.53
Breeding Swine	5.77
Turkeys	4.81
Chicken	
Broilers	4.81
Layers	5.45
Sheep	3.04
Goats	2.72
Horses and Mules	5.29

Source: U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA 230-B-92-002, (Washington, D.C.: 1992).

Methane Emissions from Animal Manure in Minnesota

In 1990 in Minnesota the total number of livestock, including poultry, is reported to have been some 104,742,200 head of livestock. These are shown in Table 78 by animal type, along with average animal weight for each animal category, the rate of production of volatile solids for each animal type, and the calculated production of volatile solids for each animal category. In total, in 1990 Minnesota livestock are estimated to have produced 11,677 million lbs. of volatile solids, or 5.8 million tons.

Maximum potential emissions from manure production are shown in Table 79. The types of manure management systems in use in Minnesota are shown in Table 80, along with the percent of animal manure managed by each system by animal type. The percentages of maximum potential emissions that might actually be realized for each manure management system are taken from the U.S. Environmental Protection Agency's *State Workbook*. These include: 0.2 percent for daily spread; 0.8 percent for pasture, range, paddock, dry-lot, and solid storage; 9 percent for pit storage of 1 month of less; 10 percent for litter

Table 78. 1990 Livestock and Generation of Volatile Solids in Manure

Livestock Type	Thousand Head of Livestock	Avg. Animal Weight (in lbs.)	lbs. Volatile solids per lb. of animal	Volatile Solids (in lbs.)
Dairy Cattle				
Cows	715.0	1,345.0	3.65	3,510,113,750
Heifers	325.0	903.0	3.65	1,071,183,750
Feedlot Cattle				
<500 lbs.	13.25	397.0[a]	2.6	13,676,650
500-699 lbs.	50.5	600.0[b]	2.6	78,780,000
700-899 lbs.	91.5	800.0[b]	2.6	190,320,000
>900 lbs.	88.5	900.0	2.6	207,090,000
>1,100 lbs.	44.25	1,100.0	2.6	126,555,000
Other Beef Cattle				
Steers	198.0	794.0	2.6	408,751,200
Bulls	40.0	1,587.0	2.6	165,048,000
Cows	350.0	1,102.0	2.6	1,002,820,000
Heifers and Other	169.0	794.0	2.6	348,883,600
Calves	517.0	397.0	2.6	533,647,400
Swine				
Market				
<60 lbs.	1,597.5	60.0	3.1	297,135,000
60-119 lbs.	980.0	90.0[b]	3.1	273,420,000
120-179 lbs.	777.5	150.0[b]	3.1	361,537,500
>180 lbs.	622.5	180.0	3.1	347,355,000
Breeding	570.0	399.0	3.1	705,033,000
Sheep	285.0	154.0	3.36	147,470,000
Goats	6.6	141.0	3.48	3,238,488
Horses and Mules	55.1	992.0	3.65	199,506,080
Turkeys	46,300.0	7.5	3.32	1,152,870,000
Chickens				
Broilers	41,300.0	1.5	6.20	384,090,000
Layers	9,646.0	3.5	4.40	148,548,400
TOTAL				**11,677,073,220**

Sources: Minnesota Department of Agriculture, *Minnesota Agriculture Statistics, 1991*, (St. Paul, MN: 1991).
U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions,* EPA 230-B-92-002, (Washington, D.C.: 1992).
(a) Average weight for calves.
(b) Average weight for this weight class.

Table 79. Maximum Potential CH_4 Emissions from Livestock Manure

Livestock Type	Maximum Potential Emissions (in cubic feet of CH_4)
Dairy Cattle	17,592,182.4
Beef Cattle	9,949,759.1
Swine	13,702,280.1
Sheep	448,310.0
Goats	8,808.7
Horses	1,055,387.2
Turkeys	5,545,305.0
Chickens-Broilers	1,847,472.9
Chickens-Layers	809,588.8

Source: Calculated from Tables 77 and 78.

Table 80. Manure Management Systems in Use in Minnesota

Livestock Type	Use of Manure Systems as a % of Total Use	Livestock Type	Use of Manure Systems as a % of Total Use
Dairy Cattle	40% daily spread 30% solid storage 30% liquid/slurry	**Beef Cattle**	85% pasture/range 13% drylot 1% liquid/slurry
Swine	40% long-term pit storage 20% drylot 20% short-term pit storage 20% other	**Sheep**	90% pasture/range 10% other
Horses	50% pasture/range 50% paddock	**Goats**	100% pasture/range
Turkeys	100% litter	**Chicken - Layers**	75% deep pit stacks 25% liquid/slurry
Chickens - Broilers	100% litter		

Source: U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA 230-B-92-002, (Washington, D.C.: 1992),Tables D7-1 through D7-9.

and deep pit stacks; 18 percent for liquid/slurry and long-term pit storage; and 90 percent for anaerobic lagoon.[54]

Total emissions of methane from livestock manure are shown in Table 81. Based on the above calculation, 72,595 tons of methane are estimated to have been produced in 1990 in Minnesota from animal manure. Swine are estimated to have accounted for 43 percent of this, cattle 32 percent, and poultry 24 percent (see Figure 12).

The degree of uncertainty in this estimate is somewhat high. Substantial uncertainties have been noted in the estimated percentages of potentially realizable emissions that might actually be realized under most manure systems. The U.S. Environmental Protection Agency recommends that, in order to bound the uncertainty, these percentages be adjusted upward roughly two-fold for liquid/slurry, pit storage, litter and

Table 81. Estimated 1990 Minnesota Methane Emission from Livestock Manure

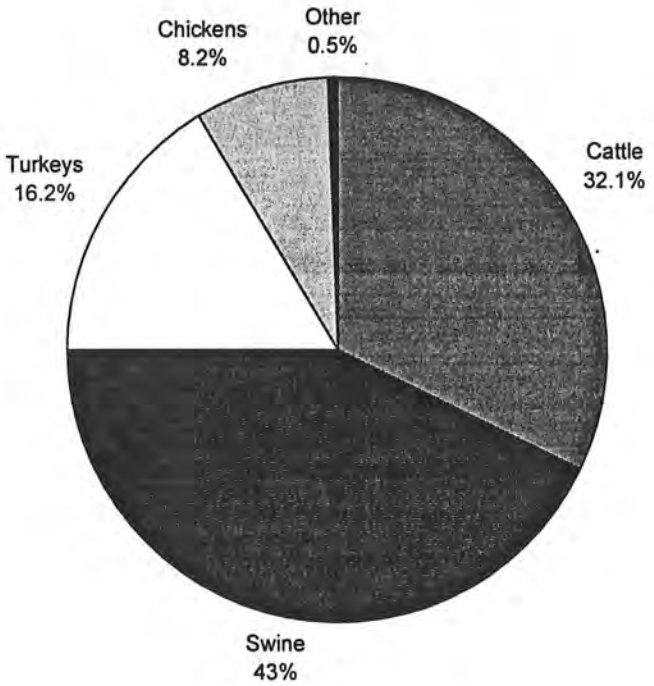
Livestock Type	CH_4 Emission (in 10^3 cu. ft.)
Dairy Cattle	1,006,272.8
Beef Cattle	95,915.7
Swine	1,474,365.3
Sheep	6,814.3
Goats	70.5
Horses	8,443.1
Turkeys	554,530.5
Chickens - Broilers	184,747.3
Chickens - Layers	97,150.7
TOTAL	**3,428,310.2(a)**

Sources: Calculated from Tables 79 and 80.

(a) Equivalent to 72,595 tons of CH_4.

deep pit stacks, and five-fold for pasture, range, daily spread, dry-lot, and solid storage. To account for the uncertainty at the low end, they recommend that 89 to 90 percent of the base estimates be assumed.[95] Applying this suggestion to our estimates results in a range of methane emission from animal manure for 1990 of 57,210 to 147,393 tons of methane, with the base case or best estimate the already reported 72,595 tons.

Figure 12. Estimated 1990 Emissions from Livestock Manure(a)



(a) Based on a total estimated emission of 72,595 tons of CH_4.

Source: Table 81.

To check the reasonableness of this estimate, an alternative calculative procedure was taken from Lodman (1993) and applied to Minnesota cattle populations.[188] Using this alternative method, an emission of 50,726 tons of methane is estimated to have resulted from cattle manure generated in 1990 in Minnesota. This is higher than the estimate given in the base case for cattle manure, but one well within the range of uncertainty specified above.[189]

Finally, as noted in the previous section, the total number of cattle in Minnesota has declined by about 25 percent since 1980. By contrast, the number of turkeys and broilers raised on Minnesota farms approximately doubled over the same period, and the number of pigs and hogs on Minnesota farms was roughly constant over this period.[187] Given these changes, and assuming no change in feed quality and manure management in the state, emissions from livestock manure in 1990 would have been only marginally different from 1980 levels.[190]

Statewide emissions of CH_4 from animal manure are estimated in 1990 to have totaled an estimated 72,595 tons.

SECTION XXII. Methane from Wild Rice Cultivation

Minnesota is one of a number of states in the nation in which wild rice is cultivated for sale. This involves cultivation in flooded rice paddies that are drained during the off-season. In Minnesota in 1992, 8,000 hectares were planted with wild rice, with 5.1 million tons of wild rice harvested.[191]

Methane is produced in rice paddies through the decomposition of organic matter by methanogenic bacteria. Much of the methane that is emitted to the atmosphere is released directly by the plant. The remainder is released through the diffusion of the gas through the paddy water and ebullition or bubbling.

A number of factors influence the rate of emission of methane from flooded rice paddies. These include: soil type, temperature, redox (oxidation-reduction) potential, soil acidity, cultivar type, and management practices. In general, these influences are poorly understood and largely unquantified.[54] In some

experiments, methane emissions were found to have increased with increasing temperature of the upper soil layer. In other experiments, emissions were found not to have increased with increasing soil temperature.[192-194] Applications of ammonium sulfate and urea commercial fertilizers have been found in some studies to enhance, and in some studies to depress, the production and emission of methane in rice paddies.[193,195] Water management practices, including the periodic draining of paddy soils, clearly influence methane production. Periodic draining increases both the soil redox potential and soil methane oxidation. Since much of emitted methane is released directly by the plant through diffusive transport, methane emissions also vary among different cultivars.[54]

Given the uncertainties surrounding those factors that control methane emissions from flooded rice fields, following the recommended U.S. Environmental Protection Agency methodology, methane emissions from wild rice paddies are estimated using a range of emissions factors taken from empirical studies conducted in Texas rice paddies by Sass (1991).[196] Methane emissions are calculated by multiplying total acre-days of rice cultivation by these emission factors.

The average annual acreage planted in wild rice in Minnesota is estimated to be 8,000 hectares, or 19,768 acres. The growing season is about 110 days.[197] Following Sass, 1.35 to 4.04 lbs. of methane are emitted per acre-day, which is broadly consistent with the results of other studies.[193,194] Thus emissions from wild rice cultivation in Minnesota would be:

$$19{,}768 \bullet 110 \bullet (1.35 - 4.04) = 2{,}913{,}803 \text{ to } 8{,}784{,}899 \text{ lbs. of } CH_4$$

or 1,457 to 4,392 tons of methane.

Statewide emissions of CH_4 from wild rice cultivation are estimated for 1990 to have totaled 1,457 to 4,392 tons.

SECTION XXIII. Nitrous Oxide and Carbon Dioxide from Fertilizers and Agricultural Liming of Fields

Farmers in Minnesota apply substantial amounts of commercial fertilizers and manure, and a small amount of municipal sludge, to agricultural fields to enhance soil fertility. Through this application, nutrients, especially nitrogen, are added to soils. Through soil microbial processes, a small percentage of this extra nitrogen is released to the atmosphere as nitrous oxide.

In addition, calcium carbonate is applied to Minnesota agricultural soils to neutralize acids that can buildup in soils, particularly in soils exposed to heavier rainfall. As these acids are neutralized, carbon dioxide is released to the atmosphere.

Nitrous Oxide from Commercial Fertilizer

Nitrous oxide is produced in soils through microbial activities that reduce nitrates to nitrogen gas (N_2), mostly in anaerobic conditions or through aerobic nitrification or oxidation of ammonium salts to nitrates and nitrites.[198] Of these two, denitrification is the dominant pathway for the production in soils of nitrous oxide.

Both of these processes are natural in character, resulting in a background N_2O emission from soils to the atmosphere. The application of commercial fertilizers enhances soil emissions of nitrous oxide.[199]

The production of N_2O in soils varies widely with environmental conditions such as soil temperature and moisture, soil organic content, soil type and pH, and soil oxygen availability. On fertilized agricultural soils, releases of nitrous oxide are also strongly influenced by rates of fertilizer application, fertilizer type, tillage practices, crop type, and irrigation and management practices. However, the response of N_2O emissions to differing management practices is poorly understood, and interactions among the different natural factors controlling nitrous oxide emissions are uncertain.[51] In general, high soil temperature, moisture content and organic content tend to correlate with enhanced emissions, whereas some specialized management practices like deep placement of fertilizer lower emissions. Tilling generally tends to lower emissions.[54]

Given the relatively poor characterization of those factors controlling the production and release of N_2O from fertilizer application, following the recommended U.S. Environmental Protection Agency methodology, emissions are estimated using a range of emission factors developed from controlled field and laboratory experiments. The range is set in the case of each individual fertilizer to bracket the range of the reported rates of emission. These are shown in Table 82. The ampleness of the range of emission coefficients given in Table 82 reflects the substantial uncertainties about actual rates of emission. It also should be noted that, as the coefficients are based on a relatively small set of field and laboratory experiments, it is possible that they do not in fact bracket the full range of possible emissions for each fertilizer type.

Table 82. Emission Factors for Commercial Nitrogen Fertilizers
(in tons of nitrogen emitted per ton applied)

	Low	Median	High
Ammonia Type			
Anhydrous Ammonia	0.0086	0.0163	0.0684
Aqua Ammonia	0.0086	0.0163	0.0684
Nitrogen Solutions	0.0086	0.0163	0.0684
Ammonium Nitrate Types			
Ammonium Nitrate	0.0004	0.0026	0.0171
Ammonium Sulfate-Nitrate	0.0004	0.0026	0.0171
Ammonium Types			
Ammonium Sulfate	0.0002	0.0012	0.015
Ammonium Phosphate(a)	0.0002	0.0012	0.015
Other(b)	0.0002	0.0012	0.015
Urea	0.0007	0.0011	0.015
Other Multiple Nutrient Types	0.00001	0.0011	0.0684
Other Nitrogen Materials	0.00001	0.0011	0.0684
Specialty Fertilizer	0.00001	0.0011	0.0684

Source: U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA 230-B-92-002, (Washington, D.C.: 1992)

(a) Includes monoammonium phosphate (11-52-0 and 10-50-0), diammonium phosphate (18-46-0), ammonium polyphosphate (10-34-0), ammoniated superphosphate (4-10-10 and 6-24-24), and ammoniated phosphate (9-18-9).
(b) Includes ammonium thiophosphate, ammonium polysulfide, and ferrous ammonium sulfide.

Average annual amounts of commercial fertilizer applied to agricultural fields and also used by homeowners are shown in Table 83 for the years 1989 through 1991. These are taken from the Minnesota Department of Agriculture's *Fertilizer Tonnage Summary* (1990-1992), which reports sales of all licensed fertilizer dealers in the state.[200] The data are averaged to remove interannual fluctuations in fertilizer use arising from weather and economic factors. This average is also expressed in terms of total nitrogen content. Fertilizer consumption for individual years and the nitrogen contents of each individual fertilizer type are given in Appendix L.

Table 83. Minnesota Commercial Fertilizer Use

	Average Annual Fertilizer Consumption, 1989-91[a]	
	Tons of Fertilizer	**Tons of Nitrogen**
Anhydrous Ammonia	391,025	320,640.5
Aqua Ammonia	861.33	137.81 to 215.33
Nitrogen Solutions	134,110.33	28,163.17 to 65,714.06
Ammonium Nitrate	10,825	3,626.38
Ammonium Sulfate-Nitrate	170	44.2
Ammonium Sulfate	30,300.67	6,363.14
Monoammonium Phosphate	41,903.33	4,609.37
Diammonium Phosphate	377,271.67	67,908.9
Ammonium Polyphosphate	39,943.33	3,994.33
Other Ammonium Phosphate	6,130.67	452.53
Other Ammonium Type	2,795.34	315.08 to 364.16
Urea	303,467	139,594.82
Other Multiple Nutrients	43,119.35	3,072.69
Other Nitrogen Solutions	1,609.67	241.45 to 321.93
Specialty Fertilizers	33,469.67	5,020.46 to 6,693.93
TOTAL[a]	**1,417,002.36**	**584,184.82 to 623,616.27**

Source: Minnesota Department of Agriculture, *Minnesota Fertilizer Tonnage Summary,* (St. Paul, MN: 1990-92).

Table 84 shows estimated emissions of nitrous oxide from commercial fertilizer use for each fertilizer type. 4,898 to 43,951 tons of nitrous oxide are estimated to have been produced in 1990 in soils and emitted to the atmosphere, with an estimated median value of 9,366 to 10,333 tons.

Table 84. Estimated 1990 Minnesota Nitrous Oxide Emission from Commercial Fertilizer Usage (in Tons of N_2O)[a]

	Median	Range
Ammonia Type	8,938 to 9,902	4,716 to 37,506
Ammonium Nitrate Type	15	2 to 99
Ammonium Types	158	26 to 1,972
Urea	241	154 to 3,290
Other	14 to 17	0 to 1,084
TOTAL	**9,366 to 10,333**	**4,898 to 43,951**

Source: Calculated from Tables 82 and 83. See Appendix L.

(a) Rounded to the nearest ton. Totals may not add due to rounding.

The U.S. Environmental Protection Agency recommends the use of the median value in assessing emissions. However, it might be noted that, given the state of our understanding of the physical processes underlying emissions, this is something of a matter of convenience. At present, there is little basis for drawing a definitive conclusion about which emission coefficients in the ranges given are best to employ.[54]

Commercial fertilizer use in 1991 was somewhat lower than the long-term average, presumably as a result of the economic recession of the early 1990s. Average annual N_2O emissions were thus also calculated for the three year period from 1988 to 1990 to determine how, if at all, suppressed fertilizer usage in 1991 might have affected estimated statewide emissions. Average annual nitrous oxide emissions for this

period are estimated to have fallen into a range of 5,194 to 17,537 tons, with a median value of 9,924 to 10,905 tons (see Appendix L). Thus while the low and median estimates of nitrous oxide emission from commercial fertilizer application are relatively insensitive to interannual fluctuations in fertilizer consumption, the upper part of the range is highly sensitive to such fluctuations. This indicates the need to better resolve the uncertainties governing emissions rates for different soils, climates and management regimes.

Statewide emissions of N_2O from the use of commercial fertilizers are estimated in 1990 to have totaled 9,366 to 10,333 tons, with a median value of 9,366 to 10,333 tons.

In general, a high degree of uncertainty attaches to the estimates of N_2O emissions from commercial fertilizer application. The emission factors presented in Table 82 are based on a relatively small set of experimental data and often apply only to the crop year or, in some cases, to only part of it. Thus it is possible that the emissions ranges employed in this inventory are substantially skewed. In its national greenhouse gas inventory, the U.S. Department of Energy concludes that estimates of N_2O production from fertilizer application are probably only accurate to within one order of magnitude.[51]

Finally, the amount of fertilizer nitrogen consumed in Minnesota in 1980 was roughly twice the amount of fertilizer nitrogen consumed in 1970, and was 30 percent above 1975 consumption. However, between 1980 and 1990, total statewide fertilizer nitrogen consumption was relatively unchanged.[201] This suggests that N_2O emissions from commercial fertilizer applications have probably been fairly constant for the past decade.

Nitrous Oxide Emissions from the Use of Animal Manure

The use of animal manure as fertilizer constitutes another possible source of N_2O emissions to the atmosphere. The total nitrogen content of the animal manure produced annually in Minnesota is roughly of the same order as that contained in commercial fertilizers and applied to agricultural fields. The few field experiments that have been conducted using manure suggest rates of emission of N_2O comparable to those from many commercial nitrogen fertilizers.

The nitrogen content of animal manure generated in Minnesota in 1990 is shown in Table 85. These estimates were calculated on the basis of livestock populations and coefficients taken from Vanderholm (1985).[202] The total amount of nitrogen contained in manure produced in 1990 is estimated to have been 317,911 tons. This is in good agreement with other estimates.[203]

A substantial portion of nitrogen in manure is thought likely to be lost due to leaching from manure collecting systems. For those manure systems typically in use in Minnesota, a value for nitrogen loss of 30 to 50 percent would be appropriate.[202]

In field experiments using manure and a small amount of ammonium nitrate (e.g., 7 percent of the total), Cates and Keeney (1987) found that 1.8 percent of the nitrogen in the applied manure-fertilizer evolved as N_2O.[204] Taken alone, ammonium nitrate is a rather weak source of N_2O, with low rates of evolution of its total nitrogen content to nitrous oxide. These are estimated at 0.1 to 0.4 percent. This suggests that a value of 1.5 percent might be a reasonable estimate for the percentage of the total nitrogen content of manure that is evolved to N_2O upon application.

Table 85. Minnesota Production of Nitrogen through Animal Manure

	Head of Livestock (in Thousands)	Lbs. of Nitrogen
Dairy Cattle	1,040	186,241,250
Feedlot Cattle	288	29,656,250
Other Beef Cattle	274	117,336,550
Swine	4,548	83,846,888
Sheep	285	4,681,125
Turkeys	46,300	162,235,200
Horses	55	5,430,105
Chickens	50,946	46,393,914
TOTAL		**635,821,282(a)**

Sources: Table 78 and Appendix M.

(a) 317,911 tons of nitrogen

Conservatively, we assume that two-thirds of all manure nitrogen is leached away from manure collecting facilities by rainfall, leaving 105,970 tons of nitrogen available for denitrification. To be conservative, we also assume that 1 percent of this evolves as nitrous oxide. At this rate, 1,665 tons of N_2O would have been emitted to the atmosphere in 1990 from the use of manure as fertilizer. This is roughly one-sixth of the emission estimated for commercial fertilizer use. Khalil and Rasmussen (1992) estimate that globally N_2O production from livestock manure is some 550,000 tons, or about one-half of global N_2O emissions resulting from the use of commercial fertilizers.[170]

Statewide emissions of N_2O from the use of animal manure fertilizers are estimated in 1990 to have totaled 1,665 tons.

Only two field experiments have been conducted on N_2O emissions from animal manure used as fertilizer. Although this is not at all dissimilar in kind from the number of field experiments on which some of the emissions coefficients for commercial fertilizers are based, e.g., ammonium sulfate, ammonium chloride, potassium nitrate, this reveals the substantial degree of uncertainty inherent in this calculation.[199] The question of nutrient loss through leaching contributes likewise to these substantial uncertainties.

Municipal Sludge

Between 1990 and 1993 an annual average of 22,252 dry tons of municipal sludge was applied to agricultural soils in Minnesota on an average of 13,000 acres.[205] At a nitrogen content of 5 percent for municipal sludge, this would amount to 1,113 tons of nitrogen available for denitrification. For commercial fertilizers and manure, an emissions rate of 0.1 to 1 percent is typical. At an emissions rate of 1 percent, 11 tons of nitrogen as nitrous oxide would have been released to the atmosphere through the denitrification of sludge applied as fertilizer, or 17 tons of N_2O. This is negligible in comparison to emissions from other sources.

Agricultural Liming of Fields

Limestone or calcium carbonate ($CaCO_3$) is applied to agricultural fields, particularly in the eastern half of Minnesota, to raise the pH of soils. During the liming of soils, calcium carbonate reacts with soil organic acids to produce various calcium salts and carbon dioxide, which is emitted to the atmosphere.[111] Most calcium carbonate that is applied to agricultural fields in Minnesota is produced either from crushed limestone, marl or is an industrial byproduct of processes involving limestone.

Over the period from 1991 to 1993, an annual average of 298,225 tons of pure calcium carbonate was applied to agricultural fields in Minnesota.[206] It is assumed that one molecule of carbon dioxide is emitted for every molecule of $CaCO_3$ that is applied, and that the liming of fields is required once every five years, at the end of which the soils can be assumed to have been returned to their original pH and all applied calcium carbonate can be assumed to have been consumed.[207] The molecular weights of carbon dioxide and $CaCO_3$ are 44.008 and 100.087, respectively. Thus the amount of carbon dioxide that is estimated to have been emitted to the atmosphere in 1990 from the agricultural liming of fields would equal

$$\frac{298{,}225 \bullet 44.08/100.087}{5}$$

or 26,268.7 tons of carbon dioxide.

Statewide emissions of CO_2 from the agricultural liming of fields are estimated in 1990 to have totaled 26,269 tons.

SECTION XXIV. Emissions Summary for Agricultural Practices

Estimated emissions of nitrous oxide, methane, and carbon dioxide from agricultural practices are shown in Table 86 for the year 1990. In total, excluding combustion-related emissions, which were treated in Part II, Section II of this inventory, agricultural practices are estimated to have resulted in 1990 in the release of

Table 86. Summary of Emissions from Agriculture

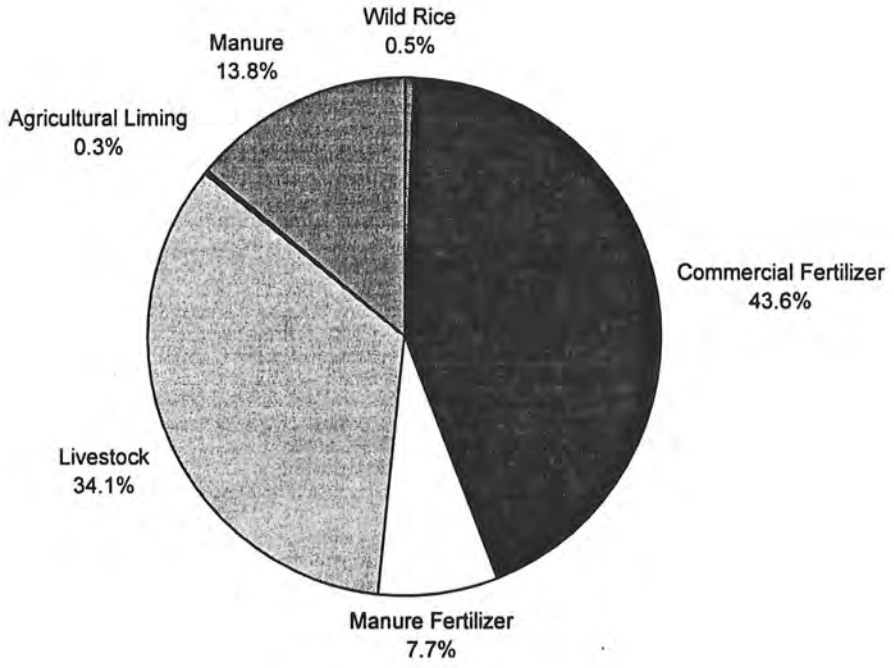
Source of Emissions	Gas	Emission (in tons)	CO_2-Equivalent Emission[a,b] (in tons)
Commercial Fertilizer	N_2O	9,366 to 10,333	2,528,820 to 2,789,910
Manure Fertilizer	N_2O	1,665	449,550
Livestock	CH_4	179,931	1,979,241
Animal Manure	CH_4	72,595	798,545
Wild Rice	CH_4	1,457 to 4,392	16,027 to 48,312
Agricultural Liming	CO_2	26,269	26,269
TOTAL			**5,798,452 to 6,091,827**

(a) Using the global warming potentials given in Table 3.
(b) Rounded to the nearest ton.

11,031 to 11,998 tons of N_2O, 253,983 to 256,918 tons of CH_4, and 26,269 tons of CO_2.

Estimated CO_2-equivalent emissions are also shown in Table 86 for agricultural practices. CO_2-equivalent emissions to the atmosphere from agricultural practices total between 5,798,452 and 6,091,827 tons, or about 5 percent of total statewide CO_2-equivalent emissions. Emissions from fertilizers and livestock comprise more than three-quarters of the total (see Figure 13).

Figure 13. CO_2-Equivalent Emissions from Agriculture[a]



(a) Of a total emission of 5,798,452 tons.

PART VII. EMISSIONS FROM LAND-USE CHANGES AND ACTIVITIES

The total land area of Minnesota is roughly 51 million acres. About 33 percent of this is forested.[208] Land-use activities on forested land can result in anthropogenic emissions of greenhouse gases or their precursors in both the short-term and the long-term, as well as in the short-term and long-term removal of these gases from the atmosphere.

Below emissions from present day land-use activities in Minnesota forests are estimated. Present day growth in the growing stock of forests on Minnesota timberlands is estimated in 1990 to have resulted in the sequestration of roughly 2.6 million tons of carbon in forest standing biomass, in the short-term offsetting 9,647,161 tons of CO_2 emissions from fossil fuel combustion and related activities. No similar significant long-term offset of emissions was identified.

Section XXV. Emissions from Land-Use Activities in Minnesota

Carbon dioxide and nonCO_2 greenhouse gases and their precursors can be released to the atmosphere as a result of land-use activities. A large amount of carbon is tied up in the standing biomass of temperate forests, and an even larger amount, almost twice as much as is held in above ground standing biomass, is contained in forest soils.[209] Upon permanent conversion of forested land to cropland or pasture, most above ground carbon and up to one-half of below ground carbon is permanently removed from terrestrial storage and is released to the atmosphere.[210]

CO_2 is also emitted to the atmosphere as a result of forest decline from air pollution effects, although whether the removal of carbon from terrestrial storage to the atmosphere is permanent depends on subsequent developments in affected forests.

NonCO_2 gases like CH_4, CO, NO_X, N_2O, and NMVOCs are emitted to the atmosphere upon land-clearing activities that involve burning.[211,212] NonCO_2 gases are also emitted to the atmosphere from prescribed burning of forest areas following clearcutting and preliminary to replanting or reseeding, and as a result of the prescribed burning of grasslands and prairies for purposes of native species preservation.[73]

Net anthropogenic emissions of CH_4 would also result from any increase in total wetland acreage or in the areal extent of flooded fields.

Finally, land-clearing and the permanent conversion of forested land and prairie to cropland or pasture reduces the ability of soils to remove excess CH_4 and CO from the atmosphere. In undisturbed conditions, forest and prairie or grassland soils act as a sink for CH_4 and CO, absorbing a part of excess atmospheric concentrations of these gases and destroying them through microbial activities.[213]

Conversely, any permanent conversion of cropland or pasture to forest or grassland or prairie has the long-term effect of enhancing the terrestrial storage of carbon and terrestrial sinks for CO and CH_4. Many temperate latitude forests have been sequestering large amounts of carbon for several decades through natural processes of forest growth and maturation, offsetting in the short- to medium-term a percentage of CO_2 emissions from fossil fuel combustion and related activities.[214] Also, there is evidence that emissions of CH_4 and N_2O decline upon soil acidification following sustained exposure of forest soils to acid precipitation.[215]

Emissions from Forestry and Forest-Clearing

In Minnesota, there are no ongoing forest-clearing activities leading to the creation of cropland. Cropland expansion at the expense of forest land climaxed in the 1940s, and the amount of total cropland in production has been declining ever since.[216]

There is in Minnesota a large wood products industry utilizing Minnesota forests, with particular emphasis on paper and pulp manufacturing. However, at present, net annual removals of wood as a result of fuel uses and uses of wood and paper and other forest products are substantially less than annual additions to standing forest biomass as a result of forest growth.[208] As a result, despite logging and fuel use activities, a large amount of carbon is currently being sequestered in Minnesota forests. This has the effect of offsetting a part of annual statewide emissions of CO_2 from fossil fuel combustion and related activities.

Timberland constitutes about 90 percent of all forested land in Minnesota. Most of the remainder is reserved forest land and forest land classified as unproductive.[217] Disturbances on reserved and unproductive forest land are minimal, although rates of carbon sequestration, especially on reserved forested land, are probably similar to those on timberland.

The average annual increase in the growing stock on timberland in Minnesota is shown in Table 87 by major tree species for the period 1980 to 1990. Also shown in Table 87 is the estimated annual increase in forest growing stock on timberland in terms of stored carbon. In total, 2,597,416.5 to 2,668,098.5 tons of

Table 87. Estimated 1990 Carbon Storage In Minnesota Forests

	Annual Increase In Growing Stock	Conversion Factor (in lb. carbon/cu. ft.)	Annual Forest Carbon Storage (in tons of carbon)
Softwoods			
Pine	43.4	13.69	297,073
Other(a)	68.8	11.41	392,504
Soft Hardwoods			
Aspen	132.4	14.45	956,590
Other(b)	59.9	12.09 to 14.45	362,095.5 to 432,777.5
Hard Hardwoods			
Oak	33.2	19.64	326,024
Other(c)	29.4	17.9	263,130
TOTAL			**2,597,416.5 to 2,668,098.5**

Sources: Jaako Poyry Consulting Inc., *Maintaining Productivity and the Forest Resource Base: A Technical Paper for a Generic Environmental Impact Statement on Timber Harvesting and Forest Management in Minnesota,* (Raleigh, NC and White Plains, NY: December 1992).
U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA 230-B-92-00, (Washington, D.C.: 1992).

(a) 60% spruce and fir, 40% northern white cedar and tamarack. See North Central Forest Experiment Station, *Minnesota Forest Statistics, 1990*, NC-141, (St. Paul, MN: U.S. Forest Service, 1992).
(b) 30% birch, 26% basswood, 22.4% soft maple, 13.9% poplar.
(c) Dominated by hard maple.
(d) Conversion factor for spruce and fir.
(e) Conversion factor for soft maple and birch.

carbon are estimated to have been stored in 1990 in Minnesota timberlands as a result of forest growth. In full CO_2 molecular equivalents, this is equivalent to 9,647,161 tons of CO_2, and thus represents a short-term storage of carbon equal to about 10.8 percent of annual statewide emissions of CO_2 from fossil fuel use and other in-state activities. This estimate is similar to other estimates of this offsetting effect.[218]

The annual sequestration of carbon in Minnesota forests in estimated presently to total an equivalent of 9,647,161 tons of CO_2.

The estimates of increase in growing stock given in Table 87 implicitly account for the effects of tree removals for paper, saw timber, and domestic and industrial fuel uses, and losses due to tree mortality. Table 88 shows the amount of carbon contained in trees harvested in 1990 for human uses. This represents the amount of carbon that would otherwise have been stored in Minnesota forests had these activities not taken place. This totals roughly 3.98 million tons of carbon.

Table 88. Carbon Removed From Minnesota Forests in 1990 Through Fuel Use And Forest Products Uses

	Tons of Carbon Removed
Fuel Uses	889,823
Forest Product Uses	3,089,408[(a)]
TOTAL	**3,979,231**

Sources: Jaako Poyry Consulting Inc., *Maintaining Productivity and the Forest Resource Base: A Technical Paper for a Generic Environmental Impact Statement on Timber Harvesting and Forest Management in Minnesota*, (Raleigh, NC and White Plains, NY: December 1992) and Table 26 above.

(a) Estimated from 3,448,000 cords using 128 cubic feet of wood per cord and 14 lb. of carbon per cubic foot of wood.

NMVOCs are emitted in substantial quantities from forest ecosystems. These include terpenes and isoprenes.[219] As forests regrow following harvesting, emissions of NMVOCs increase. NMVOCs are precursors of tropospheric ozone. Thus one of the unintended consequences of forest regrowth in Minnesota is a probable increased emission of NMVOCs and, given adequate NO_X emissions from other sources, elevated tropospheric ozone.[220]

Thus far no large-scale air pollution effects on Minnesota forests have been identified. Increasing mortality among certain tree species in Minnesota forests has resulted principally from insect damage and disease.[208,217]

Tree planting and seeding activities in Minnesota forests in 1990 are estimated to have occurred on 20,563 acres of existing timberland.[208] In the very long-term, based on average amounts of carbon stored above ground per acre in Minnesota forests, with zero mortality of planted seedlings or seeded plants, these trees will eventually sequester an estimated 378,000 tons of carbon.[221] However, since these trees will simply replace trees harvested for forest products in the interim, no long-term net sequestration of carbon should result.

By contrast, based on Forest Inventory and Analysis (U.S. Forest Service) test plots, 10,050 acres of former cropland and pasture annually are being reclaimed by forest.[208] Over the long-term, and assuming that the ability of the climate to support this forest expansion persists, 185,000 tons of carbon eventually may be sequestered in forests through aforestation.[221]

In the long-term, whether or not permanent sequestration of carbon in fact results from tree planting activities will depend a good deal less on present-day decisions than upon the decisions of multiple generations of decisionmakers in the future. Ultimately they will determine the fate and effectiveness of any present-day aforestation program.

Forest soils in Minnesota have been exposed to heightened levels of acid precipitation, but it is not now possible to narrowly estimate the effects that this exposure might have on emissions of CH_4 or N_2O from soils.

Finally, it is possible that forest soils in Minnesota timberlands are losing carbon as a result of clearcutting activities, but these are impossible to estimate at present. Following the recommended U.S. Environmental Protection Agency *State Workbook* methodology, no attempt is made to estimate these in this inventory. Emissions of nonCO_2 greenhouse gases or their precursors from prescribed burning in Minnesota are likely, but again, following the recommended U.S. Environmental Protection Agency *State Workbook* methodology, no attempt is made to estimate these. The general sense is that, in absence of human influences, these would have occurred anyway, and thus should not properly be considered an anthropogenic influence on emissions. The number of acres of prescribed forest and prairie or grasslands burning in the state of Minnesota is shown in Table 89 for 1990.

Long-term changes in the efficiency of soils in Minnesota in removing CO and CH_4 from the atmosphere are also not now possible to estimate, although that efficiency may be increasing as farmland increasingly reverts to forest, prairie and grassland.[222] It is also possible that N_2O is being emitted as a result of clearcutting activities in Minnesota forests, but again these are not now susceptible to estimation.[223]

Table 89. Acres Of Prescribed Burning In Minnesota: 1990

Type of Prescribed Burning	Number of Acres
Logging Slash	91
Reforestation Ground Preparation	1,237
Prairie and Grassland	15,000

Sources: Jaako Poyry Consulting Inc., *Maintaining Productivity and the Forest Resource Base: A Technical Paper for a Generic Environmental Impact Statement on Timber Harvesting and Forest Management in Minnesota,* (Raleigh, NC and White Plains, NY: December 1992).
Personal conversation with G. Meadows, Minnesota Department of Natural Resources, May 1994.

Emissions from Wetlands Conversion

There are an estimated 8.7 million acres of wetlands in Minnesota, covering 16.2 percent of the surface area of the state.[224] Total wetland amounts in Minnesota have declined by an estimated 40 percent since 1780, mostly as a result of agricultural activities.[225] Recent trends are uncertain. No estimate of recent trends in total statewide wetlands acreage has been offered by any agency or analyst.[226] The total amount of wetlands could be increasing as a result of agricultural set-aside programs and farmland abandonment or could be decreasing due to wetland destruction in urban and some agricultural areas.

Climate Change Effects

Minnesota's forests are thought likely to be particularly sensitive to global warming. These forests are located at the present north-south boundary between boreal forest and northern hardwood forest and relatively near the east-west boundary between prairie and parkland. It is thought that forest systems located at these boundaries are likely to be one of the more sensitive natural systems to global warming and rising regional temperatures.

The forest response to rising temperature is quite complex, and depends on a host of factors, including local topography, soil type, and the intensity of forest management. However, in general one would expect large-scale northward and eastward migration of tree distribution boundaries as temperature rises, on the order of 200 to 400 kilometers, with a northern hardwood forest generally replacing existing forests dominated by spruce, fir, pine, and aspen.[2,227-229]

The critical parameter is the rate of change in climate. If climatic change is particularly rapid, exceeding 0.1 degrees Celsius per decade, it is thought that forest die-off could result.[229] In general, the pace of the warming predicted for the midcontinent exceeds by a factor of 10 to 100 times those rates of warming to which throughout the Holocene forests at temperate latitudes have successfully adapted through slow migration.[36,230] This means simply that if mean surface temperature is allowed to rise at rates like those that are now forecast, many of the forests within the state of Minnesota will be at risk, with large additional emissions of carbon resulting from forest decline a distinct possibility.

The science underlying the estimation of the forest response to global warming is still evolving and far from mature. Thus it is possible that less dramatic outcomes could result. However, at present much of the evidence points in the direction of dramatic change in Minnesota's forests with global warming.[231]

It might be noted that future emissions of CO_2 from forest responses to climatic change, if they occur, will result as much from emissions of greenhouse gases and their precursors from the period from 1890 to 1990 as from emissions that occur in the next century. This implies the present day decisions to emit or to curtail emissions of greenhouses gases to the atmosphere will have an effect on future forest responses to global warming and on potential emissions associated with that response.

Other pools of organic carbon could also respond to rising temperature through increased rates of both aerobic and anaerobic respiration. The estimated amount of carbon presently stored in organic pools of carbon in Minnesota is given in Table 90. The total amount of carbon sequestered in these pools is equivalent to roughly 350 years worth of combustion-related CO_2 emissions from Minnesota at current rates of emission. Thus any increase in biotic respiration resulting from increasing regional temperatures would have implications for statewide emissions rates of CO_2.

It is not now possible to conclude whether significant long-term net emissions of CO_2 are either possible or likely from Minnesota soils, sediments, peat bogs, or wetlands. At a global level, significant net emissions of CO_2 are thought to be possible in response to rising global temperatures.[232]

Table 90. Organic Carbon Pools in Minnesota (in Billions of Tons of Carbon)

System	Best Estimate	Possible Range
Peatland	3.1	2.3 to 4.1
Lake Sediments	2.6	0.8 to 6.2
Soil Carbon	2.0	1.6 to 2.4
Wetlands	0.4	0.2 to 0.5
Tree Biomass	0.28	0.2 to 0.36
TOTAL	**8.4**	**5.1 to 13.6**

Source: Minnesota Department of Natural Resources, "Carbon Dioxide Budgets in Minnesota and Recommendations on Reducing Net Emissions with Trees," report to the Minnesota Legislature, St. Paul, MN, January 1991.

Conclusion

Land-use activities and changes can result in the emission to the atmosphere of greenhouse gases of both short-term and long-term significance. In Minnesota, the influence of present-day land-use activities appear to be of a predominantly short-term nature, and to involve withdrawals of carbon from the atmosphere and subsequent storage in the standing biomass of Minnesota's forests.

Present annual carbon storage in Minnesota forests is estimated to be some 2.6 million tons of carbon. In the short-term, this would offset an estimated emission of some 9,647,161 tons of carbon dioxide released to the atmosphere as a result of fossil fuel combustion. Since in forests used for commercial timber periods of sustained forest growth are followed by timber harvest, this offsetting effect will be temporary, and will give way in the next few decades to a period of net short-term emissions from timberland.

PART VIII. STATEWIDE EMISSIONS SUMMARY, RECOMMENDATIONS AND CONCLUSIONS

Section XXVI. Statewide Emissions Summary for All Emissions Sources

Estimated 1990 emissions of CO_2, CH_4, N_2O, NO_x, ozone-depleting compounds, CO, and NMVOCs are shown in Table 91 for the state of Minnesota. These are taken from Tables 40, 52, 60, 72, 86 and 87 above. Both in-state emissions and out-of-state emissions associated with in-state activities are shown. In addition, short-term carbon storage in Minnesota forests is also shown in Table 91.

In total, 89,070,822 to 89,163,827 tons of CO_2 are estimated to have been emitted from in-state activities in Minnesota involving fossil fuel use or limestone use, and 96,848,742 to 97,058,751 tons of CO_2 are estimated to have been produced and emitted to the atmosphere from in-state activities involving fossil fuel and limestone use plus out-of-state activities associated with the in-state consumption of fossil fuels and limestone and cement. Because they involve the oxidation of carbon long sequestered in either fossil fuels or limestone, they represent emissions with very long-term effects on climate.

Estimated CO_2 emissions associated with in-state activities are dominated by in-state fossil fuel consumption, processing, and transportation, which account for 99.7 percent of in-state CO_2 emissions. The direct emission of CO_2 from combustion alone accounts for 98.6 percent of all in-state CO_2 emissions.

Estimated CO_2 emissions associated with in-state fossil fuel and limestone use and out-of-state activities associated with in-state fossil fuels, limestone, and cement consumption are also dominated by in-state fossil fuels consumption, processing, and transportation, which account for 91.6 percent of all in-state plus out-of-state emissions from these sources. In-state plus out-of-state emissions of CO_2 from fossil fuel production, processing, transportation and consumption account for 98.7 percent of all in-state plus out-of-state CO_2 emissions from Minnesota. The remainder arises from the production and use of cement and limestone.

Forest growth in 1990 in Minnesota is estimated to have resulted in the short-term sequestration of 2,597,417 to 2,668,099 tons of carbon, offsetting again in the short-term an average of 9,647,161 tons of CO_2 emitted from fossil fuel, cement and limestone consumption.

Table 91-1. Total Estimated Statewide Emissions by Greenhouse Gas or Precursor Gas and Source (in Tons)[a] (Part A)

Emissions Source	CO_2	CH_4	N_2O	ODCs	CO	NO_x	NMVOCs
In-state Fossil Fuel Use, Processing, Transportation							
Fossil Fuel Combustion	87,859,509	10,119 to 10,375	3,006		749,039 to 1,095,151	339,832 to 343,337	134,819
Combustion CO Oxidation	910,847 to 962,541						
Pollution Control	3,744						
Nonfuel Uses	766						
Natural Gas Leakage	1,129	37,293					3,909
Petroleum Refinery Leakage		124					
Subtotal	**88,775,995 to 88,827,689**	**47,536 to 47,792**	**3,006**		749,039 to 1,095,151	339,832 to 343,337	**138,728**
Out-of-State Fossil Fuels Production							
Oil Production	595,908 to 712,912	10,361 to 48,617					
Natural Gas Production	1,351	47,736					
Coal Mining		7,016 to 69,471					
Energy Inputs to Finished Fuels	5,137,471						
Electricity Imports	1,107,608						
Subtotal	**6,842,338 to 6,959,342**	**65,113 to 165, 824**					
In-State Process Emissions							
Steel Manufacture	2,418						
Ozone Depleting Compounds				8,511			
Subtotal	**2,418**			**8,511**			

Sources: Tables 40, 52, 60, 72, 86, and 87.
(a) All emissions rounded to the nearest ton.

Table 91-2. Total Estimated Statewide Emissions by Greenhouse Gas or Precursor Gas and Source (in Tons) [a] (Part B)

Emissions Source	CO_2	CH_4	N_2O	ODCs	CO	NO_x	NMVOCs
Out-of-State Process Emissions							
Cement Manufacture	834,988						
Lime Manufacture	100,594						
Subtotal	**935,582**						
Landfill Leakage and Incineration							
Landfill Leakage		222,237 to 253,367					
Incineration	265,957 to 307,213	264			520 to 592	302 to 342	
Incineration CO Oxidation	183 to 238						
Subtotal	**266,140 to 307,451**	**222,501 to 253,631**			**520 to 592**	**302 to 342**	
Agriculture							
Commercial fertilizer Use			9,366 to 10,333				
Manure fertilizer Use			1,665				
Livestock		179,931					
Livestock Manure		72,595					
Wild Rice Cultivation		1,457 to 4,392					
Liming of Fields	26,269						
Subtotal	**26,269**	**253,983 to 256,918**	**11,031 to 11,998**				
TOTAL							
In-State	**89,070,822 to 89,163,827**	**524,020 to 558,341**	**14,037 to 15,004**	**8,511**	**749,559 to 1,095,743**	**340,134 to 343,679**	**138,728**
All	**96,848,742 to 97,058,751**	**589,133 to 724,165**	**14,037 to 15,004**	**8,511**	**749,559 to 1,095,743**	**340,134 to 343,679**	**138,728**
Short-Term Carbon Storage in Forests	(-) 9,647,161						

Sources: Tables 40, 52, 60, 72, 86, and 87.
(a) All emissions rounded to the nearest ton.

Total CH_4 emissions from in-state activities are estimated to have been 524,020 to 558,341 tons, and total CH_4 from in-state plus out-of-state activities associated with fossil fuels production are estimated to have been 589,133 to 724,165 tons. CH_4 emissions from in-state activities are dominated by those from agricultural activities, which are estimated to have accounted for about 47 percent of in-state emissions, and waste disposal activities, which are estimated to have accounted for about 44 percent of CH_4 emissions. In terms of in-state plus associated out-of-state emissions, out-of-state fossil fuels production and transportation activities are estimated to have accounted for about 24 percent of total in-state plus out-of-state CH_4 emissions. Waste disposal activities are estimated to have accounted for about 36 percent of in-state plus out-of-state CH_4 emissions, and agricultural activities about 39 percent.

All emissions of ozone-depleting compounds are from industrial or domestic process uses of these chemicals, and are estimated in 1990 to have totaled 8,511 tons. They include emissions of CFCs and their substitutes.

Total 1990 N_2O emissions from in-state activities are estimated to have totaled 14,037 to 15,004 tons. These are estimated to have been dominated by emissions from commercial fertilizer use, which are estimated to have accounted for 68 percent of all N_2O emissions. No out-of-state emissions of N_2O were estimated.

Total statewide CO and NO_x emissions are estimated to have been 749,559 to 1,095,743 tons in the case of CO and 340,134 to 343,679 tons in the case of NO_x. Nearly all are estimated to have resulted from combustion leading to energy production.

Finally, 138,728 tons of NMVOCs are estimated to have been emitted in 1990 as a result of in-state activities. Of identified emissions, 97 percent are estimated to have resulted from combustion.

Statewide CO_2-equivalent emissions totals are shown in Tables 92 and 93 for four long-term and four short-term emissions cases. CO_2-equivalent emissions are calculated using the Global Warming Potentials given in Table 3. As discussed in the Introduction to this inventory, the Global Warming Potential weightings calculated by the Intergovernmental Panel on Climate Change are measures of the relative effects of different greenhouse gas emissions. For a variety of reasons, these can provide only a gross sense of the relative magnitudes of the radiative effects of different greenhouse gas emissions. In the case of the CFCs and their substitutes, the effects of uncertainty are overwhelming, due largely to uncertainties relating to the radiative effects of ozone depletion. Thus it seems possible that the direct radiative effects of a present-day emission of these ozone-depleting compounds could range

Table 92. Statewide CO_2-Equivalent Emissions by Source and Case: Emissions with Long Term Effects[a,b]

Emission Type	Case A	Case B	Case C	Case D
In-State				
Fossil Fuel Combustion & Fossil Fuel CO Oxidation	89,720,540	89,720,540	89,720,540	89,720,540
Other In-State Fossil Fuel Use, Transmission, Processing	417,226	417,226	417,226	417,226
Landfill Leakage	2,615,822	2,615,822	2,615,822	2,615,822
Other Waste Disposal	289,700	289,700	289,700	289,700
Commercial Fertilizer	2,659,365	2,659,365	2,659,365	2,659,365
Livestock & Manure	3,227,336	3,227,336	3,227,336	3,227,336
Other Agriculture	58,439	58,439	58,439	58,439
ODCs	0	27,342,370	0	27,342,370
Other Process	2,418	2,418	2,418	2,418
Out-Of-State				
Fossil Fuels Production	0	0	8,170,994	8,170,994
Process Emissions	0	0	935,582	935,582
Total	**98,990,846**	**126,333,216**	**108,097,422**	**135,439,792**

Sources: Tables 40, 52, 60, 72, 86, and 87. See Appendix N.
(a) Using midpoints of emission ranges where these have been calculated.
(b) All emissions rounded to the nearest ton.

from zero to 3,500-7,000 times the effect of a comparable emission by weight of carbon dioxide.

In the case of precursor compounds like CO, NO_x, or NMVOCs, no accepting scaling or weighting factor has been offered as to their relative effects on climate through their influences on tropospheric ozone levels.

The different cases for which CO_2-equivalent emissions are calculated are shown in Table 94. The long-term emissions cases (Cases A,B,C and D) exclude consideration of the short-term effects on net CO_2 emissions of near-term carbon storage in forests. The short-term emissions cases (Cases E,F,G and H) do take into consideration this offsetting effect of near-term carbon storage in Minnesota forests. In both long-term and short-term emissions cases, CO_2-equivalent emissions of the hard-CFCs and their

Table 93. Statewide CO_2-Equivalent Emissions by Source and Case: Emissions with Long-Term and Short-Term Effects[a,b]

Emission Type	Case E	Case F	Case G	Case H
In-State				
Fossil Fuel Combustion & Fossil Fuel CO Oxidation	89,720,540	89,720,540	89,720,540	89,720,540
Other In-State Fossil Fuel Use, Transmission, Processing	417,226	417,226	417,226	417,226
Landfill Leakage	2,615,822	2,615,822	2,615,822	2,615,822
Other Waste Disposal	289,700	289,700	289,700	289,700
Commercial Fertilizer	2,659,365	2,659,365	2,659,365	2,659,365
Livestock & Manure	3,227,336	3,227,336	3,227,336	3,227,336
Other Agriculture	58,439	58,439	58,439	58,439
ODCs	0	27,342,370	0	27,342,370
Other Process	2,418	2,418	2,418	2,418
Out-Of-State				
Fossil Fuels Production	0	0	8,170,994	8,170,994
Process Emissions	0	0	935,582	935,582
Subtotal	**98,990,846**	**126,333,216**	**108,097,422**	**135,439,792**
Forest Carbon Storage	(-)9,647,161	(-)9,647,161	(-)9,647,161	(-)9,647,161
Total	**89,343,685**	**116,686,055**	**98,450,261**	**125,792,631**

Sources: Tables 40, 52, 60, 72, 86, and 87. See Appendix N.
(a) Using midpoints of emission ranges where these have been calculated.
(b) All emissions rounded to the nearest ton.

substitutes are treated assuming a range of net radiative effects equal to zero to 100 percent of the relative direct radiative effects calculated by the Intergovernmental Panel on Climate Change. Several long-term and short-term emissions cases also treat the effects of out-of-state emissions associated with in-state uses of fossil fuels, cement, and limestone (Cases C,D,G and H).

Long-term in-state CO_2-equivalent emissions are given in Cases A and B in Table 92. Total long-term in-state weighted emissions are estimated to have totaled from 98,990,846 to 126,333,216 tons, depending on how the radiative effects of the CFCs and their substitutes are treated.

Table 94. CO_2-Equivalent Emissions Cases

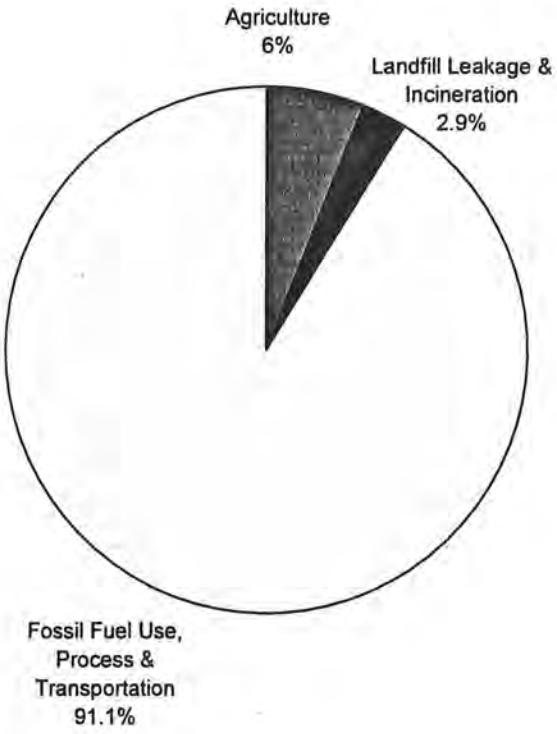
Case	Emissions Characterization
Case A	Long-term, in-state, low CFCs
Case B	Long-term, in-state, high CFCs
Case C	Long-term, in-state plus out-of-state, low CFCs
Case D	Long-term, in-state plus out-of-state, high CFCs
Case E	Short-term, in-state, low CFCs
Case F	Short-term, in-state, high CFCs
Case G	Short-term, in-state plus out-of-state, low CFCs
Case H	Short-term, in-state plus out-of-state, high CFCs

Long-term in-state CO_2-equivalent emissions are dominated by emissions from fossil fuel use, processing, and transportation, which are estimated to account for between 71 and 91 percent of all weighted emissions (see Figures 14 and 15). Weighted emissions from agricultural activities account for another 5 to 6 percent of weighted emissions, and emissions from landfill leakage and incineration between 2 and 3 percent. Weighted emissions of CFCs and their substitutes account for between 0 and 22 percent of all statewide emissions.

A more detailed breakdown of weighted emissions is shown in Figure 16 for long-term in-state CO_2-equivalent emissions where the net radiative effect of emissions of ozone depleting compounds is assumed to be zero (see Case A). This is the most conservative estimate of long-term statewide emissions of radiatively-active gases. Total CO_2-equivalent emissions are estimated in this case to be some 98.99 million CO_2-equivalent tons. Emissions from fossil fuel combustion and the associated oxidation of carbon monoxide produced as a result of energy production are estimated to have comprised 90.6 percent of all weighted statewide emissions of greenhouse gases, commercial fertilizer use an additional 2.7 percent, activities relating to animal agriculture 3.3 percent, and landfill leakage and other sources 3.4 percent of all weighted long-term emissions.

If one includes identified out-of-state emissions associated with in-state activities, total long-term statewide emissions of radiatively-active gases are estimated to fall into the range of 108,097,422 to 135,439,792 CO_2-equivalent tons (see Cases C and D, Table 92). Emissions associated with in-state fossil fuels

Figure 14. Long-term In-state CO_2-Equivalent Emissions by Emissions Source: Case A, Zero CFC Effect[a]

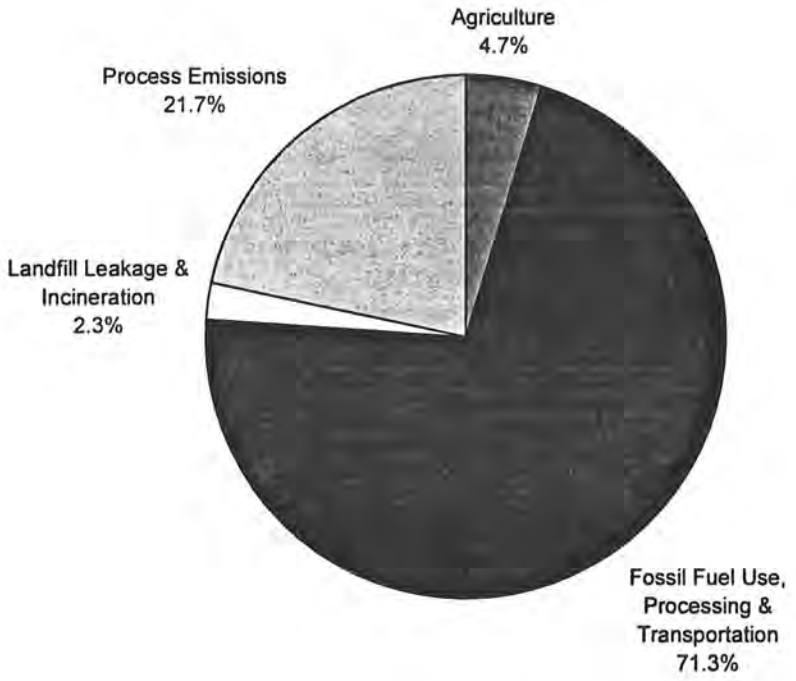


(a) Of a total of 98,990,846 CO_2-equivalent tons.

consumption, processing, and transportation and the out-of-state production of finished fossil fuels and electricity are estimated to account for 72.6 to 90.9 percent of all weighted emissions, again depending on how the net radiative effects of the CFCs and their substitutes are treated. Estimated CO_2-equivalent emissions of the CFCs and their substitutes are estimated to account for between zero and 20.2 percent of all weighted long-term emissions from in-state and associated out-of-state emissions.

In the short-term, carbon storage in Minnesota forests will offset roughly 9.6 million tons of CO_2 emitted as a result of fossil fuel combustion and related activities. Subtracting this amount from estimated 1990 emissions from in-state activities results in a short-term CO_2-equivalent emission of 89,343,685 to 116,686,055 tons (see Cases E and F, Table 93). If we assign the amount of emissions offset

Figure 15. Long-term In-state CO_2-Equivalent Emissions by Emissions Source: Case B[b]

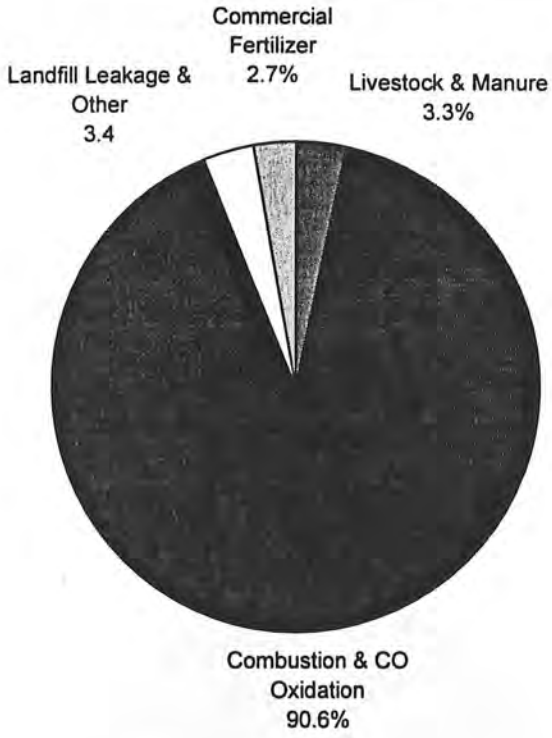


(a) Of a total of 126,333,216 CO_2-equivalent tons.

proportionally to CO_2 emissions sources according to their percent of all CO_2 emissions, short-term emissions are dominated by fossil fuel use, processing and transportation emissions, which comprise between 69 and 90 percent of weighted emissions (see Figure 17 for Case E).

Cases G and H in Table 93 show estimated CO_2-equivalent emissions from in-state plus out-of-state activities less the amount of near-term carbon storage in Minnesota's forests. Total weighted emissions in this case total 98,450,261 to 125,792,631 CO_2-equivalent tons. Weighted emissions from fossil fuel consumption and production account for between 70 and 90 percent of all weighted emissions in Cases G and H.

Figure 16. Long-term In-state CO_2-Equivalent Emissions by Emissions Source: Case A[(a)]

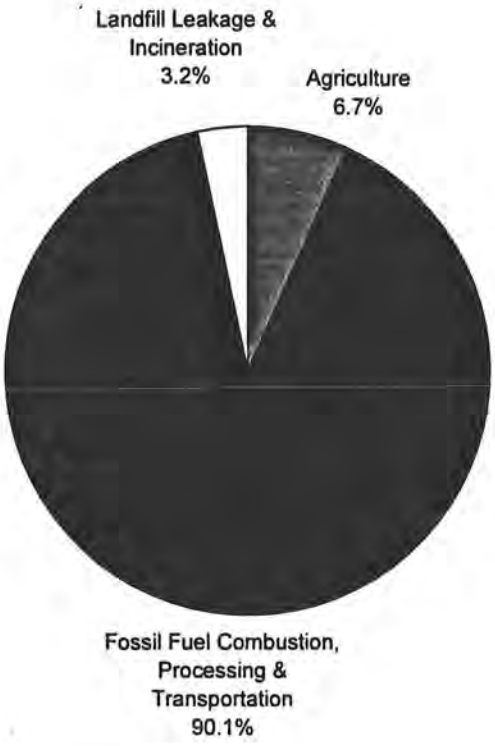


(a) Of a total of 98,990,846 CO_2-equivalent tons.

Finally, by gas, emissions of CO_2 dominate the CO_2-equivalent emissions totals for all eight emissions cases given in Tables 92 and 93. CO_2 emissions comprise roughly 70.5 to 90.1 percent of all weighted long-term in-state emissions (Cases A and B, respectively). The CFCs and their substitutes comprise between 0 and 21.7 percent of weighted emissions, while emissions of CH_4 comprise between 4.7 and 6 percent of long-term in-state CO_2-equivalent emissions. Emissions of N_2O constitute the remaining to 3.1 to 3.9 percent.

In the case of in-state plus out-of-state emissions (Cases C and D), CO_2 emissions as a percent of total long-term CO_2-equivalent emissions are slightly more important, comprising 71.4 to 90 percent of all weighted emissions, while they are slightly less important in Cases E through H, where a part of CO_2 emissions are assumed to be offset in the near-term by carbon sequestration in Minnesota forests. Generalizing across all emissions cases, CO_2 emissions account for roughly 70 to 90 percent of all CO_2-equivalent emissions, the CFCs and their substitutes account for roughly 0 to 23 percent, CH_4, roughly 5 to 7 percent, and N_2O, 3 to 4 percent.

Figure 17. Long-term In-state CO_2-Equivalent Emissions by Emissions Source: Case E[(a)]



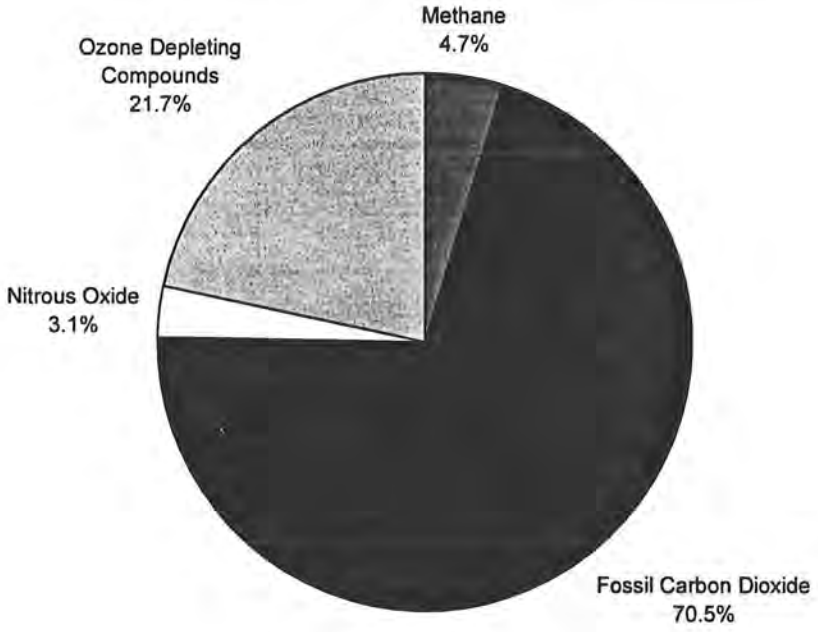
(a) Of a total of 89,343,685 CO_2-equivalent tons.

CO_2-equivalent emissions are shown by gas in Figure 18 for Case B, the most comparable case to those estimates done at the national level for the United States. At the national level for this high-CFC effect case, CO_2 emissions are estimated to constitute 70.5 percent of weighted emissions, emissions of N_2O are estimated to constitute 3.1 percent of weighted emissions, emissions of CH_4 are estimated to constitute 4.7 percent of weighted emissions, and emissions of CFCs and their substitutes are estimated to constitute 21.7 percent of all weighted emissions.[54]

Sources Not Treated

A number of emissions sources are not treated in this inventory due to lack of adequate information concerning emissions or activities underlying emissions. These are shown in Table 95. These are in addition to the process emissions that were listed in Tables 54 and 55 in Section XIV above. The most significant potential emissions sources that are not treated in this inventory probably involve N_2O production from sewage treatment activities, nitrogen fertilizer run-off, and combustion, and possibly CH_4 emissions from changing wetlands acreage. N_2O emissions from sewage treatment activities have been estimated to be the single largest anthropogenic source of N_2O globally, and those from fertilizer run-off the third largest anthropogenic source.[170]

Figure 18. Long-Term In-State CO_2-Equivalent Emissions From Minnesota: High CFC Case[a]



(a) Of a total weighted emission of CO_2-equivalent 126,333,216 tons.

At present it is not possible to even generally estimate emissions from these potential emissions sources. It is not known how they might affect the emissions estimates given above. However, given the general dominance of CO_2 emissions from fossil fuel combustion, it is unlikely that the effect of the exclusion of any one of them would be large enough to substantially affect the statewide emission totals given above.

Table 95. Emission Sources Not Treated in this Inventory

Emissions Source	Gas
Sewage treatment	N_2O
Combustion in the industrial fuel use sector	N_2O
Combustion in the agricultural fuel use sector	CH_4, N_2O, NO_x, CO, NMVOCs
Wetlands change	CH_4
Composting of wastes	CH_4
Leakage from demolition/construction landfills	CH_4
Prescribed burning and burning of slash	CH_4, N_2O, NO_x, CO, NMVOCs
Forest regrowth	NMVOCs
Decay of CH_4 emitted in prior years from natural gas pipelines and oil refineries	CO_2
Out-of-state coal coke manufacture	CO_2
Out-of-state petrochemicals and fertilizer manufacture	CO_2, N_2O, NO_x, NMVOCs
Out-of-state electronics manufacture	ODCs
Reversion of cropland to forests and grasslands	CH_4, N_2O[(a)]

(a) Constitutes a reduction in emissions strength for N_2O and an enhanced soil sink for CH_4.

Section XXVII. Recommendations for Improving the Inventorying Process

This inventory was assembled in large part following the methodologies for estimating emissions that are presented in U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA 290-92-002 (1992).[54] In a few cases where the given methodologies were deemed to be inappropriate or unworkable, resort was made to alternative calculative procedures that offered greater prospect of appropriately estimating emissions. This was particularly the case with regard to landfill emissions.

The *State Workbook* itself has the virtue in the case of many of the more important emissions of radiatively-active gases of offering simplified calculative procedures that fit nicely to the types of data that are available to state agencies.

However, this same simplification of the calculative procedures used to estimate emissions also constitutes the principal weakness of the *State Workbook*. There is in the *State Workbook* a persistent tendency to downplay or disregard the degree of uncertainty implicit in the inventorying process and in the methods used to calculate emissions. The text admits to a substantial degree of uncertainty, but nowhere provides a mechanism in the actual inventory process to deal with these uncertainties. Hence, there is a clear divergence in the *State Workbook* between statements acknowledging the uncertainty implicit in the calculative procedures and the actual practice of inventorying emissions as outlined in the *Workbook* chapters.

A case in point is nitrous oxide. At present, the atmospheric accumulation of N_2O is one of the least understood of all aspects of the question. No definitive conclusion has yet been offered as to the source of the ongoing accumulation of N_2O in the atmosphere.[2,170] The *Workbook*, however, implicitly presents fertilizer use and combustion as the principal sources of that atmospheric accumulation. This is questionable.

It would be extremely useful if greater attention were to be given to the general question of uncertainty in the calculative procedures given, and especially to methods that might be used to deal with the endemic uncertainties that are confronted in the process of estimating emissions. At the least, it would be useful if the *State Workbook* were to devote a chapter to a generalized discussion of methods for coping with uncertainty in the emissions estimation process.

In this regard, the most problematic aspect of the *Workbook* may be the presentation of the Global Warming Potential (GWP) apparatus. Relatively little discussion is offered regarding the manifest problems associated with the application of this weighting index to emissions or regarding the criticisms directed at the index by analysts in the scientific community. As a consequence, the utility of the GWP index for weighting emissions is overstated. At best, CO_2-equivalent emissions calculated using this index are approximations of the magnitude of weighted emissions. By avoiding a discussion of this question or only briefly touching upon it, the *Workbook* imputes a degree of accuracy to weighted emissions calculated using the GWP index that is probably unwarranted.

Thus one might just bring forward the general problem of weighted emissions of the ODCs, the radiative effects of which could range from zero to 3,500 to 7,000 times the effect of a like emission by weight of CO_2. Obviously, the larger discussion of uncertainty cannot be avoided in the *State Workbook*.

With regard to the estimation of emissions of greenhouse gases or their precursors in unadjusted physical units, it would be extremely useful if the *Workbook* could include not just a narrow or selective range of

emission factors or methodologies for estimating emissions but the full complement of available methodologies and emission factors, along with a discussion of their relative strengths and weaknesses. As it is presently written, the *Workbook* presents a single set of emission factors for, for instance, CO_2, from Grubb (1989)[63] without justification for the choice of these coefficients as against others given in the literature. A fuller treatment would help to build greater understanding of the inventorying process, and of emissions sources generally, at the state level.

As a related item, it would be additionally useful to state agencies if a central depository were established at the U.S. Environmental Protection Agency regional level of the major documents describing, evaluating, or containing the most important emissions estimation methodologies. Some of these might include: the proceedings from the various U.S. Environmental Protection Agency workshops on N_2O and CH_4 emissions; the national emissions inventories conducted by the U.S. Department of Energy and the U.S. Environmental Protection Agency for 1990; the U.S. Environmental Protection Agency's national methane inventory; AP-42 and its supplements; and the IEA-OECD inventories and discussions of methodologies.[51,70,73,74,95,233-236]

In the final analysis, the recommended methodologies contained in the *State Workbook* derive from a small group of published studies. These include: Grubb (1989),[63] Bingemer and Crutzen (1987),[176] Eichner (1990),[199] Sass (1991),[196] Marland and Rotty (1984),[67] Marland *et al.* (1989),[66] Crutzen *et al.* (1986),[237] Safley *et al.* (1992),[238] Birdsey *et al.* (1991),[239] and Radian (1990).[240] These might be appended to the *State Workbook* or kept in U.S. Environmental Protection Agency regional repositories.

Beyond the general question of uncertainty, there is the additional question of appropriate time-scales against which to assess emissions. Different time-scales of effect with regard to emissions imply very different treatments of emissions. A focus on emissions with long-term, 100-year, effects necessarily precludes the treatment of emissions and sink considerations characterized by substantially shorter time-scales. In the case of CO_2, the most important short-term emissions or sink considerations precluded by a long time horizon involves the short-term sequestration of carbon in forest ecosystems. By contrast, with a shorter time horizon, the effects of such short-term sequestration would be a factor in estimating emissions.

The question of the appropriateness of different time-scales turns on one's estimation of the nearness in time and intensity of projected climatic changes, and on one's estimation of the time-scales involved in effective policies aimed at reducing emissions of greenhouse gases. Are major climatic changes likely to be experienced in the next 20 to 25 years, or is significant warming likely to be experienced only 100 years into the future and at a very slow rate? Can policies implemented in the present that substantially

affect the rate of atmospheric accumulation of the offending gases over periods as short as several decades, or are the transition times of commercial energy and agricultural systems such that the influence of policy changes can be measured only over periods of time much longer than a few decades? Obviously if the time-scales of effective policies or of climate change are thought to be very long, then a long time period is the appropriate time frame of interest.

The *State Workbook* does not address this issue directly, but only implicitly in excluding CO_2 emissions from wood combustion from state inventory totals. Implicit in this decision are judgments regarding the intensity of impending climatic changes and their inevitability. These assumptions ought to be made explicit.

As a related matter, there is also a certain persistent confusion in the *Workbook* over what types of emissions constitute emissions with long-term effects and those that do not. The *State Workbook* implicitly opts for a very long time horizon. The interest is plainly with emissions with very long-term effects. This is evident from its choice of a 100-year period against which to calculate the CO_2-equivalent effects of emissions, and from its exclusion of CO_2 from wood combustion in statewide inventory totals. As noted above, emissions from wood combustion are not included in inventory estimates essentially because the time period associated with forest growth and harvesting in forests managed for the production of forests products is measured in decades rather than hundreds of years. The *State Workbook* also excludes as relevant CO_2 emissions from the burning of agricultural wastes, essentially for the same reasons. The time period associated with the growth and harvesting of agricultural products is but a few years.

However, at the same time, the *State Workbook* recommends that CO_2 emissions from the leakage of landfill gas, which originates in the anaerobic decay of yard and food wastes, paper and wood, be estimated. In estimating the typical carbon contents of waste fuels like municipal solid waste or landfill gas, the *Workbook* makes no attempt to distinguish between the petrochemical and biogenic components of these fuels, and fails to do likewise in discussing CO_2 emissions from the flaring of landfill gas.

This is confusing. Are emissions with only short-term radiative effects -- those measured in years to a few decades -- to be included in inventory estimates? The *Workbook* authors offer no definitive conclusion to this question.

This same confusion is also evident in the *Workbook*'s treatment of emissions of CH_4, CO, NO_x, and NMVOCs, gases that have atmospheric residence times measured in months to years. The present-day emission of a ton of methane, CO or any other of these compounds will have virtually no effect on climate one-hundred years from now. In the case of CO, NMVOCs, or NO_x, their effect is unlikely to persist more

than one year. Yet these compounds are included in inventory estimates. Again there is a dramatic divergence between those assumptions about the pace and likelihood of climate change made in the case of emissions from the combustion of wood and agricultural wastes and those made in the case of these short-lived pollutants.

Obviously, if the *State Workbook* is to form a coherent whole, these inconsistencies must be resolved. Conclusions regarding these issues ought to be stated unambiguously so as to resolve questions about the types of emissions to include and not to include in statewide emissions estimates.

One further source of confusion in the *Workbook* is the frequent conflation of estimates of present-day emissions that are largely the result of the decisions and commitments of prior generations with future emissions resulting from present-day decisions. Using the *State Workbook*, one calculates actual present-day emissions from fossil fuel use and production, industrial processes, and agricultural activities, but average annual future emissions from landfill activities and land-use changes resulting from present-day decisions -- and then sums the results to derive a total for present-day statewide emissions. In fact, such a total represents neither total present-day emissions nor the effects of present-day decisions, but a confused melange of the two. Either approach is legitimate taken alone, but they ought to be kept separate. Taken by itself, it is simply not obvious what a statewide emissions total calculated using the methodologies given in the *State Workbook* might signify or how it might be used to inform the policy discussion or policy.

At a more specific level, greater attention needs to be paid in the *State Workbook* to atmospheric chemistry, soil sinks for the greenhouse gases and their precursors, and natural forest sources of NMVOCs, along with the effects of each on atmospheric accumulations of infrared-active compounds or their precursor gases. Soils permanently converted from cropland to grassland or forested land constitute important sinks for atmospheric CO and CH_4. Forest systems allowed to go unharvested are large potential emitters of NMVOCs.

Furthermore, significant amounts of CO_2 can accumulate in the atmosphere from the oxidation of CO, or the oxidation of CH_4 emitted in prior years from fossil fuel use, production and transportation. In this inventory, the amount of extra CO_2 added to the atmosphere from these sources amounted to about 1 percent of all CO_2-equivalent emissions from Minnesota.

The single most important omission in the *State Workbook* may be that of an emissions methodology for N_2O from sewage treatment activities and fertilizer run-off. The general question of N_2O emissions from combustion is also important. Improvements are needed here. Overall, the *State Workbook* treats only two

of the roughly ten suspected anthropogenic sources of nitrous oxide.[170] Given the large uncertainties surrounding emissions of CH_4 and N_2O from coal mining, landfills, natural gas pipeline leakage, rice cultivation, and commercial fertilizer use, a general narrowing of uncertainties in emissions estimates is also necessary. Obviously, the mere use of the midpoint of an otherwise very broad possible range of emissions -- in some cases spanning 1 to 2 orders of magnitude -- as a point estimate for emissions does not constitute an adequate basis for estimating emissions.

In terms of CO_2 emissions from fossil fuel combustion, the *Workbook* lays relatively little emphasis on the proper characterization of the state energy use data used to estimate emissions, on measures to characterize the quality of that data, or on criteria that might be useful to an analyst choosing between competing data on statewide energy use. The types of data that are available include those compiled variously at the state level, and the multiple sets of data on statewide energy use assembled at the Federal level. In the estimation of statewide uses of energy, there can be as many different estimates of statewide energy use as their are available data sets. Since typically 70 to 90 percent of all statewide emissions of radiatively-active gases derive from fossil fuel use and production, the effect of a 5 to 10 percent variation in fossil fuel use estimates between different sources can be as large or larger than all estimated noncombustion emissions sources together.

Obviously, the proper evaluation of the competing claims of different estimates of statewide fossil fuel use is important. Thus it would be useful if a section of the *Workbook* were to be devoted to a discussion of the types of fossil fuel use data available from state and especially Federal sources, its coverage and character, its strengths and weaknesses, and measures that might be taken to improve it.

In general, the *State Workbook* needs to be continually updated to account for a rapidly changing literature on emissions sources and atmospheric processes, and to be expanded to include sources not heretofore treated. Given the scale of the potential radiative effects of industrial process emissions involving ODCs, special attention ought to be given to the identification of likely substitutes for the hard CFCs and their relative effects on climate. Also, methodologies for present-day emissions of CH_4 from landfills and CO_2 from land-use changes ought to be incorporated into the *Workbook*.

Finally, it might be useful if a well-developed set of conversion factors for use in converting back and forth between different units of energy, weight, volume, power, force, area, and distance was to be incorporated into the *Workbook*. Other useful additions might include estimates of the energy content and gaseous composition of natural gas by region and year, and of the average energy and carbon content of coals and lignite by production region. These would represent useful additions to the *State Workbook*.

Endnotes

1. V. Ramanathan, "The Greenhouse Theory of Climate Change: A Test by an Inadvertent Global Experiment," *Science*, 240 (1988): 293.

2. Intergovernmental Panel on Climate Change, *Climate Change: The IPCC Scientific Assessment,* (New York: Cambridge University Press, 1990).

3. P. Crutzen and P. Zimmermann, "The Changing Photochemistry of the Troposphere," *Tellus*, 43A (1991): 136-151.

4. World Meteorological Organization, *Atmospheric Ozone 1985: Assessment of Our Understanding of the Processes Controlling Its Present Distribution and Change*, Global Ozone Research and Monitoring Project Report no. 16, (Geneva: WMO, 1986).

5. P. Bakwin, *et al.*, Carbon Monoxide Budget in the Northern Hemisphere," *Geophysical Research Letters*, 21 (1994): 433-36.

6. J. Dignon, "NO_x and SO_x Emissions from Fossil Fuels: A Global Distribution," *Atmospheric Environment* , 26A (1992): 1,157-1,163.

7. E. Maier-Reimer and K. Hasselman, "Transport and Storage of CO_2 in the Ocean - An Inorganic Ocean Accumulation Carbon Cycle Model," *Climate Dynamics*, 2 (1987): 63-92.

8. W. Broeker and T. Peng, *Tracers in the Sea,* (New York: Columbia University Press, 1982).

9. K. Caldera and M. Rampino, "Carbon Dioxide Emissions from Deccan Volcanism and A K/T Boundary Greenhouse Effect," *Geophysical Research Letters*, 17 (1990): 1,299-1,302.

10. C. Baes, Jr., "The Role of the Oceans in the Carbon Cycle," in W. Bach, *et al.*, *Carbon Dioxide: Current Views in Energy/Climate Research,* (Dordrecht, Netherlands: D. Reidel Publishing Co., 1983).

11. J. Trabalka, *et al.*, "Human Alterations of the Global Carbon Cycle and the Projected Future, in J. Trabalka, ed., *Atmospheric Carbon Dioxide and the Global Carbon Cycle*, DOE/ER-0239 (Washington, D.C.: U.S. Department of Energy, 1985).

12. I. Fung, *et al.*, "Three-Dimensional Model Synthesis of the Global Methane Cycle," *Journal of Geophysical Research* 96 (1991): 13,033-13,045.

13. M. Prather and C. Spivikowsky, "Tropospheric OH and the Lifetimes of Hydrochlorofluorocarbons," *Journal of Geophysical Research*, 95 (1990): 18,723-18,729.

14. D. Albrimon, ed., *Proceedings of the Workshop on the Scientific Basis of GWP Indices,* 14-16 November 1990, Boulder Colorado, unpublished.

15. J. Butler, *et al.*, "Oceanic Consumption of CH_3CCl_3: Implications for Tropospheric OH," *Journal of Geophysical Research*, 95 (1992): 22,347-22,355.

16. G. Vaghjani and A. Ravishankara, "New Measurement of the Rate Coefficient for the Reaction of OH with Methane," *Nature*, 350 (1991): 406-409.

17. V. Ramanathan, *et al.*, "Climate-Chemical Interactions and Effects of Changing Atmospheric Trace Gases," *Reviews of Geophysics*, 25 (1987): 1,441.

18. J. Lelieveld, *et al*, "Climate Effects of Atmospheric Methane, *Chemosphere*, 26 (1993): 739-768.

19. S. Hameed, *et al.*, "Response of the Global Climate to Changes in Atmospheric Chemical Composition Due to Fossil Fuel Burning," *Journal of Geophysical Research*, 1980: 7,737-7,748.

20. M. Khalil and R. Rasmussen, "Causes of Increasing Atmospheric Methane: Depletion of Hydroxyl Radicals and the Rise of Emissions," *Atmospheric Environment*, 19 (1985): 397-408.

21. J. Rotmans, et al., "Global Warming Potentials," in P. Rijsherman and R. Twart, eds., *Targets and Indicators of Climatic Change,* (Stockholm: Stockholm Environmental Institute, 1990), pp. 63-92.

22. K. Shine, et al., "Radiative Forcing of Climate," in J. Houghton, *et al.*, eds., *Climate Change: The IPCC Scientific Assessment,* (Cambridge: Cambridge University Press, 1990), pp. 41-48.

23. L. Harvey, "A Guide to Global Warming Potentials (GWPs)," *Energy Policy*, 21 (1993): 24-34.

24. J. Lelieveld and P. Crutzen, "Indirect Chemical Effects of Methane on Climatic Warming," *Nature*, 355 (1992): 339-341.

25. A. Thompson and R. Cicerone, "Possible Perturbations to Atmospheric CO, CH_4, and OH," *Journal of Geophysical Research*, 91 (1986): 10,853-10,867.

26. A. Thompson, *et al.*, "Perturbations to Tropospheric Oxidants, 1985-2035: 1. Calculations of Ozone and OH in Chemically Coherent Regions," *Journal of Geophysical Research*, 95 (1990): 9,829-9,844.

27. D. Lashof and D. Tirpak, *Policy Options for Stabilizing Global Climate Change,* (Washington, D.C.: Office of Policy, Planning and Evaluation, U.S. Environmental Protection Agency, 1990).

28. V. Ramaswamy, *et al.*, Radiative Forcing of Climate from Halocarbon-Induced Global Stratospheric Ozone Loss," *Nature*, 355 (1992): 810-812.

29. A. Lacis, *et al.*, "Radiative Forcing of Climate by Changes in the Vertical Distribution of Ozone, *Journal of Geophysical Research*, 95 (1990): 9,971-9,981.

30. M. Schwartzkopf and V. Ramaswany, "Radiative Forcing Due to Ozone in the 1980s: Dependence on Altitude of Ozone Change," *Geophysical Research Letters*, 20 (1993): 205-8.

31. W. Zhong, *et al.*, "Greenhouse Gases in the Stratosphere," *Journal of Geophysical Research*, 98 (1993): 2,995-3,004.

32. A. Owens, *et al.*, "A Coupled One-Dimensional Radiative-Convective, Chemistry-Transport Model of the Atmosphere: 1. Model Structure and Steady State Perturbations Calculation," *Journal of Geophysical Research*, 90 (1985): 2,283-2,311.

33. S. Madronich and C, Granier, "Impacts of Recent Total Ozone Changes on Tropospheric Ozone Photodissociation, Hydroxyl Radicals, and Methane trends," *Geophysical Research Letters*, 19 (1992): 465-467.

34. R. Dickinson and R. Cicerone, "Future Global Warming from Atmospheric Trace Gases," *Nature*, 319 (1986): 109.

35. V. Ramanathan, *et al.*, "Trace Gas Trends and Their Potential Role in Climate Change," *Journal of Geophysical Research*, 90 (1985): 5,547-5,567.

36. World Meteorological Organization, *Developing Policies for Responding to Climatic Change: A Summary of the Discussions and Recommendations of the Workshops Held in Villach (28 September - 2 October 1987) and Bellagio (9-13 November 1987),* (Geneva: WMO 1988).

37. International Energy Agency, *Climate Change Policy Initiatives,* (Paris: 1992)

38. National Academy of Sciences, *Policy Implications of Greenhouse Warming,* (Washington, D.C.: National Academy Press, 1991).

39. P. Ciborowski and D. Abrahamson, "Policy Responses to Climate Change: Opportunities and Constraints," M. Meo, ed., *Proceedings of the Symposium on Climate Change in the Southern United States*, (Norman, OK: University of Oklahoma, 1987).

40. National Academy of Sciences, *Carbon Dioxide and Climate: A Scientific Assessment*, (Washington, D.C.: 1979).

41. World Climate Programme, *An Assessment of the Role of CO_2 on Climate Variations and Their Impact*, (Geneva: World Meteorological Organization, 1981.)

42. Carbon Dioxide Assessment Board, National Research Council, *Changing Climate*, (Washington, D.C.: National Academy Press, 1983).

43. M. MacCracken and F. Luther, eds., *Projecting the Climatic Effects of Increasing Carbon Dioxide*, State of the Art Reports, DOE/ER-0237 (Washington, D.C.: U.S. Department of Energy, 1985).

44. B. Bolin, *et al.*, eds., *The Greenhouse Effect, Climate Changes and Ecosystems*, (Chicester, U.K.: John Wiley and Sons, 1986).

45. J. Pinto, *The Current and Future Environmental Role of Atmospheric Methane: Model Studies and Uncertainties*, EPA/600/A-92/116 (Research Triangle Park, N.C.: 1992).

46. D. Victor, "Limits of Market-Based Strategies for Slowing Global Warming: The Case of Tradeable Permits," *Policy Sciences*, 22 (1990): 199-220.

47. C. Bruhl, "The Impact of the Future Scenario for Methane and Other Chemically-Active Gases on the GWP of Methane," *Chemosphere*, 26 (1993): 731-738.

48. J. Wade, *et al.*, "Passenger Car Global Warming Potential," *Energy Policy*, 22 (1994): 509-22.

49. J. Sarmiento and J. Toggweiler, "A New Model for the Role of the Oceans in Determining Atmospheric CO_2," *Nature*, 308 (1984): 622-624.

50. C. Baes and G. Killough, "Chemical and Biological Processes in CO_2-Ocean Models," in J. Trabalka and D, Reichle, eds., *The Changing Carbon Cycle: A Global Analysis*, (New York: Springer-Verlag, 1986).

51. U.S. Department of Energy, *Emissions of Greenhouse Gases in the United States, 1985-1990*, DOE/EIA-0573 (Washington, D.C.: 1993).

52. M. Ko, *et al.*, "Use of Satellite Data to Constrain the Model-Calculated Atmospheric Lifetime for N_2O: Implications for Other Greenhouse Gases, " *Journal of Geophysical Research*, 96 (1991): 7,547-7,552.

53. W. Wang, *et al.*, "Inadequacy of Effective CO_2 as a Proxy in Simulating the Greenhouse Effect of Other Radiatively-Active Trace Gases," *Nature*, 350 (1991): 573-575.

54. U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-B-92-002 (Washington, D.C.: 1992).

55. G. Marland and R. Rotty, *Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-81*, DOE/NBB-0036 (Washington, D.C.: U.S. Department of Energy, 1983).

56. M. Grubb, "On Coefficients for Determining Greenhouse Gas Emissions from Fossil Fuel Production and Consumption," in OECD, *Energy Technologies for Reducing Emissions of Greenhouse Gases*, (Paris: OECD, 1989), pp. 510-535.

57. American Gas Association, *Carbon Dioxide Emissions from Fossil Fuels Combustion and Coal Gasification*, (Arlington, VA: AGA Energy Analysis, September 2, 1987).

58. J. Brobjorg, Northern States Power, "Internal Memorandum on NSP Carbon Dioxide Emissions," Minneapolis, MN, May 7, 1990.

59. M. DeLuchi, *et al.*, "Transportation Fuels and the Greenhouse Effect," University-Wide Energy Research Group, University of California-Davis, December 1987.

60. J. Edmonds and J. Reilly, " A Long-Term Global Energy-Economic Model of Carbon Dioxide Release from Fossil Fuel Use," *Energy Economics* 5 (1983): 74.

61. Energy Information Agency, *Electric Power Annual,* DOE/EIA-0348 (1989) (Washington, D.C.: U.S. Department of Energy, 1989).

62. Energy Information Agency, *Electric Power Annual,* DOE/EIA-0348 (1990) (Washington, D.C.: U.S. Department of Energy, 1990).

63. M. Grubb, "On Coefficients for Determining Greenhouse Gas Emissions from Fossil Fuel Production and Consumption," Energy and Environmental Programme, Royal Institute of International Affairs, London, April 1989.

64. G. Marland and A. Pippin, "United States Emissions of Carbon Dioxide to the Earth's Atmosphere by Economic Activity," *Energy Systems and Policy*, 14 (1991): 101-118.

65. G. Marland, *et al.*, "Carbon Dioxide Emission Rates from Conventional and Synthetic Fuels," *Energy*, 8 (1983): 981-999.

66. G. Marland *et al.*, *Estimates of CO_2 Emissions from Fossil Fuel Burning and Cement Manufacturing Based on United Nations Energy Statistics and the U.S. Bureau of Mines' Cement Manufacturing Data*, ORNL/CDIAC-25 (Oak Ridge, TN: Oak Ridge National Laboratory, Environmental Sciences Division, May 1989).

67. G. Marland, and R. Rotty, *Carbon Dioxide Emissions from Fossil Fuels: A Procedure for Estimation and Results for 1950-1981*, DOE/NBB-0036 (Washington, D.C.: U.S. Department of Energy, June 1983).

68. G. MacDonald, *et al.* "Carbon Dioxide from Burning of Fuels" (ch. 2, pp 17-41), *The Long-Term Impacts of Increasing Atmospheric Carbon Dioxide Levels,* (Cambridge, Mass.: Ballinger, 1982).

69. G. MacDonald, "The Near- and Far-term Technologies, Uses and Future of Natural Gas," in OECD, *Energy Technologies for Reducing Emissions of Greenhouse Gases,* (Paris: OECD, 1989), pp. 510-535.

70. OECD-IEA, *Greenhouse Gas Emissions: The Energy Dimension,* (Paris: 1991).

71. M. Segal, "Ethanol Fuel and Global Warming," CRS Report to Congress, Congressional Research Service, Washington, D.C., March 6, 1989.

72. M. Steinberg and A.S. Albanese, "Environmental Control Technology for Atmospheric Carbon Dioxide Control," in W. Bach, et al., (eds.), *Interactions of Energy and Climate,* (Dordrecht, Netherlands: D. Reidel Publ. Co., 1981), pp. 521-548.

73. U.S. Environmental Protection Agency, *Compilation of Air Pollution Emission Factors* and *supplements,* AP-42 (Washington, D.C.: U.S. EPA, 1989).

74. U.S. Environmental Protection Agency, Office of Policy, Planning, and Evaluation, *Estimation of Greenhouse Gas Emissions and Sinks for the United States 1990,* (Washington, D.C.: June 1993).

75. R. Winschel, "The Relationship of Carbon Dioxide Emission with Coal Rank and Sulfur Content," *Journal of the Air and Waste Management Association*, 40 (1990): 861-865.

76. Energy Information Agency, *State Energy Data Report 1960-1990*, DOE/EIA-0214 (90) (Washington, D.C.: U.S. Department of Energy, May 1992).

77. D. Schlotthauer, "Processed Refuse Fuel Types," in W. Robinson, ed., *The Solid Waste Handbook,* (New York: John Wiley and Sons, 1986).

78. Council of Great Lakes Governors, *Biomass Energy Facilities: 1988 Directory of the Great Lakes Region,* (Chicago, IL.: 1989).

79. H. Peavy, *et al.*, *Environmental Engineering,* (New York: McGraw-Hill, 1985).

80. For the assumed gas composition, see U.S. Environmental Protection Agency, note 54 above; for the energy content of methane, see Compressed Gas Association, *Handbook of Compressed Gases*, 3rd ed., (New York: Van Nostrand Reinhold, 1990); for the origin of landfill gas by organic waste type, see Appendix B, this study.

81. Personal conversation with S. David, Koch Refining, May 23, 1994.

82. Minnesota Department of Public Service, *Minnesota Energy Data Book,* (St. Paul, MN: 1990).

83. Bureau of Census, *Statistical Abstract of the United States,* (Washington, D.C.: U.S. Department of Commerce, 1992)

84. Minnesota Pollution Control Agency, *Emission Inventory System*, Point Source Subsystem, (St. Paul, MN: 1990).

85. Federal Highway Administration, *Highway Statistics 1990,* (Washington, D.C.: U.S. Department of Transportation, 1992).

86. Energy Information Agency, *Natural Gas Annual,* DOE/EIA-0131 (80-90) (Washington, D.C.: U.S. Department of Energy, 1980-90).

87. Energy Information Agency, *Quarterly Coal Report,* DOE/EIA-0121 (84-91) (Washington, D.C.: 1985-92).

88. Energy Information Agency, *Fuel Oil and Kerosene Sales Report*, DOE/EIA-0535 (88-91) (Washington, D.C.: U.S. Department of Energy, 1991-1993).

89. Energy Information Agency, *Cost and Quality of Fuels for Electric Utility Power Plants*, DOE/EIA-0191 (90), (Washington, D.C.: U.S. Department of Energy, August 1991).

90. No current fossil fuel use data was available from the Minnesota Department of Public Service other than preliminary data for 1990, which in categories for which reported or calculated totals were incomplete, the prior year's fuel use estimates were employed.

91. Coal use estimates for 1990 from different sources are given below in thousands of tons:

	Fuel Use Sector				
	Residential	**Commercial**	**Industrial**	**Electr./Steam**	**Total**
MN Energy Data Book	6	187	793	19,995	20,981
MN Utility Data Book				16,966[a]	
Quarterly Coal Report		179	1,283	16,916	18,377
Electric Power Annual				16,916	
Cost and Quality of Fuels for Electric Power Plants				16,559	
State Energy Data Report	63	116	1,283	16,916	18,378
MPCA-EIS		199	827	17,089	18,115

Sources: See endnotes 62, 76, 82, 84, 87, 89, and 96.

(a) Adjusted to eliminate double counting of SMMPA's share of coal use in Sherburne County Plant, Boiler #3.

92. Estimates for 1990 Minnesota usage of liquid petroleum fuels are given below in thousand gallons:

	Fuel Type			
	Distillate F.O.	Residual F.O.	Kerosene	LPG
Fuel Oil and Kerosene Sales Report	774,908	37,685	3,280	NA
State Energy Data Report	776,160	40,614	1,764	250,656
MN Energy Data Book	827,700	64,900	NA	331,000
MPCA-EIS	NA	39,425	NA	NA

Sources: See endnotes 76, 82, 84, and 88.

93. Roughly two-thirds of LPG use in the state of Minnesota is in the residential sector. In the *State Energy Data Report,* the U.S. Department of Energy estimates residential LPG consumption in Minnesota for 1990 at 123,186,000 gallons, which at 0.0915 MMBTU per gallon equals 11,271.5 billion BTUs. In 1990, an estimated 135,124 housing units used LPG for space and water heating. This suggests an average fuel use per residence using LPG of 83.4 MMBTU per unit, which is close to the regional estimate of the U.S. Department of Energy of 90 MMBTU per residence and the the estimate of the Minnesota Department of Jobs and Training estimate of 100.5 MMBTU per residence for the late 1980s, as adjusted to fit the 30-year average of temperatures. By contrast, the Minnesota Department of Public Service estimates residential usage as 194,200,000 gallons, which at 135,124 residences equals 131.5 MMBTU per residence, which appears to overstate likely usage.

See Energy Information Agency, *Household Consumption and Expenditures 1990. Supplement: Regional,* DOE/EIA-0321 (90) (Washington, D.C.: Department of Energy, 1993); Minnesota Jobs and Training, Energy Assistance Program, *'EAP' 90 Program Data and 1988-89 Heating Season, Cost and Fuel Use Data,* (St. Paul, MN: February 1991); and Bureau of the Census, *1990 Census of Population and Housing: Summary of Social, Economic, and Housing Characteristics, Minnesota,* 1990, CPH-5-25 (Washington, D.C.: U.S. Department of Commerce, June 1992).

94. Estimated statewide distillate fuel oil use given in the *Minnesota Energy Data Book* is roughly 50,000,000 gallons higher than is given in either the *State Energy Data Report, the Fuel Oil and Kerosene Sales Report, or the Petroleum Marketing Annual.* Large discrepancies in estimated usage in the residential sector account for much of the difference in estimated statewide usage. The *State Energy Data Report* estimates residential distillate usage as 135 million gallons, while the *Minnesota Energy Data Book* reports 216.7 million gallons of usage. 196,094 housing units are estimated in 1990 in Minnesota to have relied on distillate fuel oil for space and water heating. Distillate fuel oil has an energy content of 138,690 BTU per gallon. Employing the *State Energy Data Report* estimates, the average consumption per residence relying on distillate fuel oil would have been 95.4 MMBTU, which is close to the regional estimate of the U.S. Department of Energy of 90 MMBTU per residence. Employing the estimated usage from the *Minnesota Energy Data Book*, consumption per household would have totaled 153 MMBTU, which seems to overstate fuel use in this sector. The typical consumption of natural gas in residences using natural in 1990 in Minnesota was an estimated 113 MMBTU.

See Energy Information Agency, *Household Consumption and Expenditures 1990,* endnote 93 above; Bureau of the Census, endnote 93 above; U.S. Department of Energy, endnote 76 above; and Energy Information Agency, *Petroleum Marketing Annual* DOE/EIA- 0487 (90) (Washington, D.C.: U.S. Department of Energy, 1990).

95. U.S. Environmental Protection Agency, Office of Air and Radiation, *Anthropogenic Methane Emissions in the U.S.: Estimates for 1990*, Report to Congress, (Washington, D.C.: 1993).

96. Minnesota Department of Public Service, *Minnesota Utility Data Book*, (St. Paul, MN: 1991).

97. Estimates for natural gas usage in Minnesota for 1990 are shown below in MMcf:

	Fuel Use Sector					
	Residential	Commercial	Industrial	Electr. /Steam	Transportation	Total
MN Energy Data Book	113,000	71,900	54,000	5,700	11,800	256,300
Natural Gas Annual	106,966	78,015	88,359	5,231	12,017	290,587
This study	106,192	76,702	83,633	9,283	12,767	288,577
MPCA-EIS	NA	5,753	83,680	9,283	12,377	NA

Sources: See endnotes 82, 84, and 86.

98. A minor amount of fuel use, principally from small municipal utilities, is not treated in this inventory. This includes fuel usage for municipal utilities in Benson, Delano, Elk River, Glencoe, Grand Marais, Granite Falls, Hastings, Janesville, Lake Crystal, Lakeville, Lanesboro, Le Sueur, Litchfield, Luverne, Madelia Park, Melrose, Moose Lake, Redwood Falls, Truman, and Windom, and a small amount of fuel used by Interstate Power and Light, United Power Association, and Minnkota Power Cooperative. The amount of fuel used by these utilities or cooperatives but not treated in this inventory for 1990 totals 263,000 gallons of distillate fuel oil and 15 MMcf of natural gas. In terms of carbon dioxide emissions, this is equal to about 3,800 tons of CO_2. For fuel usage by these utilities and cooperatives, see Minnesota Department of Public Service in endnote 96 above.

99. Illinois Department of Energy and Natural Resources, Office of Research and Planning, *Illinois Inventory of Greenhouse Gas Emissions and Sinks: 1990*, ILEN/RE-93/04 (Springfield, Ill.: September 1993).

100. See U.S. Department of Energy, *Commercial Building Characteristics, 1989*, DOE/EIA-0246(89) (Washington, D.C.: 1991).

101. U.S. Environmental Protection Agency, *Passenger Car Fuel Economy*, EPA 460/3-80-010 (Washington, D.C.: 1980).

102. Oak Ridge National Laboratory, *Transportation Energy Data Book*, 13th ed., (Oak Ridge, TN: 1993).

103. Organization for Economic Cooperation and Development, *Automobile Fuel Consumption in Actual Traffic Conditions*, (Paris: 1982).

104. Bureau of the Census, *1987 Census of Transportation: Truck Inventory and Survey*, TC87-T-24 (Washington, D.C.: 1990).

105. U.S. Department of Energy, *Household Vehicle Energy Consumption, 1988*, DOE/EIA-0464 (88) (Washington, D.C.: 1988).

106. U.S. Department of Energy, *Household Vehicle Energy Consumption, 1991*, DOE/EIA-0464 (93) (Washington, D.C.: 1993).

107. U.S. Department of Transportation, *National Transportation Statistics*, DOT-VNTSC-BTS-93-1 (Washington, D.C.: 1993).

108. Clay Boswell, Boiler 3 and Syl Laskin, Boilers 1 and 2, belonging to and operated by Minnesota Power and Light. See Minnesota Pollution Control Agency, endnote 84 above.

109. D. Cooper and A. Emanuelson, "N_2O Emissions from a Fluidized Bed Catalytic Cracker," *Energy and Fuels*, 6 (1992): 172-175.

110. M. Khalil and R. Rasmussen, "Nitrous Oxide from Coal-Fired Power-Plants: Experiment in the Plumes," *Journal of Geophysical Research*, 97D (1992): 14,645-14,649.

111. Wisconsin Department of Natural Resources, *Wisconsin Greenhouse Gas Emissions*, PUBL-AM-11-92 (Madison, WI: 1993).

112. The breakdown of CO emissions by fossil fuel and nonfossil fuel sources is taken from Tables 32 and 35 for mobile sources, which are assumed to be completely fossil fuel-based, and from Table 28 and Appendix J, Table J-2 for stationary sources. This breakdown is shown below in tons:

	Fossil CO	**Nonfossil CO**	**Total**
Mobile Highway Sources	502,251.2	0	502,251.2
Mobile Nonhighway Sources	60,514.7	0	60,514.7
Large Permitted Stationary Sources	78,246.32	3,183.68	81,430
Small Stationary Sources	3,112.2 to 3,843.2	146,730.8 to 447,111.9	149,843 to 450,955.2
Total	**644,124.42 to 644,855.52**	**149,914.48 to 450,295.58**	**794,038.9 to 1,095,151.1**

1990 emissions of CO reported in MPCA-EIS for large permitted facilities include 2,721.71 tons of nonfossil CO from wood combustion and 461.97 tons of nonfossil CO from the combustion of RDF and MSW, where by weight 64 percent of the carbon contained in MSW and RDF is assumed to be of a nonfossil wood products origin.

113. For instance, CO emission from mobile highway sources increase substantially in response to decreasing ambient temperature. Using Mobile-6, and realistic seasonal temperatures, the Minnesota Pollution Control Agency estimates that CO emissions from highway vehicles for the seven county Twin Cities Metropolitan Area alone in 1990 totaled 417,555 tons of CO. See Minnesota Pollution Control Agency, *Minnesota 1990 Base Year Carbon Monoxide State Implementation Plan Emissions Inventory for the Twin Cities Seven County Metropolitan Areas and the City of Duluth* (St. Paul, MN: 1992). For a similar effect of temperature on CH_4 emissions, see Wade, *et al.*, endnote 48 above.

114. M. Berges, *et al.*, "Nitrous Oxide from Motor Vehicles in Tunnels and their Global Extrapolation," *Journal of Geophysical Research*, 98 (1993): 18,527-18,531.

115. Minnesota Department of Public Service, *Transition into the 21st Century: 1992 Energy Policy and Conservation Report*, (St. Paul, MN: 1992).

116. R. Loft, *Energy Handbook*, 2nd ed., (New York: Van Nostrand, Co., 1984).

117. W. Bathie, "Gas Technology," in L. Wilbur, ed., *Handbook of Energy System Engineering,* (New York: John Wiley and Sons, 1985).

118. L. Sarter, *et al.*, "Natural Gas," in J. Meyers, *Handbook of Energy Technology and Economics,* (New York: John Wiley and Sons, 1986).

119. North American Manufacturing Co., *North American Combustion Handbook*, 2nd ed., (Cleveland, OH: 1978).

120. American Gas Association, *Gas Facts, 1990 Data,* (Arlington, VA: 1991).

121. Energy Information Agency, *Statistics of Interstate Pipeline Companies, 1990*, DOE/EIA-0145 (90) (Washington, D.C.: U.S. Department of Energy, 1990).

122. Personal conversations in February 1994 with: Greg Palmer, Northern States Power; Ruth Jensen, Northern Border Pipeline Co.; William Miller, Great Lakes Gas Transmission Co.; Scott Smith, Northern Natural Gas; and Barry Jardine of Central Lines of Minnesota.

123. D. Ehhalt, *et al.*, "Seasonal Cycle and Secular Trend of the Total Tropospheric Column Abundance of Ethane Above the Jungfraujoch," *Journal of Geophysical Research*, 96 (1991): 4,985-4,994.

124. Energy Information Agency, *Petroleum Supply Annual*, DOE/EIA-0340 (90)/2 (Washington, D.C.: U.S. Department of Energy, 1991).

125. DMGK, "Methane Emissions from Mineral Oil Processing and Distribution," *Coal, Oil and Natural Gas*, 43 (1990): 49 (in German).

126. D. Kirchgessner, *et al.*, "Estimate of Global Methane Emissions from Coal Mines," *Chemosphere*, 26 (1993): 453-472.

127. C. Boyer, *et al.*, *Methane Emissions from Coal Mining: Opportunities for Reduction*, EPA-400/9-90/008 (Washington, D.C.: U.S. Environmental Protection Agency, 1990).

128. In-state refining capacity in 1990 was 97,491.5 thousand barrels and the consumption of petroleum products in Minnesota in 1990 totaled 90,952 thousand barrels. See endnotes 76 and 124.

129. Energy Information Agency, *International Energy Annual*, DOE/EIA-0219(90) (Washington, D.C.: U.S. Department of Energy, 1990)

130. D. Barns and J. Edmonds, *An Evaluation of the Relationship Between the Production and Use of Energy and Atmospheric Methane Emissions*, DOE/NBB-0088P (Washington, D.C.: U.S. Department of Energy, 1990).

131. Radian Corp., "Venting and Flaring Emissions from Production, Processing, and Storage in the U.S. Natural Gas Industry," preliminary draft prepared for the U.S. Environmental Protection Agency and the Gas Research Institute, 1992.

132. D. Harper and K. Goodner, "Transportation of Energy in Minnesota: Review and Analysis," Center for Transportation Studies, University of Minnesota, June 1989.

133. In 1986, roughly 1,389 million gallons of refined petroleum products were delivered to the borders of Minnesota via petroleum products pipelines, or an amount equal to about 40 percent of 1990 Minnesota consumption of refined petroleum products. See Harper and Goodner, endnote 132 above.

134. American Gas Association, *Energy Efficiency, Economics, and Environmental Impacts off Natural Gas vs. Electric Services in Residences*, (Arlington, VA: August 1992).

135. D. Sperling and M. DeLuchi, "Transportation Energy Strategies and the Greenhouse Effect," in OECD, *Energy Technologies for Reducing Emissions of Greenhouse Gases*, (Paris: OECD, 1989).

136. IP Petroleum, "Energy Use in UK Refineries," as reported in Grubb (1989), endnote 56 above.

137. C. Cutler, *et al.*, "Energy and the U.S. Economy: A Biophysical Perspective," *Science*, 225 (1984): 890-905.

138. California Energy Commission, "1988 Inventory of California Greenhouse Gases," final draft, Sacramento, CA, October 1990.

139. S. Cassler, "Energy Fluxes Through the U.S. Economy, 1980, 1982, 1985," contractor report prepared for the Office of Technology Assessment, December 1989.

140. Office of Technology Assessment, *Industrial Energy Efficiency*, OTA-E-560 (Washington, D.C.: U.S. Congress, 1993).

141. See, for instance, Northern States Power Co., FERC Form No. 1., Annual Report of Major Electric Utilities, Licenses, and Others, report to the Federal Energy regulatory Commission, December 31, 1990.

142. E. Mills, *et al.*, "Getting Started: No-Regrets Strategies for Reducing Greenhouse Gases," *Energy Policy*, 19 (1991): 526-540.

143. G. Austin, *Shreve's Chemical Process Industries*, 5th ed., (New York: McGraw-Hill Co., 1984).

144. Information conveyed from North Star Steel to G. Pratt, Minnesota Pollution Control Agency, April 1994.

145. SRI International, *Directory of Chemical Producers in the United States,* (Menlo Park, CA: 1987).

146. The Fertilizer Institute, *The Fertilizer Handbook,* (Washington, D.C.: 1982).

147. Oil and Gas Journal, *Oil and Gas Journal Data Book,* (Tulsa, OK: Pennwell Books, 1986).

148. Office of Technology Assessment, *Changing by Degrees: Steps to Reduce Greenhouse Gases*, OTA-O-482 (Washington, D.C.: U.S. Congress, 1991).

149. Bureau of the Census, *Census of Manufacturing 1987*, MC87-A-24 (Washington, D.C.: U.S. Department of Commerce, September 1990).

150. A. Lacroix, "Unaccounted-for Sources of Fossil and Isotopically-Enriched Methane and Their Contribution to the Emissions Inventory: A Review and Synthesis," *Chemosphere*, 26 (1992): 507-557.

151. G. Austin, *Abrasive Materials 1992,* (Washington, D.C.: U.S. Bureau of Mines, 1992).

152. U.S. Bureau of Mines, *Directory of Principal Crushed Stone Producers in the United States in 1990,* (Washington, D.C.: U.S. Department of Interior, 1991).

153. U.S. Bureau of Mines, *Mineral Industry Surveys: Peat in 1990,* (Washington, D.C.: U.S. Department of Interior, 1990).

154. American Bureau of Metal Statistics, *Nonferrous Metal Data 1990,* (Secaucus, NJ: 1990).

155. U.S. Bureau of Mines, *Ferroalloys in 1990,* (Washington, D.C.: U.S. Department of Interior, 1991).

156. U.S. Bureau of Mines, *Current Industrial Reports: Inorganic Fertilizer Materials and Related Products*, MA28B (88)-1 (Washington, D.C.: U.S. Department of Interior, 1988)

157. K. Malcolm, *et al.*, "Atmospheric Sulfur Hexafluoride: Sources, Sinks, and Greenhouse Warming," *Journal of Geophysical Research*, 98 (1993): 10,499-10,507.

158. U.S. Bureau of Mines, *Minerals Yearbook*, Vol I & II, (Washington, D.C.: U.S. Department of Interior 1991).

159. U.S. Bureau of Mines, *Mineral Industries Surveys: Cement in 1990,* (Washington, D.C.: U.S. Department of Interior, 1990).

160. R. Griffin, "CO_2 Release from Cement Production, 1950-1985," in G. Marland, *et al.*, in endnote 66 above.

161. Information provided to G. Pratt, Minnesota Pollution Control Agency, by American Crystal Sugar and Southern Minnesota Sugar Cooperative, April 1994.

162. U.S. Environmental Protection Agency, *Regulatory Impact Analysis: Protection of Stratospheric Ozone,* Vol 1., (Washington, D.C.: 1988).

163. D. Fisher, *et al.*, "Model Calculations of the Relative Effects of CFCs and Their Replacements on Stratospheric Ozone," *Nature*, 344 (1990): 504-512.

164. World Meteorological Organization, *Scientific Assessment of Stratospheric Ozone: 1989*, WMO and Global Ozone Research and Monitoring Project Report #20, (Geneva: WMO, 1980).

165. W. Komhyr, "Unprecedented 1993 Ozone Decrease Over the United States from Dobson Spectrophotometer Observations," *Geophysical Research Letters*, 21 (1994): 201-204.

166. A. Lacis, *et al.*, in endnote 29 estimate that the net radiative effect of CFCs in the 1980s was negative, leading to a slight net surface cooling.

167. Minnesota Department of Public Safety, Emergency Response Commission, *1989 Toxic Release Inventory*, (St. Paul, MN: September, 1990).

168. U.S. CFC consumption is taken from U.S. Environmental Protection Agency in endnote 53, and Minnesota 1990 population is taken from Bureau of the Census, *1990 Census of Population: General Population Characteristics: Minnesota*, CP-1-25 (U.S. Department of Commerce, June 1992).

169. P. Ciborowski and D.L. Burdette, "Regulating Chlorofouorocarbons and Halons in Minnesota," report prepared for the Minnesota Pollution Control Agency, St. Paul, MN, January 1989.

170. M. Khalil and R. Rasmussen, "Global Sources of Nitrous Oxide," *Journal of Geophysical Research*, 97D (1992): 14,651-14,660.

171. As of the mid-1980s, in the Metropolitan Twin Cities area, six anaerobic digesters were in operation at wastewater treatment plants. See Metropolitan Council, "The Potential for Large-scale Sewage Sludge Composting and Co-composting in the Metropolitan Area," Final Report to the Legislative Commission in Waste Management, St. Paul. MN, 1984. In addition, six composting sites were in operation in the state of Minnesota in 1990, handling 183 tons of MSW per day. See "1990 Nationwide Listing of MSW Composting Facilities," *Biocycle*, November 1990, pp. 49.

172. Minnesota Pollution Control Agency, *Minnesota Solid Waste Management: Selected Economic and Financial Issues,* (St. Paul, MN: 1991).

173. Personal conversation with L. Peisig, Minnesota Pollution Control Agency, May 23, 1994. The density of industrial waste going into industrial landfills is estimated to be 0.375 tons per uncompacted cubic yard of waste based on the weight per cubic yard of compacted industrial and general domestic/commercial wastes in landfills, from Metropolitan Council, *Solid Waste Management Development Guide/Policy Plan,* (St. Paul, MN: 1992).

174. S. Thornloe and R. Rees, *Landfill Gas and the Greenhouse Effect*, EPA/600/D-90/219 (Research Triangle Park, NC: U.S. Environmental Protection Agency, 1990).

175. R. Peer, *et al.*, "A Comparison of Methods for Estimating Global Methane Emissions from Landfills," *Chemosphere*, 26 (1993): 387-406.

176. H. Bingemer and P. Crutzen, "The Production of Methane from Solid Wastes," *Journal of Geophysical Research,* 92 (1987): 2,181-2,187.

177. Personal conversation with D. Corton, Minnesota Pollution Control Agency, June 1994.

178. T. Meersman, "Managing Minnesota's Solid Waste," *Journal of the Minnesota Academy of Sciences*, 54 (1989): 31-36.

179. Minnesota Pollution Control Agency, "Damming the Solid Waste Stream: The Beginning of Source Separation in Minnesota," report to the Legislature, St. Paul, MN, 1975.

180. Minnesota Pollution Control Agency, "The Realities of Recycling," report to the Legislature, St. Paul, MN,1972.

181. R. Reid and R. Peterson, "Energy from Urban Solid Waste," report to the Minnesota Energy Agency for the Minnesota Alternative Energy Research and Development Policy Formulation Project, St. Paul, MN, 1977.

182. Landfill gas was flared in 1990 at Flying Cloud Sanitary Landfill and Pine Bend Sanitary Landfill. No data was available for amounts of gas flared in 1990 at Flying Cloud. The Minnesota Pollution Control Agency (see endnote 177 above) reports average annual flaring amounts for the collection systems at the Pine Bend landfill, which covered perhaps one-fifth of the landfill in 1990, of 3,706.75 cu. ft. per minute. The total amount of waste in the landfill in 1990 was an estimated 4.5 million tons. Thus the generation rate of landfill gas at this landfill would have been roughly 0.56 cu. ft. per lb. of waste, or more than 4 times the rate of emission assumed in this study. As such, these flaring amounts are not properly comparable to the statewide estimates of landfill gas generation based on

national emission rates. To properly include them in any estimated statewide estimate, it would be necessary to develop landfill-by-landfill emission rates based on actual measurements.

183. T. Levander, "The Relative Contributions to the Greenhouse Effect from the Use of Different Fuels," *Atmospheric Environment*, 24A (1990): 2,707-2,714.

184. For instance, employing the methodology for calculating methane emissions form the in-state natural gas transmission and distribution system, and using reported data on transmission pipeline and distribution main mileage (and allowing the number of city gates to decline proportionally to transmission pipeline mileage as one regresses in time), it can be estimated that between 1980 and 1990 roughly 20,440 MMcf of methane would have leaked to the atmosphere during in-state transportation of natural gas. Of this, in 1990 roughly 1,060.1 MMcf would have decayed to CO_2, leading to a production in 1990 of 63,981.1 tons of CO_2. For transmission pipeline and distribution main mileage, see American Gas Association, endnote 120 above.

185. Bureau of the Census, in endnote 168 above.

186. Alliance Technologies Corp., *Procedures for the Preparation of Emissions Inventories for Carbon Monoxide and Precursors of Ozone*, EPA-450/4-91-016 (Washington, D.C.: 1991).

187. Minnesota Department of Agriculture, *Minnesota Agricultural Statistics 1990,* (St. Paul, MN: 1991).

188. D. Lodman, *et al.*, "Estimates of Methane Emissions from the Manure of U.S. Cattle," *Chemosphere*, 26 (1993): 189-199.

189. Applying the Lodman approach to Minnesota cattle populations, one calculates 2,675 million kg of total organic matter in manure, a maximum potential methane production of 59 million cubic meters per year, and an actual methane production of 2,398 MMcf. Lodman assumes that 1 percent of potential methane production from the manure of nonfeedlot beef cattle is actually realized, that 5 percent of the potential production of methane from the manure of feedlot beef cattle is actually realized, and 16 percent of the potential production of methane from the manure of dairy cattle is actually realized.

190. With no change in management practices, methane production from cattle manure in 1980 would have been 367,396,000 cu. ft., or 7,587 tons, which is higher than in 1990, while emissions from the manure of turkeys and broilers would have been 369,639,000 cu. ft., or 7,633 tons, which is lower than in 1990, for a slightly higher overall emission in 1980 from livestock manure of 46 tons.

191. D. Johnson and J. Percich, "Wild Rice Domestication, Fungal Brown Spot Disease, and the Future of Commercial Production in Minnesota," *Plant Disease*, 76 (1992): 1,193-1,198.

192. A. Holzapfel-Pschorn and W. Seiler, "Methane Emissions During a Cultivation Period from an Italian Rice Paddy," *Journal of Geophysical Research*, 91 (1986): 11,803-11,814.

193. H. Schutz, *et al.*, "A 3-Year Continuous Record of the Influence of Daytime, Season, and Fertilizer Treatment on Methane Emission Rates from an Italian Rice Paddy," *Journal of Geophysical Research*, 94 (1989): 16,405-16,418.

194. R. Cicerone, *et al.*, "Seasonal Variation of Methane Flux from a California Rice Paddy," *Journal of Geophysical Research,* 88 (1983): 11,022-11,024.

195. R. Cicerone and J. Shetter, "Sources of Atmospheric Methane: Measurements in Rice Paddies and a Discussion," *Journal of Geophysical Research*, 86 (1981): 7,203-7,209.

196. R. Sass, *et al.*, "Methane Production and Emission in a Texas Rice Field," *Global Biogeochemical Cycles*, 4 (1990): 47-68.

197. E. Oelke, *et al.*, "Wild Rice Production Research - 1988" in *Minnesota Wild Rice Research 1987*, misc. publ. 59-1989, (St. Paul, MN: Minnesota Agricultural Experiment Station, 1989).

198 M. Umarov, "Biotic Sources of Nitrous Oxide (N_2O) in the Context of Global Budgets of Nitrous Oxide," in A. Bouwman, ed., *Soils and the Greenhouse Effect* (Chicester, UK: John Wiley and Sons, 1990).

199. M. Eichner, "Nitrous Oxide Emissions from Fertilized Soils: Summary of Available Data," *Journal of Environmental Quality*, 19 (1990): 272-280.

200. Minnesota Department of Agriculture, "Minnesota Fertilizer Tonnage Summary," St. Paul, MN, 1989-92.

201. N. Hargett and J. Berry, *Commercial Fertilizer* (Muscle Shoals, AL: Oak Ridge National Laboratory, 1980-1990).

202. D. Vanderholm, "Production Rates and Characteristics," in *Agricultural Waste Manual,* (Lincoln College, New Zealand: Agricultural Engineering Institute, 1985).

203. Minnesota Pollution Control Agency and Minnesota Department of Agriculture, "Nitrogen in Minnesota Ground Water," report prepared for the Legislative Water Commission, St. Paul, MN, December 1991.

204. R. Cates and D. Keeney, "Nitrous Oxide Production Throughout the Year from Fertilized and Manured Maize Fields," *Journal of Environmental Quality*, 10 (1987): 443-447.

205. Personal conversation with G. Defresne, Minnesota Pollution Control Agency, April 1994.

206. Minnesota Department of Agriculture, "Agricultural Liming Material Analysis Report," St. Paul, MN, 1993.

207. J. Grava, *et al.*, *Liming Minnesota Soils*, agricultural folder #210 (St. Paul, MN: Minnesota Agricultural Extension Service, 1978).

208. Jaako Poyry Consulting, Inc., *Maintaining Productivity and the Forest Resource Base: A Technical Paper for a Generic Environmental Impact Statement on Timber Harvesting and Forest Management in Minnesota,* (Raleigh, NC and White Plains, NY: December 1992).

209. R.A. Birdsey, "Estimation of Regional Carbon Yields for Forest Types in the United States," U.S. Forest Service MS on file, Rocky Mountain Station, Fort Collins, CO, 1991, as reported in R. Musselman and D. Fox, "A Review of the Role of Temperate Forests in the Global CO_2 Balance," *Journal of the Air and Waste Management Association*, 41 (1991): 798-804.

210. R. Norby, "Direct Responses of Forest trees to Rising Atmospheric CO_2," in R. Noble, *et al.*, eds., *Air Pollution Effects on Vegetation Including Forest Ecosystems: Proceedings of the Second US-USSR Symposium,* Northeastern Forest Experiment Station, 1989.

211. D. Hegg, *et al.*, "Emissions of Some Trace gases from Biomass Fires," *Journal of Geophysical Research*, 95 (d) (1990): 5,669-5675.

212. J. Levine, *et al.*, "The Effects of Fire on Biogenic Soil Emissions of Nitrous Oxide," *Global Biogeochemical Cycles*, 2 (1988): 445-449.

213. D. Ojima, *et al.*, "Effects of Land-Use Change on Methane Oxidation in Temperate Forests and Grassland Soils," *Chemosphere*, 26 (1993): 675-685.

214. R. Birdsey, "Potential Changes in Carbon Storage Through Conversion to Plantation Forests," paper presented at the North American Conference on Forestry Response to Climate Change, Washington, D.C., May 1990.

215. J. Vavitt, *et al.*, "Methane Fluxes in a Northern Hardwood Forest Ecosystem in Relation to Acid Precipitation," *Chemosphere*, 26 (1993): 721-730.

216. J. Hart, "Cleared Farmland in the Upper Lake States, 1910-1964," *Journal of the Minnesota Academy of Sciences,* 36 (1969): 29-33.

217. North Central Forest Experiment Station, *Minnesota Forest Statistics*, 1990, NC-141 (St. Paul, MN: U.S. Forest Service, 1992).

218. Minnesota Department of Natural Resources, "Carbon Dioxide Budgets in Minnesota and Recommendations on Reducing Net Emissions With Trees," report to the Minnesota Legislature, St. Paul, MN, January 1991.

219. B. Lamb, *et al.*, "A National Inventory of Biogenic Hydrocarbon Emissions," *Atmospheric Environment*, 21 (1987): 1,695-1,700.

220. R. Peer, *Global Warming Mitigation Potential of Tree Plantation Scenarios*, EPA-600/57/91/003 (Research Triangle Park, NC: April 1991).

221. Computed using the average carbon storage in above ground biomass in Minnesota taken from R. Birdsey, "Carbon Storage and Accumulation in United States Forest Ecosystems," U.S. Forest Service General technical Report, Washington, D.C., 1991, as reported in U.S. Environmental Protection Agency, endnote 54 above.

222. The U.S. Department of Agriculture estimates that 1,012,520 acres of cropland were converted to permanent grasses, legumes and native grasses from 1986 to 1989, 43,712 acres to trees, and 1,802 acres to shallow water and grass waterways. See U.S. Department of Agriculture, *Agricultural Statistics 1991*, (Washington, D.C.: 1991).

223. W. Bowden and F. Bormann, "Transport and Loss of Nitrous Oxide Soil Water After Forest Clearcutting," *Science*, 237 (1990): 867-869.

224. University of Minnesota, *Thematic Map: Available Wetlands for Bioenergy Purposes,* (Minneapolis, MN: 1981).

225. T. Dahl, *Wetlands Losses in the United States, 1780s to 1980s,* (Washington, D.C.: U.S. Fish and Wildlife Service, 1990).

226. Personal conversation with Kim Santos, National Wetlands Inventory, U.S. Fish and Wildlife Service, April 1994).

227. J. Pastor and W. Post, "Response of Northern Forests to CO_2-Induced Climate Change," *Nature*, 334 (1988): 55-57.

228. M. Davis, "Lags in Vegetation Response to Greenhouse Warming," *Climatic Change*, 15 (1989): 75-95.

229. D. Botkin, "Global Warming and Forests of the Great Lake States: An Example of Quantitative Projections in Policy Analysis," in J. Schmandt and J. Clarkson, eds., *The Regions and Global Warming: Inputs and Regional Strategies,* (New York: University of Oxford Press, 1993).

230. M. Davis, "Ecological Systems and Dynamics," in National Research Council, *Toward Understanding of Global Change*, (Washington, D.C.: National Academy Press, 1988).

231. R. Musselman and D. Fox in endnote 209 above.

232. D. Jenkinson, *et al.*, "Model Estimates of CO_2 Emissions from Soils in Response to Global Warming," *Nature*, 351 (1991): 304-6.

233. U.S. Environmental Protection Agency, *Proceedings of the International Workshop on Methane Emissions from Natural Gas Systems, Coal Mining, and Waste Management Systems,* (Washington, D.C.: 1991).

234. U.S. Environmental Protection Agency, *Proceedings of the Workshop on Greenhouse Gas Emissions from Agricultural Systems,* (Washington, D.C.: 1990).

235. OECD/OEDC, *Estimates of Greenhouse Gas Emissions and Sinks, Final Report from the OECD Experts Meeting, 18-24 February 1992,* (Washington, D.C.: 1991).

236. U.S. Environmental Protection Agency, *Methane Emissions and Opportunities for Control: Workshop Results of the Intergovernmental Panel on Climate Change*, EPA/400/9-90/007 (Washington, D.C.: 1990).

237. P. Crutzen, *et al.*, "Methane Production by Domestic Animals, Wild Ruminants and Other Herbivorous Fauna, and Humans," *Tellus*, 38B (1986): 271-284.

238. L. Safely, *et al.*, *Global Methane Emissions from Livestock and Poultry Manure*, EPA/400/1091/048 (Washington, D.C.: U.S. Environmental Protection Agency, 1992).

239. R. Birdsey, "Carbon Storage and Accumulation in United States Forest Ecosystems," U.S. Forest Service General technical Report, Washington, D.C., 1991, as reported in U.S. Environmental Protection Agency, endnote 54 above.

240 Radian Corp., *Emissions and Cost Estimates for Globally Significant Anthropogenic Combustion Sources of* NO_x, N_2O, CH_4, *CO, and* CO_2, (Washington, D.C.: 1990).

APPENDICES

Appendix A . Energy Content of Fuels

Fuel	Energy Content
Liquid Transportation Fuels	**In MMBTU/10^3 gallons**
Motor Gasoline	125.071(a)
Diesel Fuel Oil	138.690(a)
Aviation Gasoline	120.190(b)
Jet Fuel	135.000(a)
Ethanol	75.67(c)
Gasahol	127.417(c)
Non-Transportation Liquid Petroleum Fuels	**In MMBTU/10^3 gallons**
Distillate Fuel Oil	138.690(a)
Residual Fuel Oil	149.690(a)
Waste Oil (lubricants)	144.405(b)
Kerosene	135.000(a)
Liquid Petroleum Gas	95.500(a)
Propane	91.333(b)
Petroleum Coke	143.429(a)
Special Naphtha	124.952(a)
Crude Petroleum	138.095(a)
Liquids for Non-Fuel Uses	**In MMBTU/10^3 gallons**
Waxes	120.200(c)
Asphalt and Road Oil	158.000(b)
Gaseous Fuels	**MMBTU/MMcf**
Methane	1,012(d)
Ethane	1,784(d)
Propane	2,518(d)
Propane-Air	1,260(e)
Natural Gas	1,006(f)
Refinery Gas	1,150(g)
Landfill Gas	506(h)
Solid Fuels	**MMBTU/Short Ton**
Bituminous Coal	22(i)
Subbituminous Coal	17(a)
Lignite	13(a)
Coal Coke	26.8(a)
Petroleum Coke	28.4(i)
Solid Resins	28(j)
Municipal Solid Waste	9.7(a)
Refuse-Derived Fuel	11.1(a)
Wood	12.8(k)
Sawdust	16.18(i)
Crop Residues	7.8(a)

(a) U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA-230-B-92-002, (Washington, D.C.: 1992).
(b) U.S. Department of Energy, *State Energy Data Report*, (Washington, D.C.: 1991).
(c) Oak Ridge National Laboratories, *Transportation Energy Data Book*, 11th ed., (Oak Ridge, TN: 1990).
(d) Compressed Gas Association, Inc., *Handbook of Compressed Gases*, 3rd ed., (New York, Van Nostrand Reinhold, 1990).
(e) Calculated at 50% propane and 50% air.
(f) Average energy content of natural gas combusted in Minnesota in 1990 from: U.S. Department of Energy, *Natural Gas Annual*, DOE/EIA-0131 (1990), (Washington, D.C.: 1991).
(g) Personal communication with S. David, Koch Refinery, May 23, 1994.
(h) Calculated at 50% CH_4 and 50% CO_2 and an energy content for methane of 1,012 MMBTU/MMcf.
(i) J. Brobjorg, Northern States Power Co., "Internal Memorandum on NSP CO_2 Emissions," (Minneapolis, MN: May 7, 1990).
(j) Calculated from typical energy content of plastic of 14,000 BTU/lb.
(k) Minnesota Department of Public Service, *Minnesota Energy Data Book*, (St. Paul, MN: 1991).

Appendix B . Carbon Content of Solid Wastes

	Carbon Content of Waste	Percentage Breakdown of Waste by Component (by weight)				Carbon Content of Each Category of Waste as a %, by Weight, of Waste			
	Percent Carbon By Weight	Statewide MSW(d)	Industrial/ Commer-cial(e)	General Medical (e)	Post-Sort RDF(d,f)	Statewide MSW	Industrial/ Commer-cial	General Medical	Post-Sort RDF
Petrochemical Component									
HDPE	82.01	0.7	0.53		0.78	0.57	0.43		0.64
Plastic film	78.32	4.7	6.22		5.84	3.68	4.87		4.57
PET	66.83	0.3	0.19		0.26	0.2	0.13		0.17
Polystyrene	86.93(b)	1.1	1.31		1.17	0.96	1.14		1.02
Other Plastics	76.7	4.5	4.28		7.4	3.53	3.28		5.68
Total Plastics		11.4	12.53	34.8	15.45	8.94	9.85	26.1	12.08
Textiles (1/2 plastic)	35.57(b)	1.6	1.14		1.69	0.57	0.41		0.6
Tires/Oil Filters/ Hazardous waste	66.85 (b,c)	1	0.85		0.78	0.67	0.57		0.52
Diapers	70	2.4	1.41		3	1.68	0.99		2.1
TOTAL		16.4	15.83	34.8	20.92	11.86	11.82	26.1	15.3
Wood/Paper Component									
Newsprint	41.46	4	2.59		4.42	1.66	1.07		1.83
Corrugated/Kraft	44.92	8.8	11.44		12.21	3.95	5.14		5.48
High Grade Paper	37.72	4.4	4.95		6.1	1.66	1.87		2.3
Magazines	31.5(b)	2.9	2.04		3.51	0.92	0.64		1.11
Other Paper	32.25	20	19.25		25.06	7.05	6.79		8.83
Total Paper		40.1	40.27	59.8	51.3	15.24	15.51	23.92	19.55
Wood Waste	45	6.5	8.4		9.87	2.93	3.78		4.44
TOTAL		46.6	48.67	59.8	61.17	18.17	19.29	23.92	23.99
Agric./Yard Component									
Textile-1/2 natural fiber	35.57	1.5	1.14		1.56	0.53	0.41		0.55
Food Waste	13.15	13.3	15.27		5.58	1.75	2.01		0.73
Yard Waste	21.86	2.9	1.24		4.42	0.63	0.27		0.97
TOTAL		17.7	17.65	0	11.56	2.91	2.69	0	2.25
Inorganic Component	0	19.3	17.85	5.4	6.35	0		0	0
TOTAL		100	100	100	100	32.94	33.8	50.02	41.5

(a) Franklin Associates, *Dakota County Solid Waste Generation and Characterization Study*, (Prairie Village, Kansas: 1991).
(b) D. Wilson, ed., *Handbook of Solid Waste Management*, Table 2.38, (New York: Van Nostrand Reinhold, 1985).
(c) Value for hazardous waste and oil filters. Tire disposal in landfills is prohibited by law and typically is near zero.
(d) Minnesota Pollution Control Agency, *Solid Waste Composition Study, 1990-91*, Parts 1 & 2, (St. Paul, MN: 1992-3).
(e) Minnesota Pollution Control Agency, *Estimated Cost of Waste Disposal/Incineration Alternatives*, (St. Paul, MN: 1993).
(f) Post-sort percentage reductions taken from H. Hickman, Jr., *et al.*, *Thermal Conversion System for Municipal Solid Waste*, (Park Ridge, NJ: Moyer Publications, 1984). Percentage reductions include 96% for glass, metals and the inorganic, and 94% for small electrical appliances and demolition/construction materials.

Appendix C . 1990 Minnesota Fossil Fuel Use (in MMBTU)

	Residential	Commercial	Industrial	Electrical Generation	Agricultural	Transportation	TOTAL
Natural Gas	106,410,656	76,856,388	84,628,744	9,569,072		12,843,602	290,308,462
Propane-Air Gas	27,720	20,160	22,680				70,560
Refinery Gas			27,674,175				27,674,175
Bituminous Coal	129,800	680,108	6,561,302	5,919,232			13,290,442
Subbituminous Coal		2,859,145	14,968,330	285,906,425			303,733,900
Lignite			383,006	18,564			401,570
Coal Coke			882,283				882,283
Solid Resins			168				168
Refused - Derived Fuel		369,086		6,070,679			6,439,765
MSW - Mass Burn		274,636		4,893,834			5,168,470
Liquid Transportation Fuels							
Motor Gasoline		269,403	1,060,727		4,660,896	249,724,138	255,715,164
Aviation Gasoline						1,031,951	1,031,951
Jet Fuel						46,696,500	46,696,500
Diesel Fuel Oil		2,263,975	5,707,094		16,953,743	46,104,162	71,028,974
Unspecified Distillate						9,257,835	9,257,835
Non-Transportation Liquid Fuels							
Distillate Fuel Oil	18,866,001	3,223,849	3,912,722	583,885	897,463	2,635	27,486,555
LPG	11,764,263	2,077,698	3,760,312		6,106,748	228,627	23,937,648
Kerosene	319,275	43,875	11,340		64,800		439,290
Waste Solvent			20,992				20,992
Residual Fuel Oil		788,118	8,485,926	333,958		43,410	9,651,412
Waste Oil			1,261,522	3,755		144	1,265,421
Petroleum Coke			454,457	4,148,785			4,603,242
TOTAL	**137,517,715**	**89,726,441**	**159,795,780**	**317,448,189**	**28,683,650**	**365,933,004**	**1,099,104,779**

Source: Calculated from Table 11 using Appendix A.

Appendix D . Sources of Fossil Fuel Use Data for Estimating CO_2 Emissions

Fuel and Use Sector	Type of Data	Source
Coal		
Electrical	Firm-reported	MPCA-EIS
Commercial	Firm-reported	MPCA-EIS
Residential	Modelled	*MN Energy Data Book*
State Use Total	Production, distribution & large industrial use reporting	*Quarterly Coal Report*
Coke, Petroleum Coke, Solid Resins		
Electrical	Firm-reported	MPCA-EIS
Industrial	Firm-reported	MPCA-EIS
Refuse-Derived Fuel, MSW		
Electrical	Firm-reported	MPCA-EIS
Commercial	Firm-reported	MPCA-EIS
Jet Fuel	State-reported from tax receipts	*MN Energy Data Book*
Other Transportation Fuels		
Other Transportation	State-reported from tax receipts	*Highway Statistics 1990*
Agriculture	Sales survey data	*Fuel Oil & Kerosene Sales Report*
Industrial/Commercial	Sales survey data	*Fuel Oil & Kerosene Sales Report*
Other Distillate Fuel Oil		
Electrical	Firm-reported	MPCA-EIS
Transportation	Firm-reported	MPCA-EIS
State Use Total	Sales survey data	*State Energy Data Report*
Residential, Commercial, Industrial, Agricultural(a)	Sales survey data	*Fuel Oil & Kerosene Sales Report*
LPG, Kerosene	Sales survey data	*State Energy Data Report*
Residual Fuel Oil, Waste Oil		
Industrial	Firm-reported	MPCA-EIS
Electrical	Firm-reported	MPCA-EIS
Commercial	Firm-reported	MPCA-EIS
Refinery Gas		
Industrial	Firm-reported	Refinery-reporting
Propane-Air Gas	Sales survey data	*Natural Gas Annual*
Natural Gas		
Pipeline Leakage	Calculated	Section V, this study
Total Received at State Borders	Pipeline company-reported	*Natural Gas Annual*
Gas Pipeline Usage	Pipeline company-reported	*Natural Gas Annual*
Electrical, Industrial	Firm-reported	MPCA-EIS
Petroleum Pipeline Usage	Firm-reported	MPCA-EIS
Residential, Commercial, Industrial(a)	Gas utility-reported	*Natural Gas Annual*

(a) Percentage breakdowns of use among listed sectors set according to percentage distribution of use among sectors in fuel data source.

Appendix E . Fossil Fuel Use in the Electrical Generation/Steam and Industrial Sectors

Table E-1A. Fossil Fuel Use in the Electrical Generation/Steam Sector (in Physical Units): Part A

Table E-1B. Fossil Fuel Use in the Electrical Generation/Steam Sector (in Physical Units): Part B

Table E-2A. Fossil Fuel Use in the Industrial Fossil Fuel Use Sector Reported in MPCA-EIS (in Physical Units): Part A

Table E-2B. Fossil Fuel Use in the Industrial Fossil Fuel Use Sector Reported in MPCA-EIS (in Physical Units): Part B

Table E-1A. Fossil and Waste Fuel Use in the Electrical Generation/Steam Sector (in physical units): Part A

	Bituminous Coal (tons)	Subbituminous Coal (tons)	Lignite (tons)	Petroleum Coke (tons)	MSW (tons)
Northern States Power	15,637	11,196,377		146,084	
Minnesota Power and Light	4,930	4,045,828			
Interstate Power and Light	76,297				
Cooperative Power Assn.					
Ottertail Power Co.		176,972	1,370		
United Power Assn.					
SMMPA [a]	74,733	1,204,005			
Austin Utilities					
Blooming Prairie Public Utility					
Blue Earth Light and Water					
Franklin Heating Station					
Hibbing Public Utilities Commission		78,408			
Hutchinson Utilities Commission					
Marshall Municipal Utilities					
Moorhead Public Service Dept.			58		
New Ulm Public Utilities Commission	2,614				
Princeton Public Utilities Commission					
Public Utilities Commission, Fairmont					
Public Utilities Commission, Springfield		1,597			
Public Utilities Commission, Spring Valley					
Rochester Public Utility					
Sleepy Eye Public Utilities		7,603			
Virginia Public Utilities Department		107,235			
Wilmar Municipal Utility Commission	46,032				
Ashcon, Inc.					
District Energy, St. Paul	28,876				
Minneapolis Energy Center					
Duluth Steam Cooperative	19,937				
Waste-to-Energy Incinerators					504,519
TOTAL	**269,056**	**16,818,025**	**1,428**	**146,084**	**504,519**

(a) Includes a portion of fuel use at Sherco 3, which is co-owned with Northern States Power.

Table E-1B. Fossil Fuel and Waste Fuel Use in the Electrical Generation/Steam Sector (in physical units): Part B

	RDF (tons)	Distillate Fuel Oil (10^3 gallons)	Diesel Fuel (10^3 gallons)	Residual (10^3 gallons)	Waste Oil (10^3 gallons)	Natural Gas (MMcf)
Northern States Power	268,937	2,076	36		20	1,279
Minnesota Power and Light		593				2
Interstate Power and Light		69		62	1	796
Cooperative Power Assn.			174			
Ottertail Power Co.						
United Power Assn.	277,971					171 (a)
SMMPA		252	22	3	2	1,162(a)
Austin Utilities						7
Blooming Prairie Public Utility			1			
Blue Earth Light and Water						55
Franklin Heating Station			64	904	2	1,395
Hibbing Public Utilities Commission						18 (a)
Hutchinson Utilities Commission		2	7			280
Marshall Municipal Utilities		7				
Moorhead Public Service Department		5				
New Ulm Public Utilities Commission		10				1,454
Princeton Public Utilities Commission			1			3
Public Utilities Commission, Fairmont		28		11		176
Public Utilities Commission, Springfield						8
Public Utilities Commission, Spring Valley			2			
Rochester Public Utility						2
Sleepy Eye Public Utilities			2			30
Virginia Public Utilities Department						64
Wilmar Municipal Utility Commission						
Ashcon, Inc.						
District Energy, St. Paul		81				273
Minneapolis Energy Center		763		1,251	1	1,921
Duluth Steam Cooperative						257
Waste to Energy Incinerators		15				159
TOTAL	**546,908**	**3,901**	**309**	**2,231**	**26**	**9,512**

Source: Minnesota Pollution Control Agency, *Emissions Inventory System* (St. Paul, MN: 1994).

(a) Natural gas usage for Hibbing Public Utilities Commission, United Power Assn., and New Prague Municipal Utilities (SMMPA) are taken from Minnesota Department of Public Service, *Minnesota Utility Data Book,* (St. Paul, MN: 1991).

Table E-2A. Fossil Fuel Use in the Industrial Fuel Use Sector Reported in MPCA-EIS (in physical units): Part A

	SIC Code	Bituminous Coal (tons)	Subbituminous Coal (tons)	Lignite (tons)	Coal Coke (tons)	Distillate Fuel Oil (10^3 gal.)	Residual Fuel Oil (10^3 gal.)	Waste Oil (10^3 gal.)
Metal Mining	10	111,532		20,225		1,439	1,507	36
Non-metal mining	14					211		
Food and Kindred	20	49,608	504,101		17,615	179	12,647	17
Textile Mill Products	22					10		
Lumber and Wood	24					86	1,451	206
Furniture and Fixtures	25							
Paper and Allied	26	46,355	115,379			12	7,245	39
Printing/Publishing	27					36	6	
Chemical and Allied	28					45		
Petroleum Refining and Related	29					1,208	33,102	8,428
Rubber and Misc. Products	30							
Leather and Leather Products	31						18	
Stone, Clay, Glass, Concrete	32				11,519	215	14	
Steel	33				3,787			
Fabricated Metal Products	34					31	508	10
Industrial/Commercial - Machinery and Computers	35					23	34	
Electric and Electronics	36					330		
Transportation Equipment	37						158	
Precision Equipment	38							
Miscellaneous Manufacturing	39					26		
TOTAL		**207,495**	**619,480**	**20,225**	**32,921**	**3,851**	**56,690**	**8,736**

Table E-2B. Fossil Fuel Use in the Industrial Fuel Use Sector Reported in MPCA-EIS (in physical units): Part B

	SIC Code	LPG (10^3 gal.)	Petroleum Coke (tons)	Gasoline (10^3 gal.)	Waste Solvents (10^3 gal.)	Solid Resins (tons)	Refinery Gas (MMcf)	Natural Gas (MMcf)
Metal Mining	10	54	16,002					32,789
Non-metal mining	14							238
Food and Kindred	20	490						7,881
Textile Mill Products	22							38
Lumber and Wood	24	1,930				6		843
Furniture and Fixtures	25							74
Paper and Allied	26	54			114			8,918
Printing/Publishing	27				42			643
Chemical and Allied	28							295
Petroleum Refining and Related	29	2,735					24,065	21,017
Rubber and Misc. Products	30	22						16
Leather and Leather Products	31							95
Stone, Clay, Glass, Concrete	32	18						2,808
Steel	33	9						4,691
Fabricated Metal Products	34	23,246			12			1,869
Industrial/Commercial-Machinery and Computers	35	40						738
Electric and Electronics	36	148		124				463
Transportation Equipment	37	5						429
Precision Equipment	38	50						288
Miscellaneous Manufacturing	39							30
TOTAL		**28,801**	**16,002**	**124**	**168**	**6**	**24,065**	**84,163**

Source: Minnesota Pollution Control Agency, *Emissions Inventory System* (St. Paul, MN: 1994).

Appendix F . Estimated Natural Gas Usage and CO_2 Emissions in the Commercial Energy Use Sector by SIC Code

Sector	Intensity of Natural Gas Use, Commercial Sector, U.S. Midwest (in cu. ft./sq. ft. floor space)	Commercial Floor Space, West North Central States (in million sq. ft.) (b)	Estimated Natural Gas Consumption in West North Central States, Commercial Sector (in MMcf)	Percentage Distribution of Estimated Natural Gas Use in North West Central states, Commercial Sector (in %)	Estimated Natural Gas Use in Minnesota Commercial Sector (in MMcf) (d)	Estimated Commercial Sector Natural Gas Use Less Use Reported in MPCA-EIS (in MMcf) (e)	CO_2 Emissions
Education	61	618	37,698	11.07	8,457.3	6,993.3	408,340.5
Food Sales	62.1 (a)	79.9(c)	4,961.8	1.46	1,115.4	1,103.8	64,451.2
Food Service	112.4	174.2(c)	19,580.1	5.74	4,385.3	4,339.7	253,396.2
Health Care	156.4	561.2(c)	87,547.2	25.7	19,634.3	18,065.0	1,054,819.9
Lodging	86.7	500	43,350.0	12.73	9,725.5	9,624.3	561,965.3
Mercantile/Services	62.1(a)	1,207	74,954.7	22	16,807.6	16,461.7	961,202.5
Office	55.8	666	37,162.8	10.91	8,335.0	6,204.3	362,270.6
Public Order and Safety	62.1	79.7(c)	4,961.8	1.46	1,115.4	1,101.5	64,316.9
Vacant Rental Space	11.1	225	2,497.5	0.73	557.7	551.9	32,225.6
Warehouse	47.1	593	27,930.3	8.2	6,264.6	6,199.5	361,990.4
TOTAL			**340,644.2**	**100**	**76,398.0 (f)**	**70,645.0**	**4,124,979.4**

(a) Assumed to be the same as mercantile/services. See U.S. Department of Energy, *Commercial Building Characteristics, 1989*, DOE/EIA-0246(89), (Washington, D.C.: 1991).
(b) Includes Minnesota, South Dakota, North Dakota, Iowa, Nebraska, and Missouri.
(c) Estimated assuming 895 million sq. ft.of floor space for food sales, food service, health care and public order, and a percentage distribution among these categories of 19.46%, 8.92%, 8.92%, and 62.7%, respectively, after the general Midwest percentage distribution of floor space between these categories. Commercial floor space in food sales and public order and safety together constitute 17.84% of commercial floor space according to the general Midwest distribution of floor space among the four categories listed above, and this is assumed to be equally divided between food sales and public order and safety, based on the national distribution of floor space. See U.S. Department of Energy, *Commercial Building Characteristics, 1989* (1991).
(d) Calculated from the estimated percentage of natural gas use in each SIC Code at the regional level.
(e) Accounts for the effects of fuel uses in sanitary services, grain storage, military uses, personal services, miscellaneous business services, health services, education, social services, engineering and accounting services, and research.
(f) Taken from Table 11 above.

Appendix G . Minnesota Highway Vehicle Fleet, Total Vehicle Miles Traveled, and Fuel Consumption

Table G-1. Minnesota Passenger Car Fleet by Model Year and Vehicle Miles Traveled

Table G-2. Minnesota Light-Duty Truck Fleet by Model Year and Vehicle Miles Traveled

Table G-3. Minnesota Heavy-Duty Truck Fleet by Model Year and Vehicle Miles Traveled

Table G-4. Gallons of Fuel Consumed by Gasoline-Powered Passenger Cars Calculated from Vehicle Miles Traveled

Table G-5. Gallons of Fuel Consumed by Gasoline-Powered Light-Duty Trucks Calculated from Vehicle Miles Traveled

Table G-6. Gallons of Fuel Consumed by Heavy-Duty Trucks Calculated from Vehicle Miles Traveled

Table G-7. Gallons of Fuel Consumed by Diesel-Powered Light-Duty Vehicles Calculated from Vehicle Miles Traveled

Table G-8. Gallons Of Fuel Consumed by Buses and Motorcycles Calculated from Vehicle Miles Traveled

Table G-9. Gallons of Fuel Consumed by Cars and Trucks by Model Year

Table G-1. Minnesota Passenger Car Fleet by Model Year and Vehicle Miles Traveled

Model Year	Vehicles in Statewide Fleet by Year (as % of total)[a,b]	Avg. VMT/ Vehicle/ Year [b,c]	Gasoline Engine # Vehicles by Model Year	Gasoline Engine Total Vehicle Miles	Diesel Engine # Vehicles by Model Year	Diesel Engine Total Vehicle Miles
1990	5.00	13,340	120,305.80	1,604,879,372	1,832.05	24,439,547
1989	7.75	13,340	186,473.99	2,487,563,026.6	2,839.68	37,881,297.9
1988	8.00	13,118	192,489.28	2,525,074,375	2,931.28	38,452,531.0
1987	8.35	12,689	200,910.69	2,549,355,694.7	3,059.52	38,822,293.7
1986	8.2	12,199	197,301.51	2,406,881,144.9	3,004.56	36,652,651.8
1985	8.15	11,705	196,098.45	2,295,332,404	2,986.24	34,953,956.8
1984	6.85	11,406	164,818.95	1,879,924,898.1	2,509.91	28,628,016.4
1983	6.45	10,929	155,194.48	1,696,120,493.8	2,363.34	25,828,992.0
1982	5.45	10,481	131,133.32	1,374,408,347.9	1,996.93	20,929,870.5
1981	5.1	10,207	122,711.92	1,252,520,526.6	1,868.69	19,073,729.0
1980	5.4	9,407	129,930.26	1,222,253,993.5	1,978.61	18,612,821.9
1979	4.9	8,960	117,899.68	1,056,381,168.6	1,795.41	16,086,864.6
1978	4.6	8,960	110,681.34	991,704,770.6	1,685.49	15,101,954.6
1977	3.5	8,181	84,214.06	688,955,224.9	1,282.44	10,491,600.7
1976	2.4	8,181	57,746.78	472,426,439.9	879.38	7,194,240.5
1975	1.9	8,181	45,716.20	374,004,264.9	696.18	5,695,440.4
1974 & older	8.00	6,232	192,489.28	1,199,593,193	2931.28	18,267,737.0
TOTAL			**2,406,116[d,e]**	**26,077,379,338.9**	**36,641.00**	**110,524,388.7**

(a) Oak Ridge National Laboratory, *Transportation Energy Data Book*, 11th and 12th ed., ORNL-6743 (Oak Ridge, TN: 1990 and 1993).

(b) Average of reported values for years 1988 and 1992.

(c) U.S. Department of Energy, *Household Vehicle Energy Consumption, 1988 and 1992*, DOE/EIA-0464(88 and 91), (Washington, D.C.:1988 and 1993).

(d) Total light-duty passenger vehicles reported in Federal Highway Administration, *Highway Statistics 1990,* (Washington, D.C.: U.S. Department of Transportation, 1992), less 288,800 minivans, panels, vans, and sport utilities. For reported numbers of minivans, panels, vans and sport utilities, see Bureau of the Census, *1987 and 1992 Census of Transportation: Truck Inventory and Use Survey*, TC87-T-24, (Washington, D.C.: 1990 and 1994).

(e) 98.5% of all passenger cars registered in Minnesota after the national 1987 average. See Oak Ridge National Laboratory (1990).

Table G-2. Minnesota Light-Duty Truck Fleet by Model Year and Vehicle Miles Traveled

Model Year	Vehicles in Statewide Fleet by Year (as % of total)[a,b]	Avg. VMT/ Vehicle/ Year [b,c]	Gasoline Engine # Vehicles by Model Year	Gasoline Engine Total Vehicle Miles	Diesel Engine # Vehicles by Model Year	Diesel Engine Total Vehicle Miles
1990	5.70	14,189.5	46,846.42	664,727,262.4	939.76	13,334,710.3
1989	7.60	14,189.5	62,461.89	886,303,016.5	1,253.01	17,779,613.8
1988	7.10	12,600	58,352.56	735,242,218.2	1,170.56	14,749,270.2
1987	9.00	13,285	73,968.03	982,665,278.6	1,483.83	19,712,681.6
1986	6.70	12,551.4	55,065.09	691,143,958.1	1,104.63	13,864,640.4
1985	6.30	12,551.4	51,777.62	649,881,632.2	1,038.68	13,036,900.7
1984	5.50	12,551.4	45,202.69	567,356,980.5	906.79	11,381,421.3
1983	5.50	10,800	45,202.69	488,188,998.0	906.79	9,793,278.0
1982	6.50	10,800	53,421.36	576,950,634.0	1,071.66	11,573,874.0
1981	5.00	10,800	41,093.35	443,808,180.0	824.35	8,902,980.0
1980	5.60	9,175.6	46,024.55	422,302,879.3	923.27	8,471,574.6
1979	4.90	9,175.6	40,271.48	369,515,019.4	807.86	7,412,627.7
1978	4.30	9,175.6	35,340.28	324,268,282.3	708.94	6,504,959.0
1977	3.20	7,605	26,299.74	200,009,553.1	527.58	4,012,276.3
1976	2.30	7,605	18,902.94	143,756,866.3	379.2	2,883,823.6
1975	2.40	7,605	19,724.81	150,007,164.8	395.69	3,009,207.2
1974 & older	12.40	6,233	101,911.51	635,214,429.4	2,044.39	12,742,670.4
TOTAL			**821,867[d,e]**	**8,931,342,353.0**	**16,487**	**53,940,118.9**

(a) Oak Ridge National Laboratory, *Transportation Energy Data Book*, 11th and 12th ed., ORNL-6743 (Oak Ridge, TN: 1990 and 1993).
(b) Average of reported values for years 1988 and 1992.
(c) U.S. Department of Energy, *Household Vehicle Energy Consumption, 1988 and 1991*, DOE/EIA-0464 (88 and 93), (Washington, D.C.:1988 and 1993).
(d) 594,554 registered pickup trucks and other light trucks from Federal Highway Administration, *Highway Statistics 1990* (Washington, D.C.: U.S. Department of Transportation, 1992) plus 288,800 minivans, panels, vans, and sport utilities, the average of reported values for the years 1987 and 1992, from Bureau of the Census, *1987 and 1992 Census of Transportation: Truck Inventory and Use Survey*, TC87-T-24, (Washington, D.C.: 1990 and 1994).
(e) 97 percent of pickup trucks and other light trucks, after Bureau of Census (1990 and 1994).

Table G-3. Minnesota Heavy-Duty Truck Fleet by Model Year and Vehicle Miles Traveled

		Gasoline Engine			Diesel Engine		
Model Year	**Vehicles in State-Wide Fleet by Year (as % of Total) [a,b]**	**# Vehicles by Model Year**	**Avg. VMT/ Vehicle/yr[d]**	**Total Vehicle Miles[e]**	**# Vehicles by Model Year**	**Avg. VMT/ Vehicle/yr[a]**	**Total Vehicle Miles**
1990	3	3,124.26	13,557	42,355,592.8	2,262.39	42,000	95,020,380
1989	2.7	2,811.83	13,548	38,094,727.0	2,036.15	42,000	85,518,342
1988	3.1	3,228.4	13,480	43,518,859.0	2,337.8	41,800	97,720,165.4
1987	4.1	4,269.82	16,861	71,993,468.7	3,091.93	52,200	161,398,902.6
1986	3.4	3,540.83	12,236	43,325,571.4	2,564.04	37,900	97,177,191.8
1985	2.9	3,020.12	13,554	40,934,679.4	2,186.98	42,000	91,853,034
1984	3.4	3,540.83	11,707	41,452,473.4	2,564.04	36,300	93,074,724.6
1983	3.8	3,957.4	9,871	39,063,455.9	2,865.69	30,600	87,690,236.4
1982	6.4	6,665.09	10,162	67,730,624.3	4,826.43	31,500	152,032,608
1981	4.4	4,582.25	6,158	28,217,483.2	3,318.17	19,100	63,377,085.2
1980	4	4,165.68	6,107	25,439,807.8	3,016.52	18,900	57,012,228
1979	4	4,165.68	6,107	25,439,807.8	3,016.52	18,900	57,012,228
1978 & older	54.8	57,069.82	2,420	138,108,954.7	41,326.32	7,500	309,947,430
TOTAL		**104,142[b,c]**		**645,675,505.3[f]**	**75,413[b,g]**		**1,448,834,556**

(a) Bureau of the Census, *1987 and 1994 Census of Transportation: Truck Inventory and Use Survey*, TC87-T-22, (Washington D.C.: 1990 and 1994).
(b) Average of reported values for years 1988 and 1992.
(c) 57 percent of all reported heavy-duty trucks, after Bureau of the Census (1990 and 1994). The total number of heavy-duty trucks is taken from Federal Highway Administration, *Highway Statistics 199*, (Washington, D.C.: U.S. Department of Transportation, 1992).
(d) Calculated from total vehicle miles traveled per vehicle type and vehicle numbers.
(e) Total vehicle miles traveled of 645,675,505.3 VMTs distributed by model year according to the percentage distribution by model year of heavy-duty diesel trucks.
(f) Based on an average for all years of 6,200 vehicle miles travelled per vehicle after Bureau of the Census (1990 and 1994), and an estimated 104,142 vehicles.
(g) 43 percent of all reported heavy-duty trucks after Bureau of the Census (1990 and 1994).

Table G-4. Gallons of Fuel Consumed by Gasoline-Powered Passenger Cars Calculated from Vehicle Miles Traveled

Model Year	Total VMTs	Miles per Gallon[a]	Gallons of Fuel Used
1990	1,604,879,372	24.2	66,317,329.4
1989	2,487,563,027	24.6	101,120,448.2
1988	2,525,074,375	26.2	96,376,884.5
1987	2,549,355,695	25.9	98,430,721.8
1986	2,406,881,145	25.4	94,759,100.2
1985	2,295,332,404	24.3	94,458,123.6
1984	1,879,924,898	23.2	81,031,245.6
1983	1,696,120,494	22.8	74,391,249.7
1982	1,374,408,348	22.6	60,814,528.7
1981	1,252,520,527	21	59,643,834.6
1980	1,222,253,993	19.5	62,679,692.0
1979	1,056,381,169	18.1	58,363,600.5
1978	991,704,770.6	16.8	59,030,045.9
1977	688,955,224.9	15.5	44,448,724.2
1976	472,426,439.9	14.2	33,269,467.6
1975	374,004,264.9	14.1	26,525,125.2
1974 & older	1,199,593,193	14.1	85,077,531.4
TOTAL	**26,077,379,339**		**1,196,737,653.1**

(a) Based on average new car fuel economy ratings reported in Oak Ridge National Laboratory, *Transportation Energy Data Book*, 12th ed., ORNL-6743, (Oak Ridge, TN: 1993), adjusted for the estimated effects of vehicle age, vehicle speeds, and average annual ambient temperature. The relative effects of age are estimated by :

$$\text{relative MPG} = 0.938 + (0.35)^2(A + 0.5)e^{-0.03(A+1)}$$

where A is age in years, as taken from U.S. Environmental Protection Agency, Motor Vehicle Emissions Laboratory, *Passenger Car Fuel Economy*, EPA 460/3-80-010, (Washington, D.C.: 1980). The estimated effects of highway speed on fuel economy per miles per hour (MPH) in excess of 55 MPH are taken from Oak Ridge National Laboratory (1993), and from total highway vehicle miles travelled at different speeds. These are given in Federal Highway Administration, *Highway Statistics 1990,* (Washington, D.C.: U.S. Department of Transportation, 1992). 55 MPH is the test speed at which new car fuel economy is estimated. The effects of ambient temperature on vehicle fuel economy are taken from OECD, *Automotive Fuel Consumption in Actual Traffic Conditions,* (Paris: 1982), which reports a decline in fuel economy of 0.2 percent for each degree Celsius departure from ambient conditions prevailing during U.S. fuel economy trials. Fuel economy trials are conducted at an ambient temperature of 77 degrees Fahrenheit. The average annual temperature in Minneapolis/St. Paul is 44.7 degrees Fahrenheit. This is assumed to represent the statewide average.

Table G-5. Gallons of Fuel Consumed by Gasoline-Powered Light-Duty Trucks Calculated from Vehicle Miles Traveled

Model Year	Total VMTs	Miles per Gallon[a]	Gallons of Fuel Used
1990	664,727,262.4	18	36,929,292.4
1989	886,303,016.5	17.7	50,073,616.8
1988	735,242,218	19.1	38,494,357.0
1987	982,665,278.6	19.1	51,448,443.9
1986	691,143,958.1	18.9	36,568,463.4
1985	649,881,632.2	18.3	35,512,657.5
1984	567,356,980.5	17.7	32,054,066.7
1983	481,188,998	17.3	28,219,017.2
1982	576,950,634	17.2	33,543,641.5
1981	443,808,180	16.2	27,395,566.7
1980	422,302,879.3	15.2	27,783,084.2
1979	369,515,019.4	14.6	25,309,247.9
1978	324,268,282.3	14	23,162,020.2
1977	200,009,553.1	13.4	14,926,086.1
1976	143,756,866.3	12.8	11,231,005.2
1975	150,007,164.8	12.5	12,000,573.2
1974 & older	635,214,429.4	12.5	50,817,154.4
TOTAL	**8,931,342,353**		**535,468,294.0**

(a) See note (a), Table G-4.

Table G-6. Gallons of Fuel Consumed by Heavy-Duty Trucks Calculated from Vehicle Miles Traveled

		Diesel Engine		Gasoline Engine	
Model Year	Miles Per Gallon[a]	Total VMTs	Gallons of Fuel Used	Total VMTs	Gallons of Fuel Used
1990	6	95,020,380	15,836,730	42,355,592.8	7,059,265.5
1989	5.97	85,518,342	14,324,680.4	38,094,727.0	6,381,026.3
1988	5.94	97,720,165.4	16,451,206.3	43,518,859	7,326,407.2
1987	5.91	161,398,902.6	27,309,459.0	71,993,468.7	12,181,636.0
1986	5.88	97,177,191.8	16,526,733.3	43,325,571.4	7,368,294.5
1985	5.85	91,853,034	15,701,373.3	40,934,679.4	6,997,381.1
1984	5.82	93,074,724.6	15,992,220.7	41,452,473.4	7,122,418.1
1983	5.79	87,690,236.4	15,145,118.6	39,063,455.9	6,746,710.9
1982	5.76	152,032,608	26,394,550	67,730,624.3	11,758,788.9
1981	5.74	63,377,085.2	11,041,304.0	28,217,483.2	4,915,937.8
1980	5.7	57,012,228	10,002,145.3	25,439,807.8	4,463,124.2
1979	5.68	57,012,228	10,037,364.1	25,439,807.8	4,478,839.4
1978 & older	5.54	309,947,430	55,947,189.5	138,108,954.7	24,929,414.2
TOTAL		**1,448,834,556**	**250,710,074.5**	**645,675,505.3**	**111,729,244.1**

(a) This schedule for fuel economy is based on a 1990 fuel economy of 6 miles per gallon, after Bureau of the Census, *1994 Census of Transportation: Truck Inventory and Use Survey*, TC87-T-22, (Washington, D.C.: 1994), declining 0.5 percent per year as one goes backward in time, the average annual rate of decline from 1990 to 1970 for combination trucks and large single unit trucks. See Oak Ridge National Laboratory, *Transportation Energy Data Book*, 12th ed., ORNL-6743, (Oak Ridge, TN: 1993).

Table G-7. Gallons of Fuel Consumed by Light-Duty Diesel-Powered Vehicles Calculated from Vehicle Miles Traveled

Vehicle Type	Model Years	Total VMTs	Miles per Gallon[a]	Gallons of Fuel Used
Passenger Cars				
	1985 to 1990	211,202,278.2	24.93	8,471,812.2
	1982 to 1984	75,386,878.9	20.92	3,603,579.3
	1974 & older to 1981	110,524,388.7	20.92	5,283,192.6
	Subtotal	**397,113,545.8**		**17,358,584.1**
Light-Duty Trucks				
	1985 to 1990	92,477,817.0	18.11	5,106,450.4
	1982 to 1984	32,748,573.3	14.09	2,324,242.3
	1974 & older to 1981	53,940,118.9	14.09	3,828,255.4
	Subtotal	**179,166,509.2**		**11,258,948.1**
TOTAL		**576,280,055.0**		**28,617,532.2**

(a) Wisconsin Department of Natural Resources, *Wisconsin Greenhouse Gas Emissions*, PUBL-AM-11-92, (Madison, WI: 1993).

Table G-8. Gallons of Fuel Consumed by Buses and Motorcycles Calculated from Vehicle Miles Traveled

Vehicle Type	# of Vehicles[a]	Avg. VMTs/ Vehicle/Year (c)	Total VMTs	Miles per Gallon[c]	Gallons of Fuel Used
Buses					
Commercial	2,302	38,499	88,624,698	7	12,660,671.1
School Buses					
Gasoline	3,778	10,000	37,780,000	4.38	8,625,570.8
Diesel	8,815	10,000	88,150,000	9[d]	9,794,444.4
Total	14,895[b]		214,554,698		**31,080,686.3**
Motorcycles	122,207	2,245	274,354,715	50	**5,487,094.3**

(a) Federal Highway Administration, *Highway Statistics 1990,* (Washington, D.C.: U.S. Department of Transportation, 1992).
(b) 15 percent is assumed to be gasoline-powered and 85 percent is assumed to be diesel-powered after personal communications with representatives of Ryder Student Transportation Co., Comfort Bus Co., National School Service, Inc., and Medicine Lake Lines, December 7, 1994.
(c) U.S. Department of Transportation, *National Transportation Statistics*, DOT-VNTSC-BTS-93-1, (Washington, D.C.: 1993).
(d) Personal conversation with representatives of Ryder Student Transportation Co., December 8, 1994.

Table G-9. Gallons of Fuel Consumed by Cars and Trucks by Model Year

	Model Years [a]	Gallons of Fuel Consumed
Gasoline Passenger Cars	1989-90	167,437,777.7
	1981-88	659,905,688.8
	1975-80	284,316,655.3
	1974 & earlier	85,077,531.4
	ALL	**1,196,737,653.1**
Diesel Passenger Cars	1985-90	8,471,812.2
	1982-84	3,603,579.3
	1974-81	5,283,192.6
	ALL	**17,358,584.1**
Gasoline Light-Duty Trucks	1989-90	87,002,909.1
	1981-88	283,236,213.9
	1975-80	114,412,016.7
	1974 & earlier	50,817,154.4
	ALL	**535,468,294.0**
Diesel Light-Duty Trucks	1985-90	5,106,450.4
	1982-84	2,324,242.3
	1974-81	3,828,255.4
	ALL	**11,258,948.1**
Gasoline Heavy-Duty Trucks	1990	7,059,265.5
	1979-89	79,740,564.4
	1978 & earlier	24,929,414.2
	ALL	**111,729,244.1**
Diesel Heavy-Duty Trucks	1985-90	106,150,182.3
	1979-84	88,612,702.7
	1978 & earlier	55,947,189.5
	ALL	**250,710,074.5**

(a) Ranges of years correspond to years of use of particular vehicle emissions control technology. See Wisconsin Department of Natural Resources, *Wisconsin Greenhouse Gas Emissions*, PUBL-AM-11-92, (Madison, WI: 1993).

Appendix H . Fuel Use and CO_2 Emissions for 1980, 1986, and 1988

Table H-1. 1980 Minnesota Fossil Fuel Use (in physical Units)

Table H-2. Estimated 1980 Minnesota Carbon Dioxide Emissions from Fossil Fuel Combustion

Table H-3. 1986 Minnesota Fossil Fuel Use (in physical Units)

Table H-4. Estimated 1986 Minnesota Carbon Dioxide Emissions from Fossil Fuel Combustion

Table H-5. 1988 Minnesota Fossil Fuel Use (in physical Units)

Table H-6. Estimated 1988 Minnesota Carbon Dioxide Emissions from Fossil Fuel Combustion

Table H-1. 1980 Minnesota Fossil Fuel Use (in physical units)

	Residential	Commercial	Industrial	Electrical Generation/ Steam	Agricultural	Transportation	TOTAL
Natural Gas (MMcf)	102,703	61,766	98,250	12,124		9,188	284,031
Propane-Air Gas (MMcf)	19	11	18				48
Refinery Gas (MMcf[a])			24,065				24,065
Bituminous Coal (tons)	12,500	142,935	258,185	3,273,803			3,687,423
Subbituminous Coal (tons)		10,138	11,949	8,959,919		13,638	8,995,644
Lignite (tons)			393,547	849,908			1,243,455
Coal Coke (tons)							
Petroleum Coke (tons)							
Solid Resins (tons)							
Refuse-Derived Fuel (tons)							
MSW-Mass Burn (tons)							
Motor Gasoline (10^3 gallons)		3,762	3,762		50,424	1,965,298	2,023,246
Aviation Gasoline						6,728	6,728
Jet Fuel						196,500	196,500
Distillate Fuel Oil	249,732	60,606	71,921	4,968	167,815	340,914	895,956
LPG	123,018	21,714	27,917		147,769	2,856	323,274
Kerosene	4,788		617		3,499		8,904
Waste Solvent			23				23
Residual Fuel Oil		16,814	47,435	18,579		3,244	86,072
Waste Oil			99				99

Source: See Appendix D and text.

(a) 1990 refinery-reported value

Table H-2. Estimated 1980 Minnesota Carbon Dioxide Emissions from Fossil Fuel Combustion (in tons of CO_2)

	Residential	Commercial	Industrial	Electrical Generation/ Steam	Agricultural	Transportation	TOTAL
Natural Gas	5,996,854.1	3,606,532.3	5,736,842.3	707,923.4		536,489.6	16,584,641.7
Propane-Air Gas	1,646.6	953.3	1,559.9				4,159.8
Refinery Gas			1,641,410.7				1,641,410.7
Bituminous Coal	28,436.6	325,166.8	587,352.2	7,447,664.8			8,388,620.4
Subbituminous Coal		18,443.7	21,738.3	16,300,423.1		24,811.1	16,365,416.2
Lignite			566,061.4	1,222,471.7			1,788,533.1
Coal Coke							
Petroleum Coke							
Solid Resins							
Refuse-Derived Fuel							
MSW-Mass Burn							
Motor Gasoline		35,673.5	35,673.5		478,149.8	18,636,105.3	19,185,602.1
Aviation Gasoline						62,790.4	62,790.4
Jet Fuel						2,065,141.7	2,065,141.7
Distillate Fuel Oil	2,776,741.5	673,871.2	799,681.3	55,238.6	1,865,915.7	3,790,583.8	9,962,032.1
LPG	762,867.1	134,654.2	173,120.7		916,354.6	17,710.8	2,004,707.4
Kerosene	50,531.1		6,511.6		36,927.4		93,970.1
Waste Solvent			223.2				223.2
Residual Fuel Oil		212,782.9	600,294.8	235,119.2		41,053.1	1,089,250.0
Waste Oil			1,212.5				1,212.5
TOTAL	**9,617,077**	**5,088,077.9**	**10,171,682.**	**25,968,840.8**	**3,297,347.5**	**25,174,685.8**	**79,237,711.4**

Source: Calculated from Table H-1.

Table H-3. 1986 Minnesota Fossil Fuel Use (in physical units)

	Residential	Commercial	Industrial	Electrical Generation/ Steam	Agricultural	Transportation	TOTAL
Natural Gas (MMcf)	102,492	73,607	53,977	5,135		7,698	**242,909**
Propane-Air Gas (MMcf)	1		1				**2**
Refinery Gas MMcf[a]			24,065				**24,065**
Bituminous Coal (tons)	5,600	16,969	396,254	613,261		1,960	**1,034,044**
Subbituminous Coal (tons)		163,349	594,750	9,479,273			**10,237,372**
Lignite (tons)		7,082		217,502			**224,584**
Coal Coke (tons)			29,129				**29,129**
Petroleum Coke (tons)			58,914	116,426			**175,340**
Solid Resins (tons)							
Refuse-Derived Fuel (tons)		30,000					**30,000**
MSW-Mass Burn (tons)		8,682		25,380			**34,062**
Motor Gasoline (10^3 gallons)		1,657	6,391		60,356	1,883,393	**1,951,797**
Aviation Gasoline						7,336	**7,336**
Jet Fuel						298,100	**298,100**
Distillate Fuel Oil	167,916	45,234	71,366	2,849	166,522	339,654	**793,541**
LPG	117,432	20,706	28,735		91,595	5,292	**263,760**
Kerosene	3,696	168	195		1,107		**5,166**
Waste Solvent							
Residual Fuel Oil		6,804	74,224	7,228		1,244	**89,500**
Waste Oil			5,910	3,003			**8,913**

Source: See Appendix D and text.

(a) 1990 refinery-reported value

Table H-4. Estimated 1986 Minnesota Carbon Dioxide Emissions from Fossil Fuel Combustion (in tons of CO_2)

	Residential	Commercial	Industrial	Electrical Generation/ Steam	Agricultural	Transportation	TOTAL
Natural Gas	5,984,533.7	4,297,931.3	3,151,730.6	299,833.9		449,488.2	14,183,517.7
Propane-Air Gas	86.7		86.7				173.4
Refinery Gas			1,641,410.7				1,641,410.7
Bituminous Coal	12,739.6	38,603.2	901,449.2	1,395,124.4		4,458.9	2,352,375.3
Subbituminous Coal		297,174.3	1,082,004.9	17,245,263.2			18,624,442.4
Lignite		10,186.4		312,845.7			323,032.1
Coal Coke			100,392.3				100,392.3
Petroleum Coke			196,625.0	388,570.8			585,195.8
Solid Resins							
Refuse-Derived Fuel		16,566.8					16,566.8
MSW-Mass Burn		3,395.7		9,926.8			13,322.5
Motor Gasoline		15,712.6	60,603.2		572,330.8	17,859,430.5	18,508.077.1
Aviation Gasoline						68,464.7	68,464.7
Jet Fuel						3,132,919.9	3,132,919.9
Distillate Fuel Oil	1,867,038.8	502,951.7	793,510.4	31,677.7	1,851,539.0	3,776,573.9	8,823,291.5
LPG	728,226.8	128,403.4	178,193.3		568,004.8	32,817.1	1,635,645.4
Kerosene	39,006.5	1,773.0	2,058.0		11,682.9		54,520.4
Waste Solvent							
Residual Fuel Oil		86,105.3	939,312.4	91,471.1		15,742.9	1,132,631.7
Waste Oil			72,383.2	36,779.5			109,162.7
TOTAL	**8,631,632.1**	**5,398,803.7**	**9,119,759.9**	**19,811,493.1**	**3,003,557.5**	**25,339,896.1**	**71,305,142.4**

Source: Calculated from Table H-3 above.

Table H-5. 1988 Minnesota Fossil Fuel Use (in physical units)

	Residential	Commercial	Industrial	Electrical Generation/ Steam	Agricultural	Transportation	TOTAL
Natural Gas (MMcf)	108,742	79,041	71,670	10,563		11,528	**281,544**
Propane-Air Gas (MMcf)	158	115	112				**385**
Refinery Gas Mmcf [a]			24,065				**24,065**
Bituminous Coal (tons)	6,100	22,147	164,718	460,958		1,400	**655,323**
Subbituminous Coal (tons)		205,227	578,980	16,187,974			**16,972,181**
Lignite (tons)		525		46,871			**47,396**
Coal Coke (tons)			29,951				**29,951**
Petroleum Coke (tons)			13,860	43,253			**57,113**
Solid Resins (tons)							
Refuse-Derived Fuel (tons)		45,500		173,615			**219,115**
MSW-Mass Burn (tons)		27,152		158,957			**186,109**
Motor Gasoline (10^3 gallons)		1,999	6,616		45,227	2,015,494	**2,069,336**
Aviation Gasoline						6,182	**6,182**
Jet Fuel						303,200	**303,200**
Distillate Fuel Oil	183,792	46,284	67,968	5,675	154,086	378,630	**836,435**
LPG	119,448	21,084	24,684		67,800	3,108	**236,082**
Kerosene	4,338	179	176		1,092		**5,785**
Waste Solvent		3,000					**3,000**
Residual Fuel Oil		2,779	66,051	2,738		984	**72,552**
Waste Oil			7,108	140		1	**7,249**

Source: See Appendix D and text.

(a) 1990 refinery-reported value

Table H-6. Estimated 1988 Minnesota Carbon Dioxide Emissions from Fossil Fuel Combustion (in tons of CO_2)

	Residential	Commercial	Industrial	Electrical Generation/ Steam	Agricultural	Transportation	TOTAL
Natural Gas	6,349,472.8	4,615,223.9	4,184,829.4	616,776.2		673,122.8	16,439,425.1
Propane-Air Gas	13,692.7	9,966.2	9,706.2				33,365.1
Refinery Gas			1,641,410.7				1,641,410.7
Bituminous Coal	13,877.1	50,382.8	374,721.5	1,048,646.1		3,184.9	1,490,812.4
Subbituminous Coal		373,361.3	1,053,315.2	29,450,135.2			30,876,811.7
Lignite		755.1		67,417.3			68,172.4
Coal Coke			103,225.3				103,225.3
Petroleum Coke			46,257.6	144,356.5			190,614.1
Solid Resins							
Refuse-Derived Fuel		25,126.2		95,874.5			121,000.7
MSW-Mass Burn		10,619.8		62,172.1			72,791.9
Motor Gasoline		18,955.7	62,736.8		428,868.8	19,112,089.2	19,622,650.5
Aviation Gasoline						57,694.8	57,694.8
Jet Fuel						3,186,519.0	3,186,519.0
Distillate Fuel Oil	2,043,562.2	514,626.5	755,728.4	63,099.7	1,713,264.6	4,209,943.6	9,300,225.0
LPG	740,728.6	130,747.4	153,072.0		420,445.7	19,273.5	1,464,267.2
Kerosene	45,782.5	1,889.1	1,857.5		11,524.6		61,053.2
Waste Solvent		29,106.9					29,106.9
Residual Fuel Oil		35,168.5	835,882.3	34,649.7		12,452.6	918,153.1
Waste Oil			87,055.8	1,714.7		12.2	88,782.7
TOTAL	**9,207,115.4**	**5,815,929.4**	**9,309,798.7**	**31,584,842.0**	**2,574,103.7**	**27,274,292.6**	**85,766,081.8**

Source: Calculated from Table H-5 above.

Appendix I . Emissions from Stationary Sources: MPCA Component

Table I-1. CH_4 Emissions from Stationary Sources in the Electrical Generation/Steam Sector: MPCA-EIS Component

Table I-2. CH_4 Emissions from Stationary Sources in The Industrial Sector: MPCA-EIS Component

Table I-3. CH_4 Emissions from Stationary Sources in the Commercial Sector: MPCA-EIS Component

Table I-4. CH_4 Emissions From Stationary Sources in the Transportation Sector

Table I-5. Nitrous Oxide Emissions from Combustion

Table I-1. CH_4 Emissions from Stationary Sources in the Electrical Generation/Steam Sector: MPCA-EIS Component

Source	Fuel Use		Emission	
	Tons	MMBTU	lb. CH_4/ MMBTU	In tons of CH_4
Coal fired boilers				
Bituminous & subbituminous	17,087,081	291,825,657.00	0.0013	189.7
Lignite				
Pulverized	1,370	17,810.00	0.013	0
Spreader stoker	58	754.00	0.0015	0
Petroleum coke boilers	146,084	4,148,785.60	0.0015	3.1
Wood boilers	151,869	1,943,923.20	0.0398	38.7
RDF- fired boilers	546,908	6,070,678.80	0.0007	2.1
MSW-fired boilers	504,519	4,893,834.30	NE	NE
	10^3 gallons	MMBTU		
Waste oil burners	26	3,754.50	0.0015	0
Residual oil boilers	2,231	333,958.40	0.0015	0.3
Distillate fuel oil				
Electric utility boilers	2,347	325,505.40	0.00007	0
Industrial boilers	194	26,905.90	0.00037	0
Diesel turbines	1,410	195,552.90	0.0124	1.2
Diesel reciprocating engines	259	35,920.70	0.00007	0
	MMcf	MMBTU		
Natural Gas				
Boilers	8,648	8,699,888.00	0.0002	0.9
Reciprocating engines	47	47,282.00	0.913(a)	21.6
Turbines	433	435,598.00	0.0124	2.7
Industrial boilers	77	77,462.00	0.0029	0.1
Process fuel uses	78	78,468.00	0.0029	0.1
TOTAL				260.5

Sources: Minnesota Pollution Control Agency, *Emissions Inventory System*, (St. Paul, MN:1994).
U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA 230-B-92-002, (Washington, D.C.: 1992).
U.S. Environmental Protection Agency, *Compilation of Air Polllution Emissions Factors, Vol. 1 - Stationary Point & Area Sources*, 4th ed., (Research Triangle Park, NC: 1985).

(a) Average of values given in U.S. Environmental Protection Agency, (1985), Supplement E for SCC code 20200202.

Table I-2. CH_4 Emissions from Stationary Sources in the Industrial Sector: MPCA-EIS Component

Source	Fuel Use		Emissions	
	Tons	MMBTU	lb. CH_4/ MMBTU	In tons of CH_4
Coal fired boilers	724,863	13,259,021.0	0.0053	35.1
Coal in-process fuels	40,450	707,875.0	0.0053(a)	1.9
Coal fired dryers	8,887	1,392,079.0	0.0022	1.5
Coke-fired kilns	17,615	472,082.0	0.0022	0.5
Coke in-process fuels	15,306	410,201.0	0.0053	1.1
Wood fired boilers	957,329	12,253,811.2	0.3(b)	143.6
Wood in-process fuels	232,589	2,977,139.2	0.015(b,c)	1.7
Wood sludge boilers	32,860	420,608.0	4.6(b)	75.6
Petroleum coke in-process fuels	16,002	454,456.8	0.0053	1.2
	10^3 gallons	MMBTU		
Residual oil				
Boilers	15,715	2,352,378.4	0.0064	7.5
In-process fuels	1,486	222,439.3	0.0024	0.3
Dryers & kilns	12,005	1,797,028.5	0.0022(c)	2.0
Waste oil				
Boilers	320	46,209.6	0.0064(d)	0.1
Dryers	8,416	1,215,312.5	0.002(d)	1.3
Distillate oil				
Boilers	1,008	139,799.5	0.00037	0
Dryers & kilns	1,295	179,603.6	0.0022	0.2
In-process fuels	1,116	154,778.0	0.00037(a)	0
Space heaters	46	6,379.7	0.00037(a)	0
Incinerator	55	7,628.0	0.00037(a)	0
Turbines	15	2,080.4	0.0048	0.0
Reciprocating engines	316	43,826.0	0.0174(e)	0.4
LPG				
Boilers	823	78,596.5	0.0009(e)	0.0
Dryers & kilns	4,525	432,137.5	0.0022(e)	0.5
In-process fuels	23,379	2,232,694.5	0.0018(e)	2.0
Space Heaters	56	5,348	0.0009(a,e)	0
Incinerators	18	1,719	0.0009(a,e)	0

Table I-2. CH_4 Emissions from Stationary Sources in the Industrial Sector: MPCA-EIS Component (continued)

	Fuel Use		Emissions	
	MMCF	MMBTU		
Natural gas				
Boilers	21,600	21,729,600.0	0.0029	31.5
Dryers & kilns	5,568	5,601,408.0	0.0023	6.4
In-process fuels	37,909	38,136,454.0	0.0029(a)	55.3
Space heaters	320	321,920.0	0.0029(a)	0.5
Incinerators	60	60,360.0	0.0029(a)	0.1
Gas engines	42	42,252.0	0.913	19.3
Refinery Operations				
Natural gas	18,664	18,775,985.0	0.0029(f)	27.2
Refinery gas	24,065	27,674,750.0	0.0029(f,g)	40.1
Residual Oil	27,484	4,114,080.0	0.0024(f)	4.9
LPG	3,021	288,505.5	0.0018(f)	0.2
TOTAL				462.0

Sources: Minnesota Pollution Control Agency, *Emissions Inventory System*, (St. Paul, MN: 1994).
U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA 230-B-002, (Washington, D.C.: 1992).
U.S. Environmental Protection Agency, *Compilation of Air Pollution Emissions Factors, Vol. 1- Stationary Point and Area Sources*, 4th edition, (Research Triangle Park, NC: 1993).
U.S. Environmental Protection Agency, *Air Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Pollutants*, EPA 450/4-90-003, (Research Triangle Park, NC: 1990).

(a) Assumed to be the same as that for boilers. See U.S. Environmental Protection Agency, *Air Facility Subsystem* (1990) for equivalence of emission factors.
(b) lbs. of CH_4 per ton of fuel.
(c) Estimated based on the ratio of VOC emissions in in-process uses to VOC emissions in boiler applications.
(d) Assumed to be the same as that for residual fuel oil.
(e Estimated from the ratio of CH_4 to VOC emissions given in U.S. Environmental Protection Agency (1993) for this particular fuel use and VOC emissions factors given in U.S. Environmental Protection Agency, *Air Facility Subsystem* (1990).
(f) In-process fuel use.
(g) Assumed to be the same as that for natural gas.

Table I-3. CH_4 Emissions from Stationary Sources in the Commercial Sector: MPCA-EIS Component

Source	Tons	MMBTU	lb. CH_4/MMBTU	In tons of CH_4
Coal-fired boilers	199,099	3,539,253.00	0.0221	39.1
Wood-fired boilers	2,531	32,396.80	0.0331	0.5
Wood reactors	4,578	58,598.4	NE	NE
MSW-fired boilers	28,313	274,655.50	0.0064(a)	0.1
RDF-fired boilers	33,251	369,086.10	0.0064(a)	0.1
	10^3 gallons	MMBTU		
Residual oil boilers	5,265	788,117.90	0.0035	1.4
Distillate fuel oil				
Boilers	896	124,266.2	0.0013	0.1
Reciprocating engines	53	7,350.6	1.26(b)	4.6
LPG				
Dryers	25	2,387.5	0.0022(c)	0
Boilers	169	16,139.5	0.0009(c)	0
	MMcf	MMBTU		
Natural gas				
Boilers	5,556	5,589,336	0.0025	7.00
Dryers	197	198,182	0.0023	0.2
TOTAL				53.1

Sources: Minnesota Pollution Control Agency, *Emissions Inventory System,* (St. Paul, MN: 1994).
U.S. Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA 230-B-002, (Washington, D.C.: 1992).
U.S. Environmental Protection Agency, *Compilation of Air Pollution Emissions Factors, Vol. 1- Stationary Point and Area Sources*, 4th edition, (Research Triangle Park, NC: 1993).
U.S. Environmental Protection Agency, *Air Facility Subsystem Source Classification Codes and Emission Factor Listing for Criteria Pollutants*, EPA 450/4-90-003, (Research Triangle Park, NC: 1990).
U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions in the United States: Estimates for 1990*, EPA 430-R-93-003, (Washington, D.C.: 1993).

(a) Lbs. of CH_4 per ton of fuel

(b) Estimated from the ratio of CH_4 to VOC emissions for this fuel use given in U.S. Environmental Protection Agency, *Anthropogenic Methane Emissions* (1993) and the VOC emission factor given U.S. Environmental Protection Agency, *Air Facility Subsystem* (1990).

(c) Asumed to be the same as the emission factor for distillate oil dryers.

Table I-4. CH_4 Emissions from Stationary Sources in the Transportation Sector: MPCA-EIS Component

Source	Tons	MMBTU	lb. CH_4/MMBTU	In tons of CH_4
Wood boilers	6,637	84,953.60	0.0331	**1.4**
	10^3 gallons	MMBTU		
Residual oil boilers	290	43,410.10	0.0035	**0.1**
Waste oil boilers	1	144,405	NE	**NE**
Distillate oil				
Boilers	45	6,241.1	0.0013	**0**
Reciprocating engines	229	31,760	1.26(a)	**20**
	MMcf	MMBTU		
Natural gas				
Boilers	827	831,962	0.0025	**1.00**
Reciprocating engines	4,103	4,127,618	1.124(a)	**2,319.70**
Turbines	7,447	7,491,682	0.0198(a)	**74.2**
Total				**2,416.40**

Sources: See Table I-3.

(a) See note (b), Table I-3.

Table I-5. Nitrous Oxide Emissions from Combustion: MPCA-EIS Component

Fuel Use Sector	Tons	MMBTU	lb. N_2 0/MMBTU	Emissions (in tons of N_2 O)
Electric generation/Steam				
Coal boilers[a]	17,029,092	290,756,746	0.0018	261.7
Commercial				
Coal boilers	199,099	3,539,253	0.131	231.8
Wood boilers	2,531	32,397	0.0095	0.2
	103 gallons	MMBTU		
Residual oil boilers	5,265	788,118	0.103	40.6
Distillate oil boilers	896	124,266	0.035	2.2
	MMcf	MMBTU		
Natural gas boilers	5,556	5,589,336	0.005	14
Total				550.5

Sources: Minnesota Pollution Control Agency, *Emission Inventory System*, (St. Paul, MN: 1994).
US Environmental Protection Agency, *State Workbook: Methodologies for Estimating Greenhouse Gas Emissions*, EPA 230-B-92-002, (Washington, DC: 1992).

(a) Includes all boiler types except atmospheric fluidized bed.

Appendix J . NO_x, CO, N_2O, CH_4 Emissions From Fuel Use Not Accounted For By MPCA's Emissions Inventory System

Table J-1. Statewide NO_x Emissions from Fuel Use Not Accounted for by MPCA-EIS By Sector and Fuel

Table J-2. Statewide CO Emissions from Fuel Use Not Accounted for by MPCA-EIS by Sector and Fuel

Table J-3. Statewide N_2O Emissions from Fuel Use Not Accounted for by MPCA-EIS by Sector and Fuel

Table J-4. Statewide CH_4 Emissions from Fuel Use Not Accounted for by MPCA-EIS by Sector and Fuel

Table J-1. Statewide NO_x Emissions from Fuel Use Not Accounted for by MPCA-EIS by Sector and Fuel (in Tons)

	Residential	Commercial	Industrial	Transportation	Electric Utility	Total
Coal	33.9	0	1,638.4 - 2,392.1	0	0	1,672.3 - 2,426.0
Natural Gas	5,226.8	3,491.6- 3,562.9	0	58.5 - 663.1	64.4	8,841.3 - 9,517.2
Propane - Air	1.4	1.0	1.2 - 1.5	0	0	3.6 - 3.9
Distillate	1,065.9	172.7 - 215.5	608.2	0	0	1,846.8 - 1,889.6
LPG	626.6	107.1	52.5 - 65.6	10.5 - 11.9	0	796.7 - 811.2
Wood	2,777.1 - 4,794.8	24.7	206.1	0	0	3,007.9 - 5,025.6
Total	**9,731.7 - 11,749.4**	**3,797.1 - 3,911.2**	**2,506.4 - 3,273.5**	**69.0 - 675.0**	**64.4**	**16,168.6 - 19,673.5**

Sources: Tables 29 and 30.

Table J-2. Statewide CO Emissions from Fuel Use Not Accounted for By MPCA-EIS by Sector and Fuel (in Tons)

	Residential	Commercial	Industrial	Transportation	Electric Utility	Total
Coal	28.0	0	675.0 - 1,297.6	0	0	703 - 1,325.6
Natural Gas	1,120.0	712.6 - 748.2	0	23.3 - 83.8	4.6	1,860.5 - 1,956.6
Propane - Air	0.3	0.2	0.2 - 0.4	0	0	0.7 - 0.9
Distillate	273.6	44.3 - 53.5	59.1	0	0	377.0 - 386.2
LPG	132.6	22.7	13.6 - 16.2	2.2 - 2.5	0	171.1 - 174
Wood	143,844.5 - 444,225.6	148.7	2,737.6	0	0	146,730.8 - 447,111.9
Total	**145,399.0 - 445,780.1**	**928.5 - 973.3**	**3,485.5 - 4,110.9**	**25.5 - 86.3**	**4.6**	**149,843.1 - 450,955.2**

Sources: Tables 29 and 30.

Table J-3. Statewide N_2O Emissions from Fuel Use Not Accounted for by MPCA-EIS by Sector and Fuel (in Tons)

	Residential	Commercial	Total
Coal	8.5		8.5
Wood		3.2	3.2
Total	8.5	3.2	11.7

Sources: Tables 29 and 30.

Table J-4. Statewide CH_4 Emissions from Fuel Use Not Accounted for by MPCA-EIS by Sector and Fuel (in Tons)

	Residential	Commercial	Industrial	Transportation	Total
Coal	1.4	0	7.2 - 17.4	0	8.6 - 18.8
Natural Gas	112.0	74.8 - 89.1	0	3.9 - 220.5	190.7 - 421.6
Propane - Air	0	0	0	0	0
Distillate	103.8	2.0 - 16.8	22.0	0	127.8 - 142.6
LPG	14.5	2.5	1.4	0.3	18.7
Wood	1,779.1	11.2	27.3	0	1,817.6
Total	2,010.8	90.5 -119.6	57.9 - 68.1	4.2 - 220.8	2,163.4 - 2,419.3

Sources: Tables 29 and 30.

Appendix K . Decay of CH_4 to CO_2 from Prior Year Landfill Emissions by Year of Emission

Table K-1. Annual Methane Generation from the Increment of Waste Added Annually to Landfills

Table K-2. Decay of CH_4 to CO_2 from Prior Year Landfill Emissions by Year of Emission

Table K-1. Annual Methane Generation from the Increment of Waste Added Annually to Landfills

Year	Waste Landfilled (tons)	1990 Emission of CH_4 From Waste Landfilled in In Prior Years (in MMcf)[a]
1990	2,464.897.2	320.4
1989	2,359,398.6	306.7
1988	2,952,435.6	338.8
1987	2,940,239.1	382.2
1986	3,229,535.7	419.8
1985	3,143,102.1	408.6
1984	3,162,567.0	411.1
1983	3,082,376.7	400.7
1982	2,995,582.2	389.4
1981	3,117,601.8	405.3
1980	3,221,310.3	418.8
1979	3,194,814	415.3
1978	3,152,723.4	409.9
1977	3,104,638.8	403.6
1976	3,070,953.3	399.2
1975	3,031,913.4	394.1
1974	3,005,416.2	390.7
1973	2,981,334.9	387.6
1972	2,958,112.2	384.6
1971	2,931,940.2	381.2
1970	2,877,906.9	374.1
1969	1,414,379.7 to 2,545,883.5	183.9 to 331.0
1968	1,387,347.45 to 2,497,225.4	180.4 to 324.6
1967	1,364,605.8 to 2,456,290.4	177.4 to 319.3
1966	1,342,756.95 to 2,416,962.5	174.6 to 314.2
1965	1,327,387.65 to 2,389,297.8	172.6 to 310.6
1964	1,308,739.2 to2,355,730.6	170.1 to 306.2
1963	1,292,769.75 to 2,326,985.6	168.1 to 302.5
1962	1,280,172.3 to 2,304,310.1	166.4 to 299.6
1961	1,258,569 to 2,265,424.2	163.6 to 294.5
1960	1,232,448.6 to 2,218,407.5	160.2 to 288.4
Total	75,546,857.4 to 86,114,198.5	9,859.4 to 11,233[b]

(a) Calculated at 0.065 cubic feet of CH_4/ of waste.

(b) Represents total 1990 CH_4 emission from municipal solid waste landfills with adjusting for landfill gas collected and combusted for purposes of energy production or gas flared. This total differs marginally from that given in Table 64 due to rounding in this Appendix.

Table K-2. Decay of CH_4 to CO_2 from Prior Year Landfill Emissions by Year of Emission

Year of CH_4 Emission From Landfill	% of Annual Emission in the Listed Year Decayed in 1990 to CO_2 (%)	Annual CH_4 Emission for the Given Year (in MMcf)	CH_4 Decayed to CO_2 in 1990 from Prior Years Emissions (in MMcf)
1990	NA	9,859.4 to 11,233	
1989	9.52	9,539 to 10,912.6	908.1 to 38.9
1988	8.61	9,232.3 to 10,605.9	794.9 to 913.2
1987	7.79	8,893.5 to 10,267.1	692.8 to 799.8
1986	7.05	8,511.3 to 9,884.9	600.0 to 696.9
1985	6.38	8,091.5 to 9,465.1	516.2 to 603.9
1984	5.77	7,682.9 to 9,056.5	443.3 to 522.6
1983	5.22	7,271.8 to 8,645.4	379.6 to 451.3
1982	4.73	6,871.1 to 8,244.7	325 to 390
1981	4.27	6,481.7 to 7,855.3	276.8 to 335.4
1980	3.87	6,076.4 to 7,450	235.2 to 288.3
1979	3.50	5,676.6 to 7,031.2	198.7 to 246.1
1978	3.17	5,242.3 to 6,615.9	160.2 to 209.7
1977	2.87	4,832.4 to 6,206	138.7 to 178.1
1976	2.59	4,428.8 to 5,802.4	114.7 to 105.3
1975	2.35	4,029.6 to 5,403.2	94.7 to 127.0
1974	2.12	3,635.5 to 5,009.1	77.1 to 117.7
1973	1.92	3,244.8 to 4,618.4	62.3 to 88.7
1972	1.74	2,857.2 to 4,230.8	49.7 to 73.6
1971	1.57	2,472.6 to 3,846.2	38.8 to 60.4
1970	1.43	2,091.4 to 3,465	29.9 to 49.5
1969	1.28	1,717.3 to 3,090.9	22 to 39.6
1968	1.17	1,533.4 to 2,759.9	17.9 to 32.3
1967	1.05	1,353 to 2,435.3	14.2 to 25.6
1966	0.96	1,175.6 to 2,116	11.3 to 20.3
1965	0.86	1,001 to 1,801.8	8.6 to 15.5
1964	0.78	828.4 to 1,491.2	6.5 to 11.6
1963	0.71	658.3 to 1,185	4.7 to 8.4
1962	0.64	490.2 to 882.5	3.1 to 5.6
1961	0.58	323.8 to 582.9	1.9 to 3.4
1960	0.52	160.2 to 288.4	0.9 to 1.7
Total			**6,233.8 to 7,505.4**

Appendix L . Nitrogen Fertilizer Use and Nitrous Oxide Emissions, 1989-1991 and 1988-1990

Table L-1. Nitrogen Fertilizer Consumption and Nitrous Oxide Emissions, 1989-1991: Part A

Table L-2. Nitrogen Fertilizer Consumption and Nitrous Oxide Emissions, 1989-1991: Part B

Table L-3. Nitrogen Fertilizer Consumption and Nitrous Oxide Emissions, 1988-1990: Part A

Table L-4. Nitrogen Fertilizer Consumption and Nitrous Oxide Emissions, 1988-1990: Part B

Table L-1. Nitrogen Fertilizer Consumption and Nitrous Oxide Emissions, 1989-1991: Part A

	Fertilizer Consumption (in tons)					
	1989	1990	1991	3 Yr. Avg. (in tons)	% N Per Fertilizer Type	3 Yr. Avg. (in tons of N)
Ammonia Type						
Anhydrous ammonia	422,925	456,986	293,164	391,025.00	82	320,640.50
Aqua ammonia	1,157	137	1,290	861.33	16-25	215.33
Nitrogen solutions	130,855	147,807	123,609	134,110.33	21-49	28,163.17-65,714.06
Ammonium nitrate types						
Ammonium nitrate	14,654	9,292	8,529	10,825.00	33.5	3,626.38
Ammonium sulfate-nitrate	164	326	20	170.00	26	44.20
Ammonium types						
Ammonium sulfate	18,301	42,916	29,685	30,300.67	21	6,363.14
Ammonium thiosulfate	1,066	1,768	2,563	1,799.00	12(a)	215.88
Ammonium polysulfide	2,125	443	377	981.67	10-15(a)	98.17-147.25
Ferrous ammonium sulfate	11	33	0	14.67	7(a)	1.03
Ammonium phosphate						
Monoammonium phosphate	41,561	38,606	45,543	41,903.33	11	4,609.37
Diammonium phosphate	353,380	409,149	369,286	377,271.67	18	67,908.90
Ammonium polyphosphate	38,336	45,975	35,519	39,943.33	10	3,994.33
Ammoniated superphosphate	1,221	4,733	0	1,984.67	4	79.39
Ammoniated phosphate	5,202	3,572	3,664	4,146.00	9	373.14
Urea	294,194	335,152	281,055	303,467.00	46	139,594.82
Nitrate types (potassium nitrate)	0	0	0	0	13	0
Other multiple nutrients:						
9-23-30	15,778	4,503	4,176	8,152.33	9	733.71
7-21-7	14,194	14,704	13,386	14,094.67	7	986.63
3-9-30	7,591	8,696	6,375	7,554.00	3	226.62
7-23-5	3,846	3,166	2,939	3,317.00	7	232.19
10-26-26	5,165	2,286	0	2,483.67	10	248.37
8-24-0	0	1,740	4,643	2,127.67	8	170.21
5-14-42	5,055	0	0	1,685.00	5	84.25
10-30-05	2,931	0	0	977.00	10	97.70
3-10-30	0	2,148	1,079	1,075.67	3	32.27
19-5-0	0	2,138	1,368	1,168.67	19	222.05
8-10-20	0	1,451	0	483.67	8	38.69
Subtotal	54,560	40,832	33,966	43,119.35		3,072.69
Other nitrogen materials	1,254	1,907	1,668	1,609.67	15 - 20(a)	241.45 - 321.93
Specialty fertilizer(b)	33,011	35,636	31,762	33,469.67	15 - 20(a)	5,020.45 - 6,693.93

Table L-2 . Nitrogen Fertilizer Consumption and Nitrous Oxide Emissions, 1989-1991: Part B

	Fertilizer Consumption	Percent of Fertilizer Nitrogen Evolved as N_2O			Emissions of N_2O-N			N_2O Emissions		
	3 Yr. Avg. (in N-tons)	Low EF	Med. EF	High EF	Low	Med.	High	Low	Med.	High
Ammonia Type										
Anhydrous ammonia	320,640.50	0.86	1.63	6.84	2,757.51	5,226.44	21,931.81	4,333.23	8,212.98	34,464.27
Aqua ammonia	215.33	0.86	1.63	6.84	1.19-1.85	2.25-3.51	9.43-14.73	1.87-2.91	3.54-5.52	14.82-23.15
Nitrogen solutions	28,163.17-65,714.06	0.86	1.63	6.84	242.2-565.14	459.06-1,071.14	1,926.36-4.494.84	380.6-888.08	721.38-1,683.22	3,027.14-7,063.32
Ammonium nitrate types										
Ammonium nitrate	3,626.38	0.04	0.26	1.71	1.45	9.43	62.01	2.28	14.82	97.44
Ammonium sulfate-nitrate	44.20	0.04	0.26	1.71	0.02	0.11	0.76	0.03	0.17	1.19
Ammonium types										
Ammonium sulfate	6,363.14	0.02	0.12	1.5	1.27	7.64	95.45	2.00	12.01	149.99
Ammonium thiosulfate	215.88	0.02	0.12	1.5	0.04	0.26	3.24	0.06	0.41	5.09
Ammonium polysulfide	98.17-147.25	0.02	0.12	1.5	0.02-0.03	0.12-0.18	1.47-2.21	0.03-0.05	0.19-0.28	2.31-3.47
Ferrous ammonium sulfate	1.03	0.02	0.12	1.5	0	0	0.02	0	0	0.03
Ammonium phosphate										
Monoammonium phosphate	4,609.37	0.02	0.12	1.5	0.92	5.53	69.14	1.45	8.69	108.65
Diammonium phosphate	67,908.90	0.02	0.12	1.5	13.58	81.49	1,018.63	21.34	128.06	1,600.70
Ammonium polyphosphate	3,994.33	0.02	0.12	1.5	0.80	4.79	59.91	1.26	7.53	94.14
Ammoniated superphosphate	79.39	0.02	0.12	1.5	0.02	0.1	1.19	0.03	0.16	1.87
Ammoniated phosphate	373.14	0.02	0.12	1.5	0.07	0.45	5.60	0.11	0.71	8.80
Urea	139,594.82	0.07	0.11	1.5	97.72	153.55	2,093.92	153.56	241.29	3,290.45
Nitrate types (potassium nitrate)	0	0.001	0.03	0.5	0	0	0	0	0	0
Multiple nutrients	3,072.69	0.001	0.11	6.84	0.03	3.38	210.17	0.05	5.31	330.27
Other nitrogen materials	241.45 - 321.93	0.001	0.11	6.84	0 - 0	0.27-0.35	16.52-22.02	0	.42-.55	25.96-34.60
Specialty fertilizer(b)	5,020.45 - 6,693.93	0.001	0.11	6.84	0.05-0.07	5.52-7.36	343.40-457.86	0.08-0.11	8.67-11.53	539.63-719.49

(a) Greg Regimbal, Minnesota Department of Agriculture, 1994.
(b) Includes most home lawn and garden fertilizer.

Table L-3. Nitrogen Fertilizer Consumption and Nitrous Oxide Emissions, 1988-1990: Part A

	Fertilizer Consumption (in tons)					
	1988	1989	1990	3 Yr. Avg.	% N Per Fertilizer Type	3 Yr. Avg. (in N-tons)
Ammonia Type						
Anhydrous ammonia	368,187	422,925	456,986	416,032.67	82	341,146.8
Aqua ammonia	591	1,157	137	628.33	16-25	100.5-157.1
Nitrogen solutions	129,463	130,855	147,807	136,061.67	21-49	28,573-66,670.2
Ammonium nitrate types						
Ammonium nitrate	10,674	14,654	9,292	11,540	33.5	3,865.9
Ammonium sulfate-nitrate	91	164	326	193.67	26	50.35
Ammonium types						
Ammonium sulfate	12,596	18,301	42,916	24,604.33	21	5,166.9
Ammonium thiosulfate	1,113	1,066	1,768	1,315.67	12(a)	157.9
Ammonium polysulfide	723	2,125	443	1,097	10-15(a)	109.7-164.6
Ferrous ammonium sulfate	42	11	33	28.67	7(a)	2
Ammonium phosphate						
Monoammonium phosphate	39,018	41,561	38,606	39,728.33	11	4,370.12
Diammonium phosphate	422,015	353,380	409,149	394,848	18	71,072.6
Ammonium polyphosphate	51,991	38,336	45,975	45,434	10	4,543.4
Ammoniated superphosphate	968	1,221	4,733	2,307.33	4	92.3
Ammoniated phosphate	1,512	5,202	3,572	3,428.67	9	308.6
Urea	355,530	294,194	335,152	328,298	46	151,017.1
Nitrate types (potassium nitrate)	0	0	0	0	13	0
Other multiple nutrients:						
9-23-30	19,225	15,778	4,503	13,168.67	9	1,185.2
7-21-7	10,637	14,194	14,704	13,178.33	7	922.5
3-9-30	10,774	7,591	8,696	9,020.33	3	270.6
7-23-5	4,375	3,846	3,166	3,795.67	7	265.7
10-26-26	4,117	5,165	2,286	3.856	10	385.6
8-24-0	5,841	0	1,740	2,527	8	202.2
5-14-42	4,261	5,055	0	3,105.33	5	155.3
10-30-05	0	2,931	0	977	10	97.7
3-10-30	0	0	2,148	716	3	21.5
19-5-0	0	0	2,138	712.67	19	135.4
8-10-20	0	0	1,451	483.67	8	38.7
Subtotal	59,230	54,560	40,832	51,540.67	NA	3,680.4
Other nitrogen materials	948	1,254	1,907	1,369.67	15 - 20(a)	205.5-273.9
Specialty fertilizer(a)	37,749	33,011	35,636	35,465.33	10 - 15(a)	3,546.5-5,319.8

Table L-4. Nitrogen Fertilizer Consumption and Nitrous Oxide Emissions, 1988 - 1990: Part B

	Fertilizer Consumption	Percent of Fertilizer Nitrogen Evolved as N_2O			Emissions of N_2O-N			Emissions of N_2O		
	3 Yr. Avg. (in N-tons)	Low EF	Med. EF	High EF	Low	Median	High	Low	Median	High
Ammonia Type										
Anhydrous ammonia	341,146.8	0.86	1.63	6.84	2,933.86	5,560.69	23,334.44	4,610.35	8,738.23	3,668.41
Aqua ammonia	100.5-157.1	0.86	1.63	6.84	0.86-1.35	1.64-2.56	6.87-10.75	1.35-2.12	2.58-4.02	10.8-16.89
Nitrogen solutions	28,573-66,670.2	0.86	1.63	6.84	245.73-573.36	465.74-1,086.72	1,954.39-4,560.24	386.15-900.99	731.88-1,707.7	3,071.18-7,166.09
Ammonium nitrate types										
Ammonium nitrate	3,865.9	0.04	0.26	1.71	1.55	10.05	66.11	2.44	15.79	103.89
Ammonium sulfate-nitrate	50.35	0.04	0.26	1.71	0.02	0.13	0.86	0.03	0.2	1.35
Ammonium types										
Ammonium sulfate	5,166.9	0.02	0.12	1.5	1.03	6.2	77.5	1.62	9.74	121.79
Ammonium thiosulfate	157.9	0.02	0.12	1.5	0.03	0.19	2.37	0.05	0.30	3.72
Ammonium polysulfide	109.7-164.6	0.02	0.12	1.5	0.02-0.03	0.13-0.2	1.65-2.47	0.03-0.05	0.2-0.31	2.59-3.88
Ferrous ammonium sulfate	2	0.02	0.12	1.5	0	0	0.03	0	0	0.05
Ammonium phosphate										
Monoammonium phosphate	4,370.12	0.02	0.12	1.5	0.87	5.24	65.55	1.37	8.23	103.01
Diammonium phosphate	71,072.6	0.02	0.12	1.5	14.21	85.29	1,066.09	22.33	134.03	1,675.28
Ammonium polyphosphate	4,543.4	0.02	0.12	1.5	0.91	5.45	68.15	1.43	8.56	107.09
Ammoniated superphosphate	92.3	0.02	0.12	1.5	0.02	0.11	1.38	0.03	0.17	2.17
Ammoniated phosphate	308.6	0.02	0.12	1.5	0.06	0.37	4.63	0.09	0.58	7.28
Urea	151,017.1	0.07	0.11	1.5	105.71	166.12	2,265.26	166.12	261.05	3,559.69
Nitrate types (potassium nitrate)	0	0.001	0.03	0.5	0	0	0	0	0	0
Multiple nutrients	3,680.4	0.001	0.11	6.84	0.04	4.05	251.74	0.06	6.36	395.59
Other nitrogen materials	205.5-273.9	0.001	0.11	6.84	0	0.23-0.3	14.06-18.73	0	0.36-0.47	22.09-29.43
Specialty fertilizer	3,546.5-5,319.8	0.001	0.11	6.84	0.04-0.05	3.90-5.85	242.58-363.87	0.06-0.08	6.13-9.19	381.20-571.80
TOTAL								**5,193.5-5,709.2**	**9,924.4-10,904.9**	**13,237.2-17,537.4**

(a) Greg Regimbal, Minnesota Department of Agriculture, 1994.

Appendix M . Minnesota Production of Nitrogen through Animal Manure Production

Livestock Type	Manure Nitrogen Production (in lb. nitrogen/ day/animal)[a]	Manure Nitrogen Production (in lb. nitrogen/ yr./animal)	Thousand Head of Livestock in 1990	Manure Nitrogen Production (in lb.)
Dairy				
Cows	0.55	200.75	715.0	**143,536,250.0**
Heifers	0.36	131.40	325.0	**42,705,000.0**
Feedlot Cattle				
<500 lbs.	0.13	47.45	13.3	**628,712.5**
500-699 lbs.	0.2	73	50.5	**3,686,500.0**
700-899 lbs.	0.28	102.2	91.5	**9,351,300.0**
grter that 900 lbs	0.31	113.15	88.5	**10,013,775.0**
grter than 1,000 lbs.	0.37	135.05	44.3	**5,975,962.5**
Other Beef Cattle				
Steers	0.28	102.2	198.0	**20,235,600.0**
Bulls	0.55	200.75	40.0	**8,030,000.0**
Cows	0.37	135	350.0	**47,267,500.0**
Heifers	0.28	102.2	169.0	**17,271,800.0**
Calves	0.13	47.45	517.0	**24,531,650.0**
Swine				
Market	0.045	16.425	3977.5	**65,330,437.5**
Breeding	0.089	32.485	570.0	**18,516,450.0**
Sheep	0.045	16.425	285.0	**4,681,125.0**
Turkeys	0.0096	3.504	46300.0	**162,235,200.0**
Horses	0.27	98.55	55.1	**5,430,105.0**
Chickens				
Broilers	0.0024	0.876	41300.0	**36,178,800.0**
Layers	0.0029	1.059	9646.0	**10,215,114.0**
TOTAL				**635,821,282.0**

Source: Midwest Service Plan, *Livestock Waste Facilities Handbook,* 2nd ed. (Ames, IA:1985).

(a) Adapted from Minnesota Service Plan using the following animal weight from Table 72: Dairy cows 1345 lbs., Heifers 903 lbs., Steers 794 lbs., Bulls 1,587 lbs., Beef cows 1,102 lbs., Beef heifers 794 lbs., Calves 397 lbs., Market swine 101 lbs., Breeding swine 399 lbs., Sheep 100 lbs., Turkeys 16 lbs., Horses 1,100 lbs., Chickens - layers 4 lbs., Chickens - broilers 2 lbs..

Appendix N . CO_2-Equivalent Emissions by Emissions Case and Source for 1990

Table N-1. CO_2-Equivalent Emissions by Emissions Case and Source for 1990 (Part A)
Table N-2. CO_2-Equivalent Emissions by Emissions Case and Source for 1990 (Part B)

Table N-1. CO_2-Equivalent Emissions by Emissions Case and Source for 1990 (Part A)

	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
In-state Fossil Fuel Consumption, Processing and Transportation								
Fossil Fuel Combustion - CO_2	87,859,509	87,859,509	87,859,509	87,859,509	87,859,509	87,859,509	87,859,509	87,859,509
Fossil Fuel CO Oxidation - CO_2	936,694	936,694	936,694	936,694	936,694	936,694	936,694	936,694
Natural Gas Leakage - CO_2	1,129	1,129	1,129	1,129	1,129	1,129	1,129	1,129
Nonfuel Fossil Fuels Uses - CO_2	766	766	766	766	766	766	766	766
Pollution Control - CO_2	3,744	3,744	3,744	3,744	3,744	3,744	3,744	3,744
Combustion - CH_4	112,717	112,717	112,717	112,717	112,717	112,717	112,717	112,717
Natural Gas Leakage - CH_4	410,223	410,223	410,223	410,223	410,223	410,223	410,223	410,223
Petroleum Refinery Leakage - CH_4	1,364	1,364	1,364	1,364	1,364	1,364	1,364	1,364
Combustion - N_2O	811,620	811,620	811,620	811,620	811,620	811,620	811,620	811,620
Subtotal	**90,137,766**	**90,137,766**	**90,137,766**	**90,137,766**	**90,137,766**	**90,137,766**	**90,137,766**	**90,137,766**
Out-of-state Fossil Fuels Production & Processing								
Oil Production - CO_2	0	0	654,410	654,410	0	0	654,410	654,410
Natural Gas Production, Processing, & Transportation - CO_2	0	0	1,351	1,351	0	0	1,351	1,351
Energy Inputs to Finished Fuels - CO_2	0	0	5,137,471	5,137,471	0	0	5,137,471	5,137,471
Electricity Imports	0	0	1,107,608	1,107,608	0	0	1,107,608	1,107,608
Oil Production - CH_4	0	0	324,379	324,379	0	0	324,379	324,379
Coal Mining - CH_4	0	0	420,679	420,679	0	0	420,679	420,679
Natural Gas Production, Processing & Transportation - CH_4	0	0	525,096	525,096	0	0	525,096	525,096
Subtotal	**0**	**0**	**8,170,994**	**8,170,994**	**0**	**0**	**8,170,994**	**8,170,994**
Process Emissions								
Steel Manufacture - CO_2	2,418	2,418	2,418	2,418	2,418	2,418	2,418	2,418
Ozone Depleting Compounds - ODCs	0	27,342,370	0	27,342,370	0	27,342,370	0	27,342,370
Out-of-state Cement Manufacture - CO_2	0	0	834,988	834,988	0	0	834,988	834,988
Out-of-state lime manufacture - CO_2	0	0	100,594	100,594	0	0	100,594	100,594
Subtotal	**2,418**	**27,344,788**	**938,000**	**28,280,370**	**2,418**	**27,344,788**	**938,000**	**28,280,370**

Sources: Tables 3 and 91.

Table N-2. CO_2-Equivalent Emissions by Emissions Case and Source for 1990 (Part B)

	Case A	Case B	Case C	Case D	Case E	Case F	Case G	Case H
Landfill Leakage & Incineration								
Incineration - CO_2	286,585	286,585	286,585	286,585	286,585	286,585	286,585	286,585
Oxidation of Incineration CO - CO_2	211	211	211	211	211	211	211	211
Landfill Leakage - CH_4	2,615,822	2,615,822	2,615,822	2,615,822	2,615,822	2,615,822	2,615,822	2,615,822
Incineration - CH_4	2,904	2,904	2,904	2,904	2,904	2,904	2,904	2,904
Subtotal	**2,905,522**	**2,905,522**	**2,905,522**	**2,905,522**	**2,905,522**	**2,905,522**	**2,905,522**	**2,905,522**
Agriculture								
Commercial Fertilizer - N_2O	2,659,365	2,659,365	2,659,365	2,659,365	2,659,365	2,659,365	2,659,365	2,659,365
Manure Fertilizer - N_2O	449,500	449,500	449,500	449,500	449,500	449,500	449,500	449,500
Livestock - CH_4	1,979,241	1,979,241	1,979,241	1,979,241	1,979,241	1,979,241	1,979,241	1,979,241
Animal Manure - CH_4	798,545	798,545	798,545	798,545	798,545	798,545	798,545	798,545
Wild Rice - CH_4	32,170	32,170	32,170	32,170	32,170	32,170	32,170	32,170
Agricultural Liming - CO_2	26,269	26,269	26,269	26,269	26,269	26,269	26,269	26,269
Subtotal	**5,945,140**	**5,945,140**	**5,945,140**	**5,945,140**	**5,945,140**	**5,945,140**	**5,945,140**	**5,945,140**
Land Use Change								
Forest Carbon Storage	0	0	0	0	(-)9,647,161	(-)9,647,161	(-)9,647,161	(-)9,647,161
TOTAL	**98,990,846**	**126,333,216**	**108,097,422**	**135,439,792**	**89,343,685**	**116,686,055**	**98,450,261**	**125,792,631**

Sources: Tables 3 and 91.