Final Michigan Greenhouse Gas Inventory and Reference Case Projections 1990-2025

Center for Climate Strategies
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Principal Authors: Randy Strait, Maureen Mullen, Dan Wei, Andy Bollman, Luana Williams

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Executive Summary

The Center for Climate Strategies (CCS) prepared this report for the Michigan Department of Environmental Quality (MDEQ). The report presents an assessment of the State's greenhouse gas (GHG) emissions and anthropogenic sinks (carbon storage) from 1990 to 2025. The preliminary draft inventory and forecast estimates served as a starting point to assist the State, as well as the Michigan Climate Action Council (MCAC) and Technical Work Groups (TWGs), with an initial comprehensive understanding of Michigan's current and possible future GHG emissions, and thereby informed the identification and analysis of policy options for mitigating GHG emissions.[1] The MCAC and TWGs have reviewed, discussed, and evaluated the draft inventory and methodologies as well as alternative data and approaches for improving the draft GHG inventory and forecast. The inventory and forecast as well as this report have been revised to address the comments provided and approved by the MCAC.

Emissions and Reference Case Projections (Business-as-Usual)

Michigan's anthropogenic GHG emissions and anthropogenic sinks (carbon storage) were estimated for the period from 1990 to 2025. Historical GHG emission estimates (1990 through 2005)[2] were developed using a set of generally accepted principles and guidelines for State GHG emissions, relying to the extent possible on Michigan-specific data and inputs when it was possible to do so. The initial reference case projections (2006-2025) are based on a compilation of various projections of electricity generation, fuel use, and other GHG-emitting activities for Michigan, along with a set of simple, transparent assumptions described in the appendices of this report.

The inventory and projections cover the six types of gases included in the US Greenhouse Gas Inventory: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Emissions of these GHGs are presented using a common metric, CO_2 equivalence (CO_2e), which indicates the relative contribution of each gas, per unit mass, to global average radiative forcing on a global warming potential- (GWP-) weighted basis.[3]

As shown in Table ES-1, activities in Michigan accounted for approximately 248 million metric tons (MMt) of *gross*[4] CO_2e emissions (consumption basis) in 2005, an amount equal to about

[1] "Draft Michigan Greenhouse Gas Inventory and Reference Case Projections, 1990-2020," prepared by the Center for Climate Strategies for the Michigan Department of Environmental Quality, January 2008.
[2] The last year of available historical data varies by sector; ranging from 2000 to 2005.
[3] Changes in the atmospheric concentrations of GHGs can alter the balance of energy transfers between the atmosphere, space, land, and the oceans. A gauge of these changes is called radiative forcing, which is a simple measure of changes in the energy available to the Earth-atmosphere system (IPCC, 2001). Holding everything else constant, increases in GHG concentrations in the atmosphere will produce positive radiative forcing (i.e., a net increase in the absorption of energy by the Earth), See: Boucher, O., et al. "Radiative Forcing of Climate Change." Chapter 6 in *Climate Change 2001: The Scientific Basis*. Contribution of Working Group 1 of the Intergovernmental Panel on Climate Change Cambridge University Press. Cambridge, United Kingdon. Available at: http://www.grida.no/climate/ipcc_tar/wg1/212.htm.
[4] Excluding GHG emissions removed due to forestry and other land uses and excluding GHG emissions associated with exported electricity.

3.5% of total US gross GHG emissions (based on 2005 US data).[5] Michigan's gross GHG emissions are rising slower than those of the nation as a whole (gross emissions exclude carbon sinks, such as forests). Michigan's gross GHG emissions increased by about 12% from 1990 to 2005, while national emissions rose by 16% from 1990 to 2005. The growth in Michigan's emissions from 1990 to 2005 is primarily associated with the electricity consumption and transportation sectors.

Estimates of carbon sinks within Michigan's forests, including urban forests and land use changes, have also been included in this report. The current estimates indicate that about 13 $MMtCO_2e$ were stored in Michigan forest biomass in 2005. This leads to *net* emissions of 235 $MMtCO_2e$ in Michigan in 2005, an amount equal to 3.8% of total US net GHG emissions.

Figure ES-1 illustrates the State's emissions per capita and per unit of economic output.[6] On a per capita basis, Michigan residents emitted about 24 metric tons (t) of gross CO_2e in 1990, lower than the1990 national per capita emissions of 25 $MtCO_2e$. Both Michigan and national per capita emissions remained nearly constant from 1990 to 2005. Like the nation as a whole, Michigan's economic growth exceeded emissions growth throughout the 1990-2005 period (leading to declining estimates of GHG emissions per unit of state product). From 1990 to 2005, emissions per unit of gross product dropped by 23% in Michigan and by about 26% nationally.[7]

The principal sources of Michigan's GHG emissions are electricity consumption; residential, commercial, and industrial (RCI) fuel use; and transportation accounting for 36%, 24%, and 24% of Michigan's gross GHG emissions in 2005, respectively.

As illustrated in Figure ES-2 and shown numerically in Table ES-1, under the reference case projections, Michigan's gross GHG emissions continue to grow, and are projected to climb to about 292 $MMtCO_2e$ by 2025, reaching 32% above 1990 levels. As shown in Figure ES-3, the electric consumption sector is projected to be the largest contributor to future emissions growth in Michigan, followed by emissions associated with the increasing use of HFCs as substitutes for ozone-depleting chlorofluorocarbons (CFCs),[8] and then by emissions from transportation.

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[5] The national emissions used for these comparisons are based on 2005 emissions from *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2006*, April 15, 2008, US EPA #430-R-08-005, (http://www.epa.gov/climatechange/emissions/usinventoryreport.html).

[6] Michigan population statistics for 1990 and 2000, compiled by Michigan Information Center from US Census Bureau, are available at http://www.michigan.gov/documents/PopByCty_26001_7.pdf. Population data for 2000 to 2004 are available from Michigan Department of History, Arts, and Libraries at http://www.michigan.gov/hal/0,1607,7-160-17451_28388_28392-106981--,00.html. Michigan projections (2005-2030) available from Michigan Department of History, Arts, and Libraries at http://www.michigan.gov/hal/0,1607,7-160-17451_28388_28392-116118--,00.html.

[7] Based on real gross domestic product (millions of chained 2000 dollars) that excludes the effects of inflation, available from the US Bureau of Economic Analysis (http://www.bea.gov/regional/gsp/). The national emissions used for these comparisons are based on 2005 emissions. (http://www.epa.gov/climatechange/emissions/usinventoryreport.html).

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

Some data gaps exist in this analysis, particularly for the reference case projections. Key tasks include review and revision of key emissions drivers that will be major determinants of Michigan's future GHG emissions (such as the growth rate assumptions for electricity generation and consumption, transportation fuel use, and RCI fuel use). Appendices A through H provide the detailed methods, data sources, and assumptions for each GHG sector. Also included are descriptions of significant uncertainties in emission estimates or methods and suggested next steps for refinement of the inventory. Appendix I provides background information on GHGs and climate-forcing aerosols.

GHG Reductions from Recent Actions[9]

The federal Energy Independence and Security Act (EISA) of 2007 was signed into law in December 2007. This federal law contains several requirements that will reduce GHG emissions as they are implemented over the next few years. During the MCAC process, sufficient information was identified (e.g., implementation schedules) to estimate GHG emission reductions associated with implementing the Corporate Average Fuel Economy (CAFE) requirements in Michigan. The MCAC also identified recent actions that Michigan has undertaken to control GHG emissions while at the same time conserving energy and promoting the development and use of renewable energy sources. One recent action was identified for which data were available to estimate the emission reductions of the action relative to the business-as-usual reference case projections. The GHG emission reductions projected to be achieved by these recent State and Federal actions are summarized in Table ES-2. This table shows a total reduction of about 8.9 $MMtCO_2e$ in 2025 from the business-as-usual reference case emissions, or a 3.1% reduction from the business-as-usual emissions in 2025 for all sectors combined.

[9] Note that actions recently adopted by the state of Michigan have also been referred to as "existing" actions.

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

MMtCO_2e	1990	2000	2005	2010	2020	2025	Explanatory Notes for Projections
Energy Use (CO_2, CH_4, N_2O)	**192.5**	**218.6**	**214.7**	**220.2**	**238.7**	**248.5**	
Electricity Use (Consumption)	**70.3**	**86.9**	**90.0**	**91.0**	**103.9**	**111.1**	Totals include emissions for electricity production plus emissions associated with net imported/exported electricity.
Electricity Production (in-state)	64.0	68.1	71.4	72.3	85.3	92.6	*See electric sector assumptions*
Coal	*62.8*	*64.9*	*67.7*	*67.6*	*78.8*	*85.3*	*in appendix A.*
Natural Gas	*0.46*	*1.77*	*2.38*	*3.67*	*5.40*	*6.06*	
Oil	*0.66*	*0.99*	*0.71*	*0.48*	*0.48*	*0.57*	
Wood (CH_4 and N_2O)	*0.010*	*0.031*	*0.030*	*0.025*	*0.027*	*0.029*	
Pump Storage (Water)	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	
MSW/Landfill Gas	*0.12*	*0.38*	*0.34*	*0.39*	*0.44*	*0.46*	
Other (Tire-Derived)	*0.009*	*0.029*	*0.16*	*0.19*	*0.21*	*0.22*	
Imported/Exported Electricity	*6.22*	*18.8*	*18.7*	*18.7*	*18.6*	*18.5*	Negative values represent net exported electricity
Residential/Commercial/Industrial (RCI) Fuel Use	**67.5**	**66.1**	**59.9**	**60.5**	**62.1**	**62.4**	
Coal	11.7	9.34	7.32	6.12	5.67	5.56	Based on US DOE regional projections
Natural Gas	42.8	43.7	40.4	42.6	44.4	44.8	Based on US DOE regional projections
Petroleum	12.8	12.9	12.0	11.6	11.9	11.8	Based on US DOE regional projections
Wood (CH4 and N2O)	0.28	0.17	0.19	0.20	0.20	0.20	Based on US DOE regional projections
Transportation	**49.7**	**59.4**	**58.2**	**61.4**	**64.0**	**65.3**	
Onroad Gasoline	37.4	43.7	43.3	45.5	46.2	46.4	Based on US DOE regional projections and VMT projections from MDOT
Onroad Diesel	5.21	8.90	10.2	11.3	12.9	13.7	
Marine Vessels	1.87	2.61	2.25	2.18	2.52	2.70	Based on historical trends in activity
Rail, Natural Gas, LPG, other	1.10	1.16	0.90	0.93	0.95	0.95	Based on US DOE regional projections
Jet Fuel and Aviation Gasoline	4.15	3.00	1.52	1.45	1.50	1.51	Based on FAA operations projections
Fossil Fuel Industry	**4.94**	**6.13**	**6.64**	**7.25**	**8.70**	**9.66**	
Natural Gas Industry	4.69	6.03	6.55	7.19	8.67	9.64	Based on historical trends in activity
Oil Industry	0.25	0.10	0.086	0.061	0.032	0.024	Based on historical trends in activity
Industrial Processes	**15.3**	**18.1**	**18.4**	**18.9**	**23.3**	**26.4**	
Cement Manufacture (CO_2)	2.27	2.26	2.13	2.12	2.10	2.09	Historical annual decline in State production from 1995-2005
Lime Manufacture (CO_2)	0.43	0.48	0.41	0.41	0.41	0.41	No growth based on analysis of state historical production trends
Limestone and Dolomite Use (CO_2)	0.24	0.25	0.31	0.31	0.31	0.31	No growth based on analysis of state historical production trends
Soda Ash (CO_2)	0.10	0.094	0.088	0.084	0.076	0.072	Historical annual decline in State consumption from 1990-2005
Iron and Steel (CO_2)	11.2	11.0	10.2	8.47	8.12	7.95	Annual state employment growth from 2004-2014 for Primary metal manufacturing sector

MMtCO$_2$e		1990	2000	2005	2010	2020	2025	Explanatory Notes for Projections
	Taconite Production (CO_2)	0.037	0.28	0.25	0.20	0.14	0.11	Historical annual decline in State production from 1995-2005
	Magnesium Production (SF_6)	0.18	0.45	0.45	0.70	1.16	1.50	National emissions projections (US EPA)
	ODS Substitutes (HFC, PFC)	0.012	2.84	4.16	6.18	10.6	13.6	National emissions projections (US EPA)
	Electric Power T&D (SF_6)	0.82	0.47	0.40	0.37	0.34	0.33	National emissions projections (US EPA)
	Semiconductor Manufacturing (HFC, PFC, and SF_6)	0.001	0.004	0.004	0.004	0.003	0.003	National emissions projections (US EPA)
Waste Management		**4.67**	**5.30**	**6.28**	**6.98**	**8.70**	**9.74**	
	Waste Combustion	0.33	1.14	1.20	1.26	1.38	1.45	Used growth rate calculated for 1995-2005 emissions growth
	Landfills	3.16	2.86	3.75	4.34	5.82	6.73	Based on historical MI landfill emplacement; Used growth rate calculated for 1996-2005 emissions growth
	Wastewater Management	1.17	1.30	1.33	1.38	1.50	1.56	Used growth rate calculated for 1990-2005 emissions growth
Agriculture		**8.33**	**7.99**	**8.07**	**7.71**	**7.25**	**7.03**	
	Enteric Fermentation	1.53	1.36	1.40	1.38	1.33	1.31	Based on projected livestock population
	Manure Management	0.92	0.97	1.09	1.07	1.01	0.99	Based on projected livestock population
	Agricultural Soils	3.71	3.49	3.42	3.09	2.73	2.55	Used growth rate calculated for 1990-2005 emissions growth
	Agricultural Burning	0.022	0.026	0.029	0.030	0.034	0.036	Used growth rate calculated for 1990-2005 emissions growth
	Agricultural Soils (cultivation practices)	2.14	2.14	2.14	2.14	2.14	2.14	Historical and projected emissions held constant at 1997
Forest Wildfires (N_2O and CH_4)		**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	Assumed no change after 2005
Gross Emissions (Consumption Basis, Excludes Sinks)		**220.7**	**250.0**	**247.5**	**253.8**	**278.0**	**291.6**	
	increase relative to 1990		*13%*	*12%*	*15%*	*26%*	*32%*	
Emissions Sinks		**-37.9**	**-12.5**	**-12.7**	**-12.7**	**-12.7**	**-12.7**	
	Forested Landscape	-27.8	-8.77	-8.77	-8.77	-8.77	-8.77	Based on estimates from the USFS
	Urban Forestry and Land Use	-10.1	-3.69	-3.91	-3.91	-3.91	-3.91	Assumed no change after 2005
Net Emissions (Includes Sinks)		**182.9**	**237.5**	**234.8**	**241.1**	**265.3**	**278.9**	
	increase relative to 1990		*30%*	*28%*	*32%*	*45%*	*53%*	

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

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

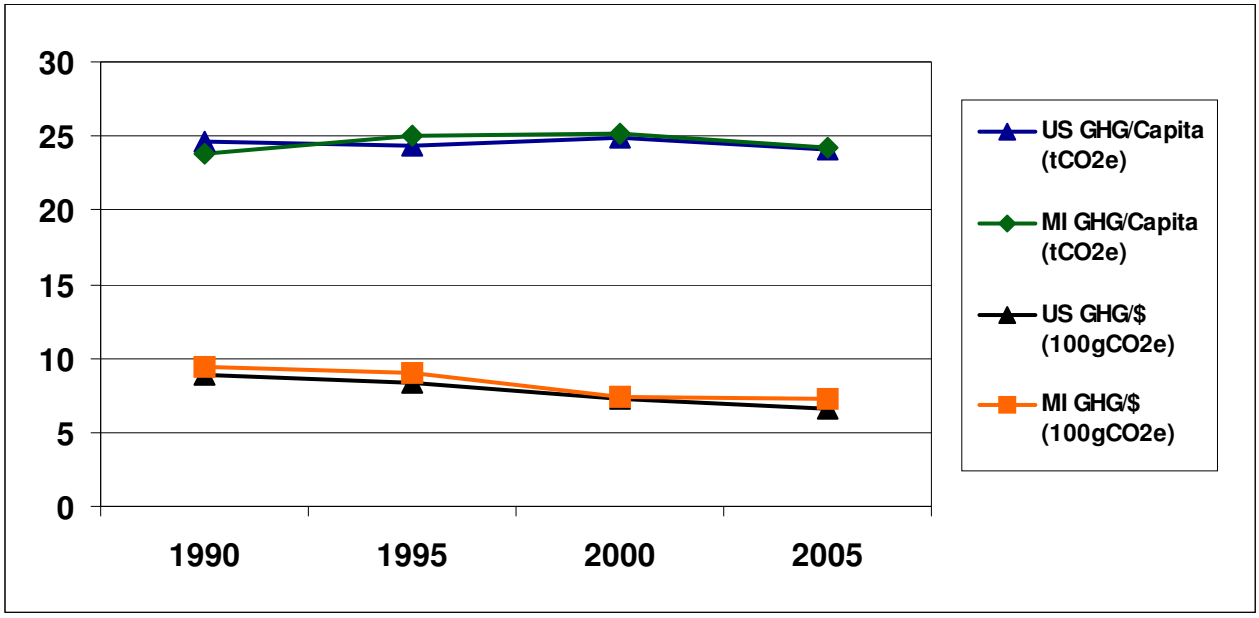
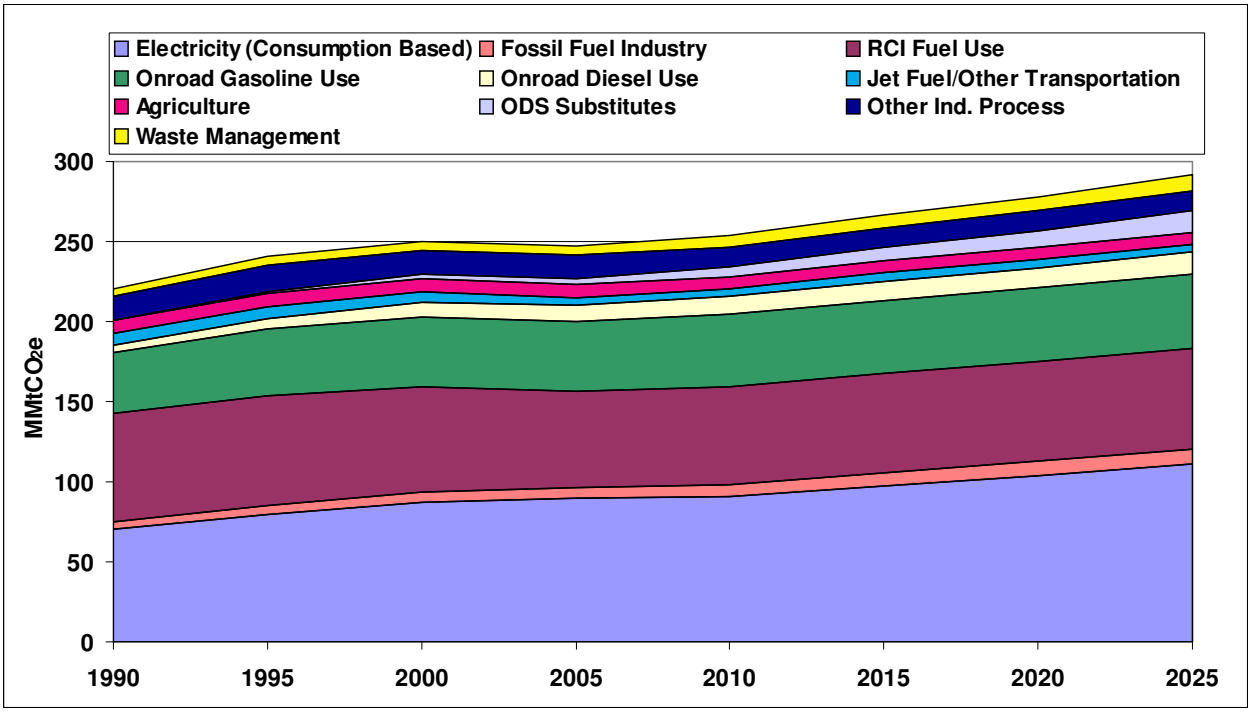
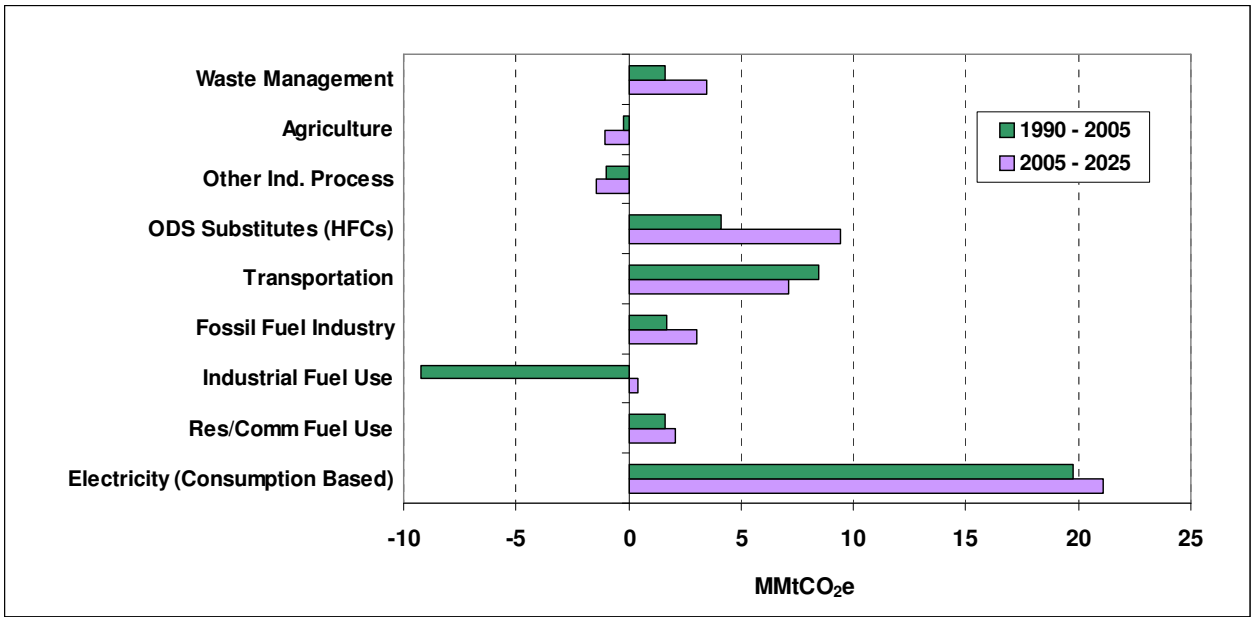


Figure ES-2. Michigan Gross GHG Emissions by Sector, 1990-2025: Historical and Projected



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

Figure ES-3. Sector Contributions to Gross Emissions Growth in Michigan, 1990-2025: Reference Case Projections ($MMtCO_2e$ Basis)



Res/Comm – direct fuel use in residential and commercial sectors. ODS – ozone depleting substance. HFCs – hydrofluorocarbons. Emissions associated with other industrial processes include all of the industries identified in Appendix D except emissions associated with ODS substitutes which are shown separately in this graph because of high expected growth in emissions for ODS substitutes.

Table ES-2. Emission Reduction Estimates Associated with the Effect of Recent Actions in Michigan (Consumption-Basis, Gross Emissions)

	GHG Reductions ($MMtCO_2e$)		GHG Emissions (MMtCO2e)	
			Business as Usual	With Recent Actions
Sector / Recent Action	2015	2025	2025	2025
Electricity Supply (ES)				
S.B. 213, Clean, Renewable and Energy Efficient Act	2.7	2.0	111	109
Transportation and Land Use (TLU)				
Federal Corporate Average Fuel Economy (CAFE) Requirements	3.6	6.9	65.3	58.4
Total (ES + TLU Sectors)	6.2	8.9	176	167
Total (All Sectors)			292	283

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Acronyms and Key Terms

AEO2007 – EIA's Annual Energy Outlook 2007

bbls – Barrels

BC – Black Carbon*

Bcf – Billion Cubic Feet

BOD – Biochemical Oxygen Demand

C – Carbon*

$CaCO_3$ – Calcium Carbonate

CCS – Center for Climate Strategies

CFCs – Chlorofluorocarbons*

CH_4 – Methane*

CO – Carbon Monoxide*

CO_2 – Carbon Dioxide*

CO_2e – Carbon Dioxide equivalent*

CRP – Federal Conservation Reserve Program

DOE – Department of Energy

EC – Elemental Carbon*

ECAR – East Central Area Reliability Coordination Agreement

EIA – US DOE Energy Information Administration

EIIP – Emission Inventory Improvement Program

FAA – Federal Aviation Administration

FAPRI – Food and Agricultural Policy Research Institute

FERC – Federal Energy Regulatory Commission

FHWA – Federal Highway Administration

FIA – Forest Inventory Analysis

Gg – Gigagrams

GHG – Greenhouse Gas*

GWh – Gigawatt-hour

GWP – Global Warming Potential*

H_2CO_3 – Carbonic Acid

H_2O – Water Vapor*

HBFCs – Hydrobromofluorocarbons*

HCFCs – Hydrochlorofluorocarbons*

HFCs – Hydrofluorocarbons*

HWP – Harvested Wood Products

IPCC – Intergovernmental Panel on Climate Change*

kg – Kilogram

km^2 – Square Kilometers

kWh – Kilowatt-hour

lb – Pound

LF – Landfill

LFG – Landfill Gas

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

LNG – Liquified Natural Gas

LPG – Liquefied Petroleum Gas

MAIN – Mid-America Interconnected Network

MCAC – Michigan Climate Action Council

MDEQ – Michigan Department of Environmental Quality

MDOT – Michigan Department of Transportation

Mg – Magnesium

Mg – Megagrams

MICHCON – Michigan Consolidated Gas Company

MMBtu – Million British thermal units

MMt – Million Metric tons

$MMtCO_2e$ – Million Metric tons Carbon Dioxide equivalent

MPSC – Michigan Public Service Commission

MSW – Municipal Solid Waste

Mt – Metric ton (equivalent to 1.102 short tons)

MW – Megawatt

MWh – Megawatt-hour

N – Nitrogen*

N_2O – Nitrous Oxide*

NASS – National Agriculture Statistical Service

NEI – National Emissions Inventory

NEMS – National Energy Modeling System

NF – National Forest

NMVOCs – Nonmethane Volatile Organic Compound*

NO_2 – Nitrogen Dioxide*

NO_x – Nitrogen Oxides*

O_3 – Ozone*

ODS – Ozone-Depleting Substance*

OM – Organic Matter*

OH – Hydroxyl radical*

OPS – Office of Pipeline Safety

PFCs – Perfluorocarbons*

PM – Particulate Matter*

POTW – Publicly Owned Treatment Works

ppb – parts per billion

ppm – parts per million

ppt – parts per trillion

ppmv – parts per million by volume

RCI – Residential, Commercial, and Industrial

SAR – Second Assessment Report*

SED – State Energy Data

SF_6 – Sulfur Hexafluoride*

SIT – State Greenhouse Gas Inventory Tool

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

SO_2 – Sulfur Dioxide*

T&D – Transmission and Distribution

TAR – Third Assessment Report*

TWh – Terawatt-hour

UNFCCC – United Nations Framework Convention on Climate Change

US – United States

US DOE – United States Department of Energy

US EPA – United States Environmental Protection Agency

USDA – United States Department of Agriculture

USFS – United States Forest Service

USGS – United States Geological Survey

VMT – Vehicle Mile Traveled

VOCs – Volatile Organic Compound*

WW – Wastewater

yr – Year

* – See Appendix I for more information.

Acknowledgements

We appreciate all of the time and assistance provided by numerous contacts throughout Michigan, as well as in neighboring States, and at federal agencies. Thanks go to in particular the staff at several Michigan State Agencies for their inputs, and in particular to Lynn Fiedler, Vince Hellwig, Steven Kulesia, and Stephen Zervas of the Michigan Department of Environmental Quality who provided key guidance for and review of this analytical effort.

The authors would also like to express their appreciation to Katie Bickel, Bill Dougherty, Steve Roe, Katie Pasko, and Jim Wilson of the Center for Climate Strategies (CCS) who provided valuable review comments during development of this report. Thanks also to Michael Gillenwater for directing preparation of Appendix I.

Summary of Findings

Introduction

The Center for Climate Strategies (CCS) prepared this report for the Michigan Department of Environmental Quality (MDEQ). This report presents estimates of the State's base year and projected greenhouse gas (GHG) emissions and anthropogenic sinks (carbon storage) for the period from 1990 to 2025. The preliminary draft inventory and forecast estimates served as a starting point to assist the State, as well as the Michigan Climate Action Council (MCAC) and Technical Work Groups (TWGs), with an initial comprehensive understanding of Michigan's current and possible future GHG emissions, and thereby informed the identification and analysis of policy options for mitigating GHG emissions.[10] The MCAC and TWGs have reviewed, discussed, and evaluated the draft inventory and methodologies as well as alternative data and approaches for improving the draft GHG inventory and forecast. The inventory and forecast, as well as this report, have been revised to address the comments provided and approved by the MCAC.

Emissions and Reference Case Projections (Business-as-Usual)

Historical GHG emission estimates (1990 through 2005)[11] were developed using a set of generally accepted principles and guidelines for State GHG emissions inventories, as described in the "Approach" section below, relying to the extent possible on Michigan-specific data and inputs. The initial reference case projections (2006-2025) are based on a compilation of various projections of electricity generation, fuel use, and other GHG-emitting activities for Michigan, along with a set of simple, transparent assumptions described in the appendices of this report.

This report covers the six gases included in the US Greenhouse Gas Inventory: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Emissions of these GHGs are presented using a common metric, CO_2 equivalence (CO_2e), which indicates the relative contribution of each gas, per unit mass, to global average radiative forcing on a global warming potential- (GWP-) weighted basis.[12]

It is important to note that the emissions estimates reflect the *GHG emissions associated with the electricity sources used to meet Michigan's demands,* corresponding to a consumption-based approach to emissions accounting (see "Approach" section below). Another way to look at electricity emissions is to consider the *GHG emissions produced by electricity generation*

[10] "Draft Michigan Greenhouse Gas Inventory and Reference Case Projections, 1990-2020," prepared by the Center for Climate Strategies for Michigan Department of Environmental Quality, January 2008.
[11] The last year of available historical data varies by sector; ranging from 2000 to 2005.
[12] Changes in the atmospheric concentrations of GHGs can alter the balance of energy transfers between the atmosphere, space, land, and the oceans. A gauge of these changes is called radiative forcing, which is a simple measure of changes in the energy available to the Earth-atmosphere system (IPCC, 1996). Holding everything else constant, increases in GHG concentrations in the atmosphere will produce positive radiative forcing (i.e., a net increase in the absorption of energy by the Earth), http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm.

facilities in the State. This report covers both methods of accounting for emissions, but for consistency, all total results are reported as *consumption-based.*

Michigan Greenhouse Gas Emissions: Sources and Trends

Table 1 provides a summary of GHG emissions estimated for Michigan by sector for the years 1990, 2000, 2005, 2010, 2020, and 2025. Details on the methods and data sources used to construct these estimates are provided in the appendices to this report**.** In the sections below, we discuss GHG emission sources (positive, or *gross*, emissions) and sinks (negative emissions) separately in order to identify trends, projections, and uncertainties clearly for each.

This next section of the report provides a summary of the historical emissions (1990 through 2005) followed by a summary of the reference-case projection-year emissions (2006 through 2025) and key uncertainties. We also provide an overview of the general methodology, principles, and guidelines followed for preparing the inventories. Appendices A through H provide the detailed methods, data sources, and assumptions for each GHG sector. Appendix I provides background information on GHGs and climate-forcing aerosols.

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

MMtCO$_2$e	1990	2000	2005	2010	2020	2025	Explanatory Notes for Projections
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Electricity Use (Consumption)	**70.3**	**86.9**	**90.0**	**91.0**	**103.9**	**111.1**	Totals include emissions for electricity production plus emissions associated with net imported/exported electricity.
Electricity Production (in-state)	64.0	68.1	71.4	72.3	85.3	92.6	*See electric sector assumptions*
Coal	*62.8*	*64.9*	*67.7*	*67.6*	*78.8*	*85.3*	*in appendix A.*
Natural Gas	*0.46*	*1.77*	*2.38*	*3.67*	*5.40*	*6.06*	
Oil	*0.66*	*0.99*	*0.71*	*0.48*	*0.48*	*0.57*	
Wood (CH_4 and N_2O)	*0.010*	*0.031*	*0.030*	*0.025*	*0.027*	*0.029*	
Pump Storage (Water)	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	*0.000*	
MSW/Landfill Gas	*0.12*	*0.38*	*0.34*	*0.39*	*0.44*	*0.46*	
Other (Tire-Derived)	*0.009*	*0.029*	*0.16*	*0.19*	*0.21*	*0.22*	
Imported/Exported Electricity	*6.22*	*18.8*	*18.7*	*18.7*	*18.6*	*18.5*	Negative values represent net exported electricity
Residential/Commercial/Industrial (RCI) Fuel Use	**67.5**	**66.1**	**59.9**	**60.5**	**62.1**	**62.4**	
Coal	11.7	9.34	7.32	6.12	5.67	5.56	Based on US DOE regional projections
Natural Gas	42.8	43.7	40.4	42.6	44.4	44.8	Based on US DOE regional projections
Petroleum	12.8	12.9	12.0	11.6	11.9	11.8	Based on US DOE regional projections
Wood (CH4 and N2O)	0.28	0.17	0.19	0.20	0.20	0.20	Based on US DOE regional projections
Transportation	**49.7**	**59.4**	**58.2**	**61.4**	**64.0**	**65.3**	
Onroad Gasoline	37.4	43.7	43.3	45.5	46.2	46.4	Based on US DOE regional projections and VMT projections from MDOT
Onroad Diesel	5.21	8.90	10.2	11.3	12.9	13.7	
Marine Vessels	1.87	2.61	2.25	2.18	2.52	2.70	Based on historical trends in activity
Rail, Natural Gas, LPG, other	1.10	1.16	0.90	0.93	0.95	0.95	Based on US DOE regional projections
Jet Fuel and Aviation Gasoline	4.15	3.00	1.52	1.45	1.50	1.51	Based on FAA operations projections
Fossil Fuel Industry	**4.94**	**6.13**	**6.64**	**7.25**	**8.70**	**9.66**	
Natural Gas Industry	4.69	6.03	6.55	7.19	8.67	9.64	Based on historical trends in activity
Oil Industry	0.25	0.10	0.086	0.061	0.032	0.024	Based on historical trends in activity
Industrial Processes	**15.3**	**18.1**	**18.4**	**18.9**	**23.3**	**26.4**	
Cement Manufacture (CO_2)	2.27	2.26	2.13	2.12	2.10	2.09	Historical annual decline in State production from 1995-2005
Lime Manufacture (CO_2)	0.43	0.48	0.41	0.41	0.41	0.41	No growth based on analysis of state historical production trends
Limestone and Dolomite Use (CO_2)	0.24	0.25	0.31	0.31	0.31	0.31	No growth based on analysis of state historical production trends
Soda Ash (CO_2)	0.10	0.094	0.088	0.084	0.076	0.072	Historical annual decline in State consumption from 1990-2005
Iron and Steel (CO_2)	11.2	11.0	10.2	8.47	8.12	7.95	Annual state employment growth from 2004-2014 for Primary metal manufacturing sector

MMtCO$_2$e		1990	2000	2005	2010	2020	2025	Explanatory Notes for Projections
	Taconite Production (CO_2)	0.037	0.28	0.25	0.20	0.14	0.11	Historical annual decline in State production from 1995-2005
	Magnesium Production (SF_6)	0.18	0.45	0.45	0.70	1.16	1.50	National emissions projections (US EPA)
	ODS Substitutes (HFC, PFC)	0.012	2.84	4.16	6.18	10.6	13.6	National emissions projections (US EPA)
	Electric Power T&D (SF_6)	0.82	0.47	0.40	0.37	0.34	0.33	National emissions projections (US EPA)
	Semiconductor Manufacturing (HFC, PFC, and SF_6)	0.001	0.004	0.004	0.004	0.003	0.003	National emissions projections (US EPA)
Waste Management		**4.67**	**5.30**	**6.28**	**6.98**	**8.70**	**9.74**	
	Waste Combustion	0.33	1.14	1.20	1.26	1.38	1.45	Used growth rate calculated for 1995-2005 emissions growth
	Landfills	3.16	2.86	3.75	4.34	5.82	6.73	Based on historical MI landfill emplacement; Used growth rate calculated for 1996-2005 emissions growth
	Wastewater Management	1.17	1.30	1.33	1.38	1.50	1.56	Used growth rate calculated for 1990-2005 emissions growth
Agriculture		**8.33**	**7.99**	**8.07**	**7.71**	**7.25**	**7.03**	
	Enteric Fermentation	1.53	1.36	1.40	1.38	1.33	1.31	Based on projected livestock population
	Manure Management	0.92	0.97	1.09	1.07	1.01	0.99	Based on projected livestock population
	Agricultural Soils	3.71	3.49	3.42	3.09	2.73	2.55	Used growth rate calculated for 1990-2005 emissions growth
	Agricultural Burning	0.022	0.026	0.029	0.030	0.034	0.036	Used growth rate calculated for 1990-2005 emissions growth
	Agricultural Soils (cultivation practices)	2.14	2.14	2.14	2.14	2.14	2.14	Historical and projected emissions held constant at 1997
Forest Wildfires (N_2O and CH_4)		**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**	Assumed no change after 2005
Gross Emissions (Consumption Basis, Excludes Sinks)		**220.7**	**250.0**	**247.5**	**253.8**	**278.0**	**291.6**	
	increase relative to 1990		*13%*	*12%*	*15%*	*26%*	*32%*	
Emissions Sinks		**-37.9**	**-12.5**	**-12.7**	**-12.7**	**-12.7**	**-12.7**	
	Forested Landscape	-27.8	-8.77	-8.77	-8.77	-8.77	-8.77	Based on estimates from the USFS
	Urban Forestry and Land Use	-10.1	-3.69	-3.91	-3.91	-3.91	-3.91	Assumed no change after 2005
Net Emissions (Includes Sinks)		**182.9**	**237.5**	**234.8**	**241.1**	**265.3**	**278.9**	
	increase relative to 1990		*30%*	*28%*	*32%*	*45%*	*53%*	

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

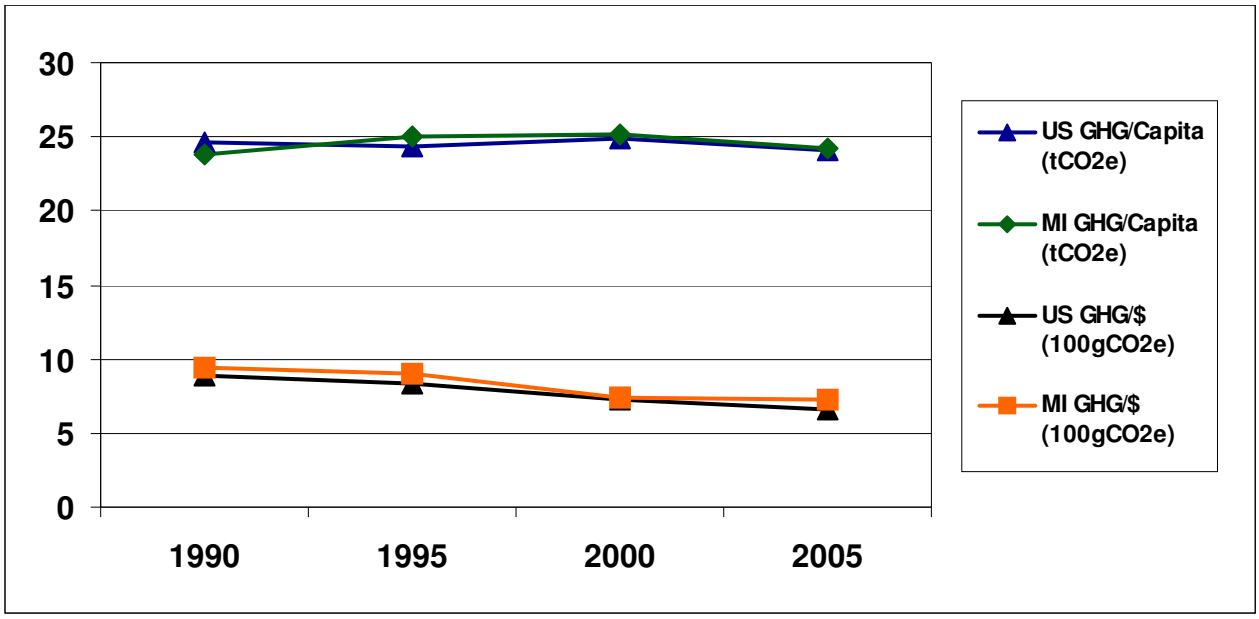
Historical Emissions

Overview

In 2005, activities in Michigan accounted for approximately 248 million metric tons (MMt) of CO_2e emissions, an amount equal to about 3.5% of total US GHG emissions (based on 2005 US emissions[13]). Michigan's gross GHG emissions are rising slower than those of the nation as a whole (gross emissions exclude carbon sinks, such as forests). Michigan's gross GHG emissions increased 12% from 1990 to 2005, while national emissions rose by 16% from 1990 to 2005.

Figure 1 illustrates the State's emissions per capita and per unit of economic output. On a per capita basis, Michigan residents emitted about 24 metric tons (t) of CO_2e annually in 1990, lower than the 1990 national average of 25 $MtCO_2e$ Both Michigan and national per capita emissions remained nearly constant from 1990 to 2005. Like the nation as a whole, Michigan's economic growth exceeded emissions growth throughout the 1990-2005 period (leading to declining estimates of GHG emissions per unit of state product). From 1990 to 2005, emissions per unit of gross product dropped by 23% in Michigan and by about 26% nationally.[14]

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



[13] The national emissions used for these comparisons are based on 2005 emissions from *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2006*, April 15, 2008, US EPA #430-R-08-005, (http://www.epa.gov/climatechange/emissions/usinventoryreport.html)..

[14] Based on real gross domestic product (millions of chained 2000 dollars) that excludes the effects of inflation, available from the US Bureau of Economic Analysis (http://www.bea.gov/regional/gsp/). The national emissions used for these comparisons are based on 2005 emissions from the 2008 version of EPA's GHG invnentory report. (http://www.epa.gov/climatechange/emissions/usinventoryreport.html).

Figure 2 compares the contribution of gross GHG emissions by sector estimated for Michigan to emissions for the U.S. for year 2005. Principal sources of Michigan's GHG emissions are electricity consumption; residential, commercial, and industrial (RCI) fuel use; and transportation accounting for 36%, 24%, and 24% of Michigan's gross GHG emissions in 2005, respectively.

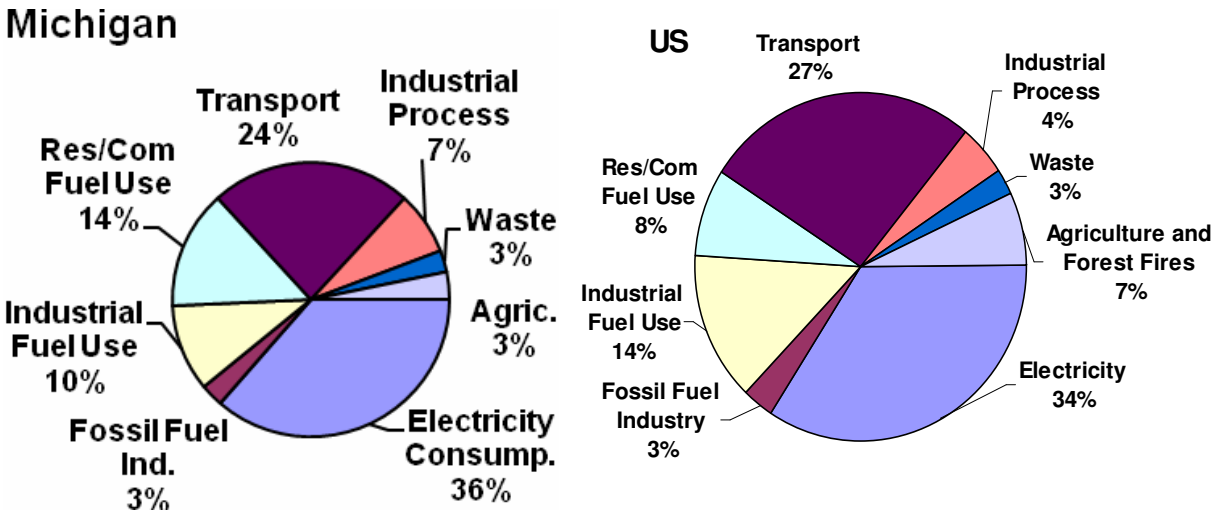
The next largest contributor is the industrial processes sector, accounting for 7% of gross GHG emissions in 2005. Although industrial process emissions are rising rapidly due to the increasing use of HFCs as substitutes for ozone-depleting chlorofluorocarbons (CFCs), their overall contribution is estimated to be only 9% of Michigan's gross GHG emissions in 2025 due to growth in other sectors.[15] Other industrial process emissions result from CO_2 released during iron and steel, cement, and lime, and manufacturing; taconite production; and soda ash, limestone, and dolomite use. In addition, SF_6 is released during magnesium production and the use of electric power transmission and distribution (T&D) equipment, while semiconductor manufacturing is responsible for the release of HFCs, PFCs, and SF_6.

The waste management, agriculture, and fossil fuel industry sectors each accounted for about 3% of Michigan's gross GHG emissions in 2005. The fossil fuel industry sector includes GHG emissions associated with natural gas production, processing, T&D, flaring, and pipeline fuel use, as well as with oil production and refining. The N_2O and CH_4 emissions associated with wildfires are also included in the inventory as a source of GHG emissions; however, these emissions are low (0.02 MMtCO2e) and do not appear in Figure 2 because of scale effects.

Forestry activities in Michigan are estimated to be net sinks for GHG emissions in all years. Forested lands are a net sink of about 13 $MMtCO_2e$ in 2005.

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

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



Notes: Res/Com = residential and commercial fuel use sectors; emissions for the residential, commercial, and industrial fuel use sectors are associated with the direct use of fuels (natural gas, petroleum, coal, and wood) to provide space heating, water heating, process heating, cooking, and other energy end-uses. The commercial sector accounts for emissions associated with the direct use of fuels by, for example, hospitals, schools, government buildings (local, county, and state), and other commercial establishments. The industrial processes sector accounts for emissions associated with manufacturing and excludes emissions included in the industrial fuel use sector. The transportation sector accounts for emissions associated with fuel consumption by all on-road and non-highway vehicles. Non-highway vehicles include jet aircraft, gasoline-fueled piston aircraft, railway locomotives, boats, and ships. Emissions from non-highway agricultural and construction equipment are included in the industrial sector. Emissions associated with forest wildfires are low (~0.2% of total agricultural and forest wildfire emissions in 2005) and are included with the Michigan agriculture sector in this figure. Electricity = electricity generation sector emissions on a consumption basis (including emissions associated with electricity imported from outside of Michigan and excluding emissions associated with electricity exported from Michigan to other states).

A Closer Look at the Three Major Sources: Electricity Consumption, RCI Fuel Use, and Transportation

Electricity Consumption Sector

Electricity generation in Michigan is dominated by steam units, which are primarily based on coal and nuclear fuel. To meet annual demand for electricity in Michigan, total gross generation by Michigan power plants were augmented by electricity imports. As shown in Figure 2, electricity consumption accounted for about 36% of Michigan's gross GHG emissions in 2005 (about 90 $MMtCO_2e$), which was higher than the national average share of emissions from electricity consumption (32%).[16] The GHG emissions associated with Michigan's electricity consumption sector increased by 20 $MMtCO_2e$ between 1990 and 2005, accounting for 74% of the state's growth in gross GHG emissions in this time period.

[16] For the US as a whole, there is relatively little difference between the emissions from electricity use and emissions from electricity production, as the US imports only about 1% of its electricity, and exports far less.

In 2005, emissions associated with Michigan's electricity consumption (90 $MMtCO_2e$) were about 19 MMtCO2e higher than those associated with electricity production (71 $MMtCO_2e$). The higher level for consumption-based emissions reflects GHG emissions associated with net imports of electricity from other states to meet electricity demand.[17] Projections of electricity sales for 2005 through 2025 indicate that Michigan will remain a net importer of electricity. . Emissions from electricity imports are projected to be constant (19 $MMtCO_2e$/yr) during the 2006-2025 period. The reference case projection indicates that production-based emissions (associated with electricity generated in-state) will increase by about 21 $MMtCO_2e$, and consumption-based emissions (associated with electricity consumed in-state) will also increase by about 21 $MMtCO_2e$ from 2005 to 2025.

The consumption-based approach can better reflect the emissions (and emissions reductions) associated with activities occurring in Michigan, particularly with respect to electricity use (and efficiency improvements), and is particularly useful for policy-making.

Residential, Commercial, and Industrial Fuel Use Sectors

Activities in the RCI[18] sectors produce GHG emissions when fuels are combusted to provide space heating, process heating, and other applications. In 2005, combustion of oil, natural gas, coal, and wood in the RCI sectors contributed about 24% (about 60 $MMtCO_2e$) of Michigan's gross GHG emissions, slightly higher than the RCI sector contribution for the nation (22%).

The residential sector's share of total RCI emissions from direct fuel use was 39% (23.6 $MMtCO_2e$), the commercial sector accounted for 18% (11 $MMtCO_2e$), and the industrial sector's share of total RCI emissions from direct fuel use was 42% (25 $MMtCO_2e$). Overall, emissions for the RCI sectors (excluding those associated with electricity consumption) are expected to increase by 4.1% between 2005 and 2025. Emissions from the commercial sector are projected to increase more rapidly than the residential or industrial sectors, with an 18% increase from 2005 to 2025. In contrast, emissions from the residential and industrial sectors are expected to increase by only 0.5% and 1.6%, respectively, from 2005 to 2025.

Transportation Sector

As shown in Figure 2, the transportation sector accounted for about 24% of Michigan's gross GHG emissions in 2005 (about 58 $MMtCO_2e$), which was lower than the national average share of emissions from transportation fuel consumption (27%). The GHG emissions associated with Michigan's transportation sector increased by 8.5 $MMtCO_2e$ between 1990 and 2005, accounting for about 32% of the State's net growth in gross GHG emissions in this time period.

From 1990 through 2005, Michigan's GHG emissions from transportation fuel use have risen steadily at an average rate of about 1.1% annually. In 2005, onroad gasoline vehicles accounted for about 74% of transportation GHG emissions. Onroad diesel vehicles accounted for another

[17] Estimating the emissions associated with electricity use requires an understanding of the electricity sources (both in-state and out-of-state) used by utilities to meet consumer demand. The current estimate reflects some very simple assumptions, as described in Appendix A.
[18] The industrial sector includes emissions associated with agricultural energy use and fuel used by the fossil fuel production industry.

18% of emissions, and marine vessels for roughly 4%. Air travel, rail, and other sources (natural gas- and liquefied petroleum gas- (LPG-) fueled-vehicles used in transport applications) accounted for the remaining 4% of transportation emissions. GHG emissions from onroad gasoline use grew 16% between 1990 and 2005. Meanwhile, GHG emissions from onroad diesel use rose 96% during that period, suggesting rapid growth in freight movement within or across the State. Emissions associated with marine fuel use increased by about 20% from 1990 to 2005, while emissions associated with aviation fuel consumption decreased by 63% in the same period.

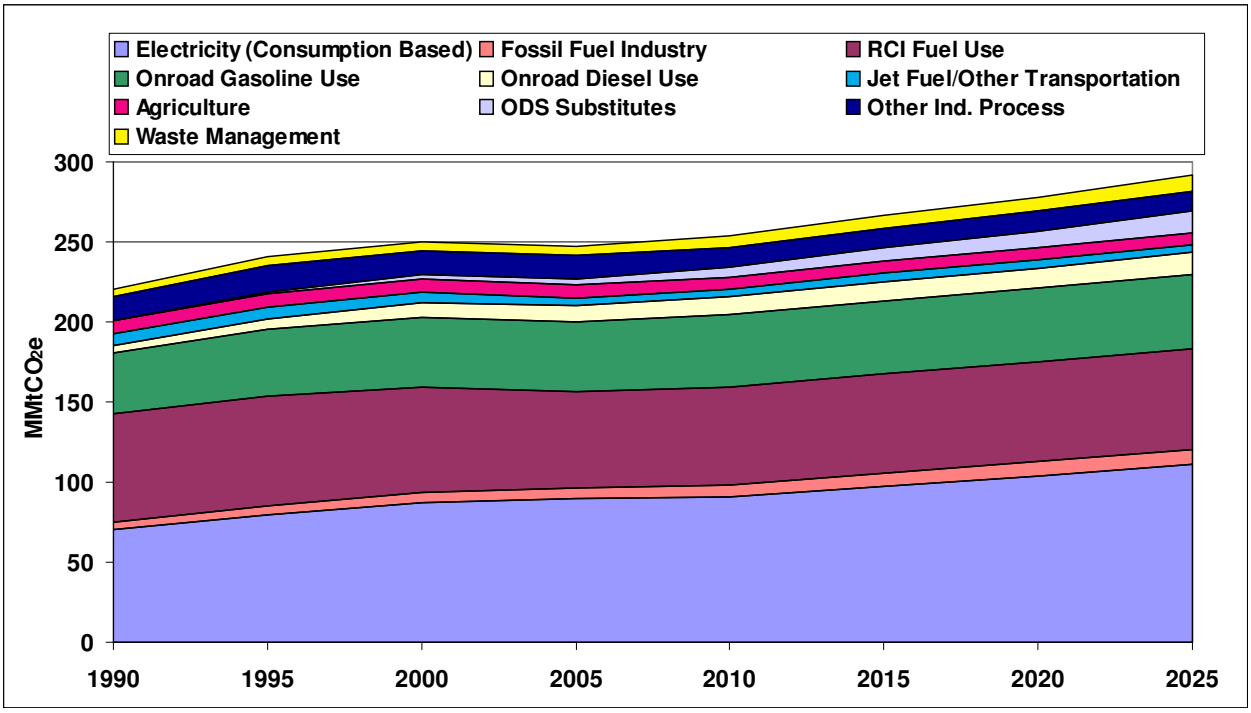
During the period from 2005 to 2025, emissions from transportation fuels are projected to rise at a rate of 0.6% per year. This leads to an increase of 7.1 $MMtCO_2e$ in transportation emissions from 2005 to 2025. The largest percentage increase in emissions over this time period is seen in onroad diesel fuel consumption, which is projected to increase by 34% from 2005 to 2025.

Reference Case Projections (Business as Usual)

Relying on a variety of sources for projections, as noted below and in the appendices, we developed a simple reference case projection of GHG emissions through 2025. As illustrated in Figure 3 and shown numerically in Table 1, under the reference case projections, Michigan gross GHG emissions continue to grow steadily, climbing to about 292 $MMtCO_2e$ by 2025, 32% above 1990 levels. This equates to an annual growth rate of 0.8% per year from 2005 to 2025. Relative to 2005, the share of emissions associated with electricity consumption and industrial processes both increase slightly to 38% and 9%, respectively, in 2025. The share of emissions from the transportation, RCI fuel use, and agriculture sectors all decrease slightly by 2025, relative to 2005, to 22%, 22%, and 2%, respectively. The share of emissions from the fossil fuel industries and the waste sector both remain the same in 2025 as their shares in 2005.

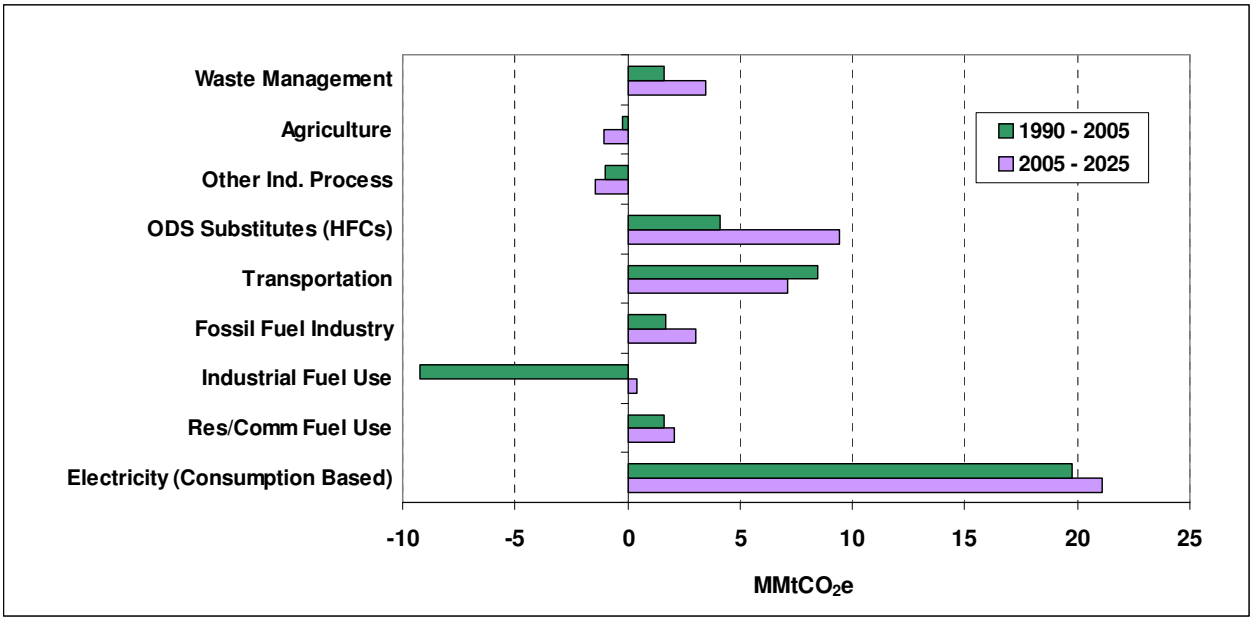
The electricity consumption sector is projected to be the largest contributor to future emissions growth, followed by emissions from ODS substitutes (HFCs), and then emissions associated with the transportation sector, as shown in Figure 4. Table 2 summarizes the growth rates that drive the growth in the Michigan reference case projections as well as the sources of these data.

Figure 3. Michigan Gross GHG Emissions by Sector, 1990-2025: Historical and Projected



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

Figure 4. Sector Contributions to Gross Emissions Growth in Michigan, 1990-2025: Historical and Reference Case Projections ($MMtCO_2e$ Basis)



Res/Comm – direct fuel use in residential and commercial sectors. ODS – ozone depleting substance. HFCs – hydrofluorocarbons. Emissions associated with other industrial processes include all of the industries identified in Appendix D except emissions associated with ODS substitutes which are shown separately in this graph because of high expected growth in emissions for ODS substitutes.

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

	1990-2005	2005-2025	Sources
Population	0.63%	0.31%	Michigan population statistics for 1990 and 2000, compiled by Michigan Information Center from US Census Bureau, are available at http://www.michigan.gov/documents/PopByCty_26001_7.pdf. Population data for 2000 to 2004 are available from Michigan Department of History, Arts, and Libraries at http://www.michigan.gov/hal/0,1607,7-160-17451_28388_28392-106981--,00.html. Michigan projections (2005-2030) available from Michigan Department of History, Arts, and Libraries at http://www.michigan.gov/hal/0,1607,7-160-17451_28388_28392-116118--,00.html
Electricity Sales **Total Sales**[a] **MI Sales**[b]	 1.97% 1.05%	 0.99% 1.27%	For 1990-2005, annual growth rate in total electricity sales for all sectors combined in Michigan calculated from EIA State Electricity Profiles (Table 8) http://www.eia.doe.gov/cneaf/electricity/st_profiles/michigan.html and sales by Michigan generators calculated by subtracting T&D losses from net generations collected from EIA Annual Electric Utility Data - 906/920 database. For 2005-2025, annual growth rates are based on data that Michigan utilities provided for gross electricity sales for 2006 through 2025 (see Appendix II, Table 15, page 101 of the *21st Century Electric Energy Plan*).
Vehicle Miles Traveled	1.6%	0.37%	Based on historical VMT and projected VMT growth rates provided by Michigan Department of Transportation and the Southeast Michigan Council of Governments.

[a] Represents annual growth in total sales of electricity by generators in Michigan to RCI sectors located within and outside of Michigan.
[b] Represents annual growth in total sales of electricity by generators in Michigan to RCI sectors located within Michigan.

MCAC Revisions

The following identifies the revisions that the Michigan Climate Action Council made to the inventory and reference case projections, thus explaining the differences between this report and the initial assessment completed in January 2008:

All Sectors: The initial assessment included GHG emission projections to 2020. This was revised to extend the GHG projections to year 2025 for all sectors.

Electric Supply:

- Production-based (in-state) and consumption-based generation and emissions:
  - Excluded electricity that Donald Cook nuclear plant exports to other states
  - Replaced this nuclear generation with electricity imports from outside the state
- Emissions from pumped storage:
  - Set emissions to zero to avoid double-counting of emissions (pumps are operated by electricity purchased from grid)
- Landfill gas (LFG)/municipal solid waste (MSW) and biomass emissions:
  - Added emissions for 1990-2000 (data for non-utilities inadvertently not included in the draft inventory and forecast).
  - For 1990-2000, only the aggregated numbers of non-utility generation (generation from independent power producers) can be obtained from the Energy Information Administration (EIA) website (EIA Electric Power Annual 2006). To get the disaggregated generation numbers of LFG, MSW, and biomass for 1990-2000

from the aggregated Other Renewable Generation number in Electric Power Annual (this number excludes hydro electricity), we applied the proportions by fuel and by plant type in 2001 to the aggregated renewable numbers of years 1990 to 2000.

- Transmission & distribution (T&D) line losses of Michigan:
  - The T&D line losses used in the draft analysis were revised based on the data provided by the Michigan Public Service Commission (MPSC). The T&D loss rate of Consumers Energy/METC, Detroit Edison/ITC, and Upper Peninsula were collected . The weighted average T&D loss rate of Michigan was computed based on the 2007 peak load on the system in each of the three regions
- Forecast for biomass net generation:
  - The forecast of biomass in the draft inventory and forecast used EIA regional projections, which show big increases in biomass generation in the forecast years. The EIA regional projections could be influenced by the existing renewable portfolio standard (RPS) in other states of the region. The electricity generation from biomass has been flat over the past 10 years or so in Michigan, about 1% of the total generation of the state. Biomass generation would be unlikely to significantly increase in Michigan in the forecast years unless there are strong policy regulations, such as an RPS. Therefore, in this report, for the business as usual condition in the forecast years, we assumed the same generation capacity from biomass as the existing capacity indicates (an average level of 2001-2005).

Transportation: MCAC approved the use of a new set of vehicle miles traveled (VMT) growth rates (for 2005-2010, 2010-2015, 2015-2020, and 2020-2025), provided by the Michigan Department of Transportation; this replaces the previous VMT growth rates used in the draft inventory and forecast.

Industrial Process: Revised iron and steel emissions by replacing the default SIT steel production data with crude steel production data provided by MDEQ for 1990-2005.

Fossil Fuel Industry: Added new estimates of the CO_2, CH_4, and N_2O emissions from the combustion of natural gas by internal combustion engines used to operate pipeline compressor stations. These emissions were not included in the initial assessment. These pipeline natural gas fuel use emissions were estimated using SIT emission factors and Michigan 1990-2005 natural gas data from EIA.

Agriculture: Projections for livestock populations were revised based on feedback from the Agriculture, Forestry, and Waste (AFW) TWG. Projections for beef cattle, swine, sheep, goats, and horses were estimated based on logarithmic forecasts of the historical 1990-2005 populations. Poultry populations were held at 2005 levels based on input from the poultry industry.[19]

Waste Sector: In the initial assessment, CH_4 captured for flaring and use in landfill gas to energy (LFGTE) plants were estimated with SIT defaults. The revised estimates are based on waste

[19] C. Vollmer-Sanders, MI Farm Bureau, communicated to R. Anderson, CCS, via telephone, May 2008.

emplacement data for controlled landfills and date of emission capture equipment installation. Information on controlled landfills was obtained from MDEQ and a database of landfill gas-to-energy (LFGTE) projects compiled by the EPA.

Open burning of Municipal Solid Waste (MSW) at residential sites was not estimated in the initial assessment. The revised report includes these emissions, which was obtained from the US EPA's 2002 National Emissions Inventory for estimates of the quantity of waste burned at residential sites in Michigan.[20]

Forestry: Carbon dioxide flux estimates for years 1994-2005 were revised to be based on the average calculated flux during this period using the Carbon Calculation Tool. This was done to minimize the influence of estimates in individual years and shifts between Forest Inventory & Analysis (FIA) measurements.

Reference Case Projections with Recent Actions[21]

The federal Energy Independence and Security Act (EISA) of 2007 was signed into law in December 2007. This federal law contains several requirements that will reduce GHG emissions as they are implemented over the next few years. During the MCAC process, sufficient information was identified (e.g., implementation schedules) to estimate GHG emission reductions associated with implementing the Corporate Average Fuel Economy (CAFE) requirements in Michigan.

The MCAC also identified recent actions that Michigan has undertaken to control GHG emissions while at the same time conserving energy and promoting the development and use of renewable energy sources. One recent action was identified for which data were available to estimate the emission reductions of the action relative to the business-as-usual reference case projections.

The GHG emission reductions projected to be achieved by these recent State and Federal actions are summarized in Table 3. This table shows a total reduction of about 8.9 $MMtCO_2e$ in 2025 from the business-as-usual reference case emissions, or a 3.1% reduction from the business-as-usual emissions in 2025 for all sectors combined.

The following provides a brief summary of the component of the EISA that was analyzed as a recent federal action.

Federal Corporate Average Fuel Economy Requirements: Subtitle A of Title I of EISA imposes new CAFE standards beginning with the 2011 model year vehicles. The average combined fuel economy of automobiles will be at least 35 mpg by 2020, with separate standards applying to passenger and non-passenger automobiles. The standard will be phased in, starting

[20] EPA, ftp://ftp.epa.gov/EmisInventory/2002finalnei/documentation/nonpoint/2002nei_final_nonpoint_documentation0206version.pdf

[21] Note that actions recently adopted by the state of Michigan have also been referred to as "existing" actions.

with the 2011 model year, so that the CAFE increases each year until the average fuel economy of 35 mpg is reached by 2020.

The following provides a brief summary of the Michigan recent action.

Clean, Renewable, & Efficient Energy Act S.B. 213: In September 2008 the Michigan Legislature enacted S.B.213, and Governor Granholm signed this bill into law (P.A. 295 of 2008) creating the "Clean, Renewable, and Efficient Energy Act," calling for the MPSC to order electric utilities to submit an energy optimization plan with the Commission demonstrating how the utility will comply with the new renewable portfolio standard. The Renewable Portfolio Standard mandates that 10% of the state's electricity be derived from renewable sources by 2015, with some exceptions.

Table 3. Emission Reduction Estimates Associated with the Effect of Recent Actions in Michigan (Consumption-Basis, Gross Emissions)

	GHG Reductions ($MMtCO_2e$)		GHG Emissions (MMtCO2e)	
			Business as Usual	With Recent Actions
Sector / Recent Action	2015	2025	2025	2025
Electricity Supply (ES)				
S.B. 213, Clean, Renewable and Energy Efficient Act	2.7	2.0	111	109
Transportation and Land Use (TLU)				
Federal Corporate Average Fuel Economy (CAFE) Requirements	3.6	6.9	65.3	58.4
Total (ES + TLU Sectors)	6.2	8.9	176	167
Total (All Sectors)			292	283

Key Uncertainties and Next Steps

Some data gaps exist in this inventory, and particularly in the reference case projections. Key tasks for future refinement of this inventory and forecast include review and revision of key drivers, such as the transportation, electricity demand, and RCI fuel use growth rates that will be major determinants of Michigan's future GHG emissions (See Table 2 and Figure 4). These growth rates are driven by uncertain economic, demographic and land use trends (including growth patterns and transportation system impacts), all of which deserve closer review and discussion.

Approach

The principal goal of compiling the inventories and reference case projections presented in this document is to provide the State of Michigan with a general understanding of Michigan's historical, current, and projected (expected) GHG emissions. The following sections explain the general methodology and the general principles and guidelines followed during development of these GHG inventories for Michigan.

General Methodology

We prepared this analysis in close consultation with Michigan agencies, in particular, with the staff at MDEQ. The overall goal of this effort is to provide simple and straightforward estimates, with an emphasis on robustness, consistency, and transparency. As a result, we rely on reference forecasts from best available State and regional sources where possible. Where reliable existing forecasts are lacking, we use straightforward spreadsheet analysis and constant growth-rate extrapolations of historical trends rather than complex modeling.

In most cases, we follow the same approach to emissions accounting for historical inventories used by the US EPA in its national GHG emissions inventory[22] and its guidelines for States.[23] These inventory guidelines were developed based on the guidelines from the IPCC, the international organization responsible for developing coordinated methods for national GHG inventories.[24] The inventory methods provide flexibility to account for local conditions. The key sources of activity and projection data used are shown in Table 4. Table 4 also provides the descriptions of the data provided by each source and the uses of each data set in this analysis.

General Principles and Guidelines

A key part of this effort involves the establishment and use of a set of generally accepted accounting principles for evaluation of historical and projected GHG emissions, as follows:

- **Transparency:** We report data sources, methods, and key assumptions to allow open review and opportunities for additional revisions later based on input from others. In addition, we report key uncertainties where they exist.

- **Consistency:** To the extent possible, the inventory and projections were designed to be externally consistent with current or likely future systems for State and national GHG emission reporting. We have used the EPA tools for State inventories and projections as a starting point. These initial estimates were then augmented and/or revised as needed to conform with State-based inventory and base-case projection needs. For consistency in making reference case projections, we define reference case actions for the purposes of projections as those *currently in place or reasonably expected over the time period of analysis*.

- **Priority of Existing State and Local Data Sources:** In gathering data and in cases where data sources conflicted, we placed highest priority on local and State data and analyses, followed by regional sources, with national data or simplified assumptions such as constant linear extrapolation of trends used as defaults where necessary.

- **Priority of Significant Emissions Sources:** In general, activities with relatively small emissions levels may not be reported with the same level of detail as other activities.

[22] *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2006*, April 15, 2008, US EPA #430-R-08-005, (http://www.epa.gov/climatechange/emissions/usinventoryreport.html).
[23] http://yosemite.epa.gov/oar/globalwarming.nsf/content/EmissionsStateInventoryGuidance.html.
[24] http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm.

- **Comprehensive Coverage of Gases, Sectors, State Activities, and Time Periods:** This analysis aims to comprehensively cover GHG emissions associated with activities in Michigan. It covers all six GHGs covered by US and other national inventories: CO_2, CH_4, N_2O, SF_6, HFCs, and PFCs. The inventory estimates are for the year 1990, with subsequent years included up to most recently available data (typically 2002 to 2005), with projections to 2010, 2020 and 2025.

- **Use of Consumption-Based Emissions Estimates:** To the extent possible, we estimated emissions that are caused by activities that occur in Michigan. For example, we reported emissions associated with the electricity consumed in Michigan. The rationale for this method of reporting is that it can more accurately reflect the impact of State-based policy strategies such as energy efficiency on overall GHG emissions, and it resolves double-counting and exclusion problems with multi-emissions issues. This approach can differ from how inventories are compiled, for example, on an in-state production basis, in particular for electricity.

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

Source	Information provided	Use of Information in this Analysis
US EPA State Greenhouse Gas Inventory Tool (SIT)	US EPA SIT is a collection of linked spreadsheets designed to help users develop State GHG inventories for 1990-2005. US EPA SIT contains default data for each State for most of the information required for an inventory. The SIT methods are based on the methods provided in the Volume VIII document series published by the Emissions Inventory Improvement Program (http://www.epa.gov/ttn/chief/eiip/techreport/volume08/index.html).	Where not indicated otherwise, SIT is used to calculate emissions for 1990-2005 from RCI fuel combustion, transportation, industrial processes, agriculture and forestry, and waste. We use SIT emission factors (CO_2, CH_4, and N_2O per British thermal unit (Btu) consumed) to calculate energy use emissions.
US DOE Energy Information Administration (EIA) State Energy Data (SED)	EIA SED provides energy use data in each State, annually to 2005 for all RCI sectors and fuels, except for commercial wood consumption for which 2003 is the latest year for which data are available from EIA.	EIA SED is the source for most energy use data. Emission factors from US EPA SIT are used to calculate energy-related emissions.
EIA State Annual Electric Utility Data — EIA 906/920 Database	EIA provides information on the electric power industry generation by primary energy source for 1990 – 2005.	EIA 906/920 Database was used to determine the mix of in-state electricity generation by fuel. Electricity sales were projected off of 2005 sales provided in this reference.
EIA State Electricity Profiles	EIA provides information on electric power industry capability, generation, retail sales, and average retail price for 1990 through 2006 in this database.	Michigan Electricity Profiles were used to determine the total electricity sales by sector for 1990-2005.
EIA AEO2007	EIA AEO2007 projects energy supply and demand for the US from 2004 to 2030. Energy production and consumption are estimated on a regional basis.	EIA AEO2007 is used to project electricity generation by fuel and changes in fuel use by the RCI sectors.
Michigan's 21st Century Electric Energy Plan	This report provides the projection of total electric generation requirements (electricity sales plus electric system losses) for the period 2006 through 2025.	The projections in this report were used to estimate Michigan's electricity sales from in-state utilities for 2006-2025.
Michigan Department of Transportation	Growth rates for projected vehicle miles traveled (VMT).	The growth rates were used to project onroad VMT.
US Department of Transportation (DOT), Office of Pipeline Safety (OPS)	Natural gas transmission pipeline mileage, distribution pipeline mileage, and number of services for 1990–2005.	OPS data entered into SIT to calculate historical emissions. Transmission pipeline emissions projected based on smallest annualized growth in Michigan transmission emissions (+3.49%) from each of 3 periods analyzed (1990-2005; 1995-2005; and 2000-2005); distribution pipeline emissions projected based on smallest annualized growth in Michigan distribution emissions (+0.45%) from each of 3 periods analyzed

Source	Information provided	Use of Information in this Analysis
EIA Natural Gas Navigator	EIA provides the number of gas and gas condensate wells and amount of gas flared and vented in Michigan for 1990-2005.	Natural Gas Navigator data entered into SIT to calculate historical emissions. Gas well emissions projected based on smallest annualized growth rate in the number of gas wells in the state (+4.72%) from each of 3 historical periods analyzed (i.e., 1990-2005, 1995-2005, and 2000-2005); gas flaring emissions projected using no growth assumption based on near constant activity throughput historical period.
PennWell Corporation Oil and Gas Journal	PennWell reports the number of gas processing plants in Michigan for 1990-2005.	PennWell data entered into SIT to calculate historical emissions. Emissions projected based on smallest annualized decline in the number of gas processing plants in Michigan (-0.89%) from each of 3 periods analyzed (1990-2005; 1995-2005, and 2000-2005).
EIA Petroleum Navigator	Volume of crude oil production in Michigan for 1990-2005, and regional crude oil input, regional refining capacity, and Michigan's refining capacity for 1990-2005 (because data were not available to estimate 1996 and 1998 refining; these years' estimates were interpolated).	EIA data entered into SIT to calculate historical emissions. Oil production emissions projected based on smallest annualized decline in state oil production (-6.84%) from each of 3 periods analyzed (i.e., 1990-2005, 1995-2005, and 2000-2005); oil refining emissions projected based on no growth assumption due to conflicting state historical refining trends across 3 periods analyzed.
US Forest Service	Data on forest carbon stocks for multiple years.	Data are used to calculate CO_2 flux over time (terrestrial CO_2 sequestration in forested areas).
USDS National Agricultural Statistics Service (NASS)	USDA NASS provides data on crops and livestock.	Crop production data used in SIT to estimate agricultural residue and agricultural soils emissions; livestock population data used in SIT to estimate manure and enteric fermentation emissions.

For electricity, we estimate, in addition to the emissions due to fuels combusted at electricity plants in the State, the emissions related to electricity *consumed* in Michigan. This entails accounting for the electricity sources used by Michigan utilities to meet consumer demands. As this analysis is refined in the future, one could also attempt to estimate other sectoral emissions on a consumption basis, such as accounting for emissions from transportation fuel used in Michigan, but purchased out-of-state. In some cases, this can require venturing into the relatively complex terrain of life-cycle analysis. In general, we recommend considering a consumption-based approach where it will significantly improve the estimation of the emissions impact of potential mitigation strategies. For example re-use, recycling, and source reduction can lead to emission reductions resulting from lower energy requirements for material production (such as paper, cardboard, and aluminum), even though production of those materials, and emissions associated with materials production, may not occur within the State.

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

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

Appendix I provides additional background information from the US EPA on GHGs and global warming potential values.

Appendix A. Electricity Supply and Use

Overview

This appendix describes the data sources, key assumptions, and the methodology used to develop an inventory of greenhouse gas (GHG) emissions over the 1990-2005 period associated with the generation of electricity to meet electricity demand in Michigan. It also describes the data sources, key assumptions, and methodology used to develop a forecast of GHG emissions over the 2006-2025 period associated with meeting electricity demand in the state. Specifically, the following topics are covered in this Appendix:

- *Data sources:* This section provides an overview of the data sources that were used to develop the inventory and forecast, including publicly accessible websites where this information can be obtained and verified.
- *Greenhouse Gas Inventory methodology:* This section provides an overview of the methodological approach used to develop the Michigan GHG inventory for the electric supply sector.
- *Greenhouse Gas Forecast Methodology – Reference Case:* This section provides an overview of methodological approach used to develop the Michigan GHG reference case projections (forecast) for the electric supply sector.
- *Greenhouse Gas Inventory Results:* This section provides an overview of key results of the Michigan GHG inventory for the electric supply sector.
- *Greenhouse Gas Forecast Results:* This section provides an overview of key results of the Michigan GHG forecast for the electric supply sector.

Data Sources

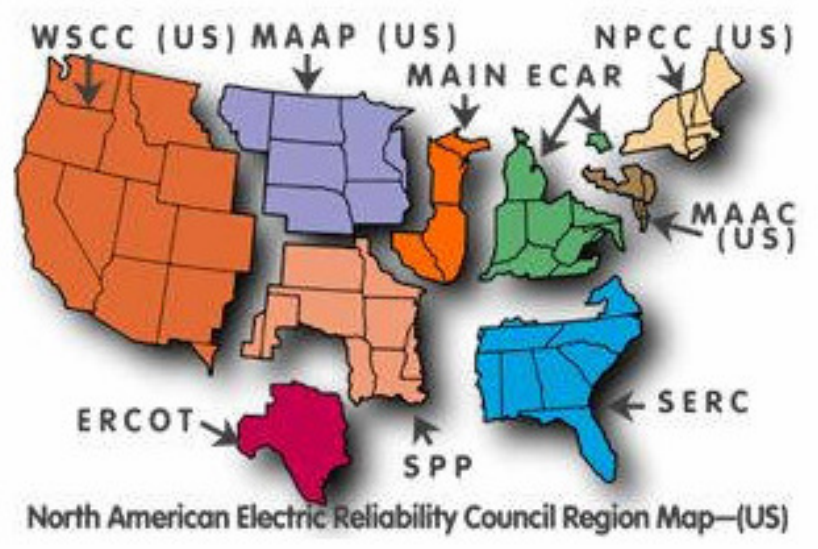
We considered several sources of information in the development of the inventory and forecast of carbon dioxide equivalent (CO_2e) emissions from Michigan power plants. These are briefly summarized below:

- *EIA-906/920 Monthly Time Series data.* This is a database file available from the Energy Information Administration (EIA) of the United States (US) Department of Energy (DOE). The information in the database is based on information collected from power plants in Forms EIA-906/920 and EIA-860. Historical data for years 1990-2005 were extracted for Michigan.[25] Year 2005 (forecast base year) data of neighboring states in the East Central Area Reliability Coordination Agreement (ECAR) region and Mid-America Interconnected Network (MAIN) region were also collected. These states include OH, IL, and IN, along with parts of KY, MD, MO, PA, VA, WI, and WV. Data from these forms provide, among other things, fuel consumption and net generation in power stations located in these states by plant

[25] Electricity generated from non-utility plants was included in the database since 2001. For 1990-2000, only the aggregated numbers of non-utility generation can be found in EIA Electric Power Annual 2006. To get the disaggregated generation numbers for 1990-2000, we applied the proportions by fuel and by plant type in year 2001 to the aggregated numbers of years 1990 to 2000.

type. This information can be accessed from http://www.eia.doe.gov/cneaf/electricity/page/eia906_920.html.

- *Michigan's 21st Century Electric Energy Plan.* This report prepared by the Michigan Public Service Commission (MPSC) provides total electric generation requirements (electricity sales plus electric system losses) for the period 2006 through 2025. The projected generation requirements are a compilation of forecasts prepared by Michigan utilities. The projections in this report are used to estimate Michigan's electricity sales from in-state utilities over the period 2006-2025 (see Appendix II, Table 15, on page 101 of the *21st Century Electric Energy Plan*). This report, which was prepared through an extensive collaborative planning process, can be accessed from http://www.dleg.state.mi.us/mpsc/electric/capacity/energyplan/index.htm.
- *Nuclear power generation from COOK 1&2 and the proportion of COOK's sales to Michigan from 1990 to 2005*. These spreadsheets are provided by Greg Clark from Indiana Michigan Power. Only a small portion of the electricity generated from COOK 1&2 was sold inside Michigan. The rest was exported to boarder states, e.g., Indiana. The amount of nuclear power exported outside Michigan is subtracted from the total in-state generation. Michigan power imports need is calculated as the difference between the total sales of the state and the total in-state generation.
- *Michigan Transmission and Distribution Losses Rate*. The T&D losses rate of different regions of Michigan is provided by Julie Baldwin of MPSC. These loss rate data are obtained from Excel Spreadsheet provided by contacts from Consumers Energy, Detroit Edison, UP Coop. Weighted average T&D loss rate of Michigan as a whole for years 1990 to 2025 are calculated based upon the 2007 peak load on the system in each region.
- *Annual Energy Outlook 2007.* This is an output of an EIA analysis using the National Energy Modeling System (NEMS), a model that forecasts electric expansion/electricity demand in the US. In particular, regional outputs for ECAR region and MAIN region were used. Michigan is partly (about three quarters) located in ECAR and partly (about one quarter) located in MAIN (see map at right). The ECAR and MAIN results include forecasts of gross generation, net generation, combustion efficiency, total sales, and exports/imports through the year 2025. This information is available in supplemental tables that can be accessed directly from http://www.eia.doe.gov/oiaf/aeo/supplement/index.html. The sources of the above map is http://www.bydesign.com/fossilfuels/crisis/html/NERC_regions_map.html.



- *Annual Energy Outlook 1996*-2006 Editions. Historical data on gross generation, net generation, total sales, on-site usage, T&D losses, and emission intensities for the ECAR and MAIN regions were extracted for years 1994-2004. The information is available in supplemental tables that can be accessed directly from http://www.eia.doe.gov/oiaf/archive.html#aeo.
- *Monthly Cost and Quality of Fuels for Electric Plants.* This information is available from the Federal Energy Regulatory Commission (FERC). The database relies on information collected from utilities in the FERC-423 form. It was used to determine the share of coal type (i.e., whether bituminous, sub-bituminous, anthracite, or lignite) as well as the coal quantity consumed in Michigan power plants over the period 1990-2005. It can be accessed directly from http://www.eia.doe.gov/cneaf/electricity/page/ferc423.html.
- *State Electricity Profiles.* This information is available from the EIA. The database compiles capacity, net generation, and total retail electricity sales by state. It was used to determine total sales of electricity across all sectors for years 1990 through 2005. It can be accessed directly from http://www.eia.doe.gov/cneaf/electricity/st_profiles/e_profiles_sum.html.
- *Energy conversion factors.* This is based on Table Y-2 of Appendix Y in the USEPA's 2003 GHG Inventory for the US. The table is entitled "Conversion Factors to Energy Units (Heat Equivalents)". This information can be accessed directly from the following website: http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/LHOD5MJTCL/$File/2003-final-inventory_annex_y.pdf.
- *Fuel combustion oxidation factors:* This is based on Appendix A of the USEPA's 2003 US GHG inventory for the US. This information can be accessed directly from: http://www.epa.gov/climatechange/emissions/downloads06/06_Annex_Chapter2.pdf.
- *Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emission factors.* For all fuels except Municipal Solid Waste (MSW), these emission factors are based on Appendix A of the USEPA's 2003 GHG inventory for the US. This information can be accessed directly from: http://www.epa.gov/climatechange/emissions/downloads06/06_Annex_Chapter2.pdf. For MSW, emission factors are based on the EIA's Office of Integrated Analysis and Forecasting, Voluntary Reporting of Greenhouse Gases Program, Table of Fuel and Energy Source: Codes and Emission Coefficients. This information can be accessed directly from http://www.eia.doe.gov/oiaf/1605/coefficients.html.
- *Global warming potentials:* These are based on values proposed by the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report. This information can be accessed directly from http://www.ipcc.ch/ipccreports/assessments-reports.htm.

Greenhouse Gas Inventory Methodology

The methodology used to develop the Michigan inventory of GHG emissions associated with electricity production and consumption is based on methods developed by the IPCC and used by the USEPA in the development of the US GHG inventory. There are four fundamental premises of the GHG inventory developed for Michigan, as briefly described below:

- The GHG inventory should be estimated based on both the production and consumption of electricity. Developing the production estimate involves tallying up the GHG emissions associated with the operation of power plants physically located in Michigan, regardless of

ownership. Developing the consumption estimate involves tallying up the GHG emissions associated with consumption of electricity in Michigan, regardless of where the electricity is produced. As Michigan is a net importer of electricity, these estimates will be different.

- The GHG inventory should be estimated based on emissions at the point of electric generation only. That is, GHG emissions associated with upstream fuel cycle process such as primary fuel extraction, transport to refinery/processing stations, refining, beneficiation, and transport to the power station are not included.
- As an approximation, in most cases, it was assumed that power generated in Michigan was consumed in Michigan. In fact, some of the power generated in Michigan is exported. We calculated the portion of electricity generated by COOK 1&2 that was exported to outside Michigan and subtracted this amount from the total in-state generation. We assume the rest power generated in Michigan was consumed inside the state. Given the similarity in the average carbon intensity of Michigan power stations and that of power stations in the surrounding ECAR and MAIN regions, the potential error associated with this simplifying assumption is small, on the order of 2%, plus or minus.
- Several key assumptions were used for making projections of CO_2, CH_4, and N_2O emissions for the electric sector out to 2025. These are summarized in Table A1.

Table A1. Key Assumptions used in the GHG Reference Case Projection

Key Assumptions	2005	2025	Average Annual Growth / Change (%)
MI electricity demand (GWh)*	110,445	134,614	0.99%
MI gross generation (excluding electricity exported outside MI from COOK 1&2) (GWh)	93,956	120,542	1.25%
MI utility sales to meet MI demand (GWh)	86,815	111,680	1.27%
Import sales from ECAR and MAIN regions (GWh)	23,629	22,935	-0.15%
Gross generation from ECAR and MAIN imports (GWh)	24,641	24,315	-0.07%
Power plant heat rate (BTU/kWh)			
Coal	10,258	10,269	0.01%
Nuclear	10,396	10,396	0.00%
Natural Gas	10,404	9,811	-0.29%
Oil	11,590	11,035	-0.24%
Municipal Solid Waste (MSW)	14,386	14,386	0.00%
Biomass	14,686	12,864	-0.66%
Landfill Gas (LFG)	12,505	12,505	0.00%
Wind	9,957	9,957	0.00%
Hydroelectric	9,957	9,957	0.00%
Losses (%)			
From on-site usage	0.42%	0.32%	-1.89%
From T&D and on-site usage	7.18%	7.03%	-0.13%

* The 2005 and 2025 values exclude losses associated with the transmission and distribution of electricity and use of fuel to operate power plants. The 2005 value is from EIA historical sales data for Michigan. The 2005 value was grown to 2025 using an annual growth rate of 1.29% obtained from data that Michigan utilities provided for gross electricity sales for 2006 through 2025 (see Appendix II, Table 15, page 101 of the *21st Century Electric Energy Plan*). The 0.99% annual growth rate for 2005 through 2025 shown here is lower than the 1.29% annual growth rate for 2006 through 2025 in part because of differences in the time periods covered and in part because the 0.99% reflects only in-state generation minus losses associated with transmission and distribution of electricity and use of fuel to operate power plants.

There were several steps in the methodology for the development of the electric sector GHG inventory for the period 1990-2005. These are briefly outlined below:

- Determine the coal quality used in Michigan power stations (i.e., share of anthracite, bituminous, lignite, sub-bituminous, and coal wastes used).
- Determine gross annual primary energy consumption by Michigan power stations by plant and fuel type.
- Determine gross annual generation associated with net power imports to satisfy Michigan electricity demand.
- Multiply gross annual primary energy consumption by Michigan power stations by CO_2e emission factors. This provides an estimate of the Michigan GHG inventory on a production basis.[26]
- Multiply annual gross generation associated with net power imports by the weighted average carbon emission intensity (in units of metric tons of CO_2e per megawatt-hour [CO_2e/MWh]) of the ECAR and MAIN regions. This provides an estimate of the additional GHG emissions associated with meeting Michigan electricity demand in excess of generation from local power plants.
- Add the emissions associated with net power imports to the production-based emissions. This provides an estimate of the GHG inventory on a consumption basis.

Greenhouse Gas Forecast Methodology – Reference Case

We consider that the most useful methodology for constructing a GHG forecast is one that attempts to build information from the bottom-up. That is, the GHG forecast was developed using detailed State-specific data regarding projected sales, gross in-state generation, supply-side efficiency improvements, planned capacity additions and retirements by plant type/vintage, and changes over time regarding losses associated with on-site use and transmission and distribution.

While some of this information was available in Michigan, some key data were not available at the time the forecast was prepared. Therefore, it was necessary to use a top-down approach. A top-down approach uses proxy information regarding future gross in-state generation, supply-side efficiency improvements, and changes over time regarding losses. This approach, while less satisfactory for representing state-specific conditions, nonetheless offers an acceptable starting point for exploring projections of GHG emissions from the electric sector in Michigan. The methodological steps used for forecasting CO_2e emissions are described below.

Coal quality. An overview of the methodology applied to forecast quality of coal used in Michigan power stations is briefly summarized below:

- For the Base Year of 2005, determine the coal quality used in Michigan power stations (i.e., share of anthracite, bituminous, lignite, sub-bituminous, and coal wastes used).

[26] Nuclear power generated from COOK 1&2 that was exported to outside Michigan was not counted in the state total gross generation. However, since GHG emissions from nuclear plant are zero, excluding exported nuclear power will not affect the results of the production-based emissions calculation.

- For the period 2006 through and including 2025, assume that the coal quality is the same as the Base year.

Electricity imports. An overview of the methodology applied to forecast annual net electricity imports to meet Michigan demand is briefly summarized below:

- For the Base Year of 2005, estimate the sales associated with imports as the difference between total sales in Michigan and the sales from Michigan power stations.
- For the period 2006 through and including 2025, assume the sales associated with imported electricity equal the average amount of historical import sales from year 2001 to year 2005.
- For the Base Year of 2005 through and including 2025, estimate the gross generation associated with imports by dividing sales from imports by one minus the percent losses from on-site usage and transmission and distribution in the ECAR and MAIN regions.

Gross generation. An overview of the methodology applied to forecast annual gross electricity generation by Michigan power stations is briefly summarized below:

- For the Base Year of 2005, estimate losses associated with on-site usage of electricity by plant type for Michigan power plants. On-site usage losses were assumed to be equal to the ECAR and MAIN regional average of 0.4% of gross generation.
- For the Base Year of 2005, combine actual net electric generation data (i.e., from the inventory) and assumed average on-site losses (i.e., from the ECAR and MAIN regions) to estimate gross generation by plant type.
- For the period 2006 through and including 2025, obtain projected total electric generation requirements (electricity sales plus electric system losses) from the *Michigan's 21st Century Electric Energy Plan* by MPSC. Subtract projected sales associated with imported electricity from the total electric generation requirements to estimate total net generation by Michigan power stations to meet the forecasted demand.
- For the period 2006 through and including 2025, estimate total gross generation of Michigan power stations by dividing the total net generation by one minus the on-site energy usage rate (of the ECAR and MAIN regions).
- For each year of the period 2006 through and including 2025, allocate total gross generation to each plant and fuel type based on the proportions of each plant and fuel type to total gross generation available from the EIA's modeling forecast for the ECAR and MAIN regions[27].

[27] The proportions of each plant and fuel type to total gross generation in each forecast year are computed based on the EIA regional forecast on growth rate of generation for the ECAR and MAIN regions, except for biomass. The EIA regional projections show big increases in biomass generation in the forecast years (e.g., a 7-fold increase between 2005 and 2010). The major driven reason for the big regional increase could be the existing RPS in other states of the region. Most of the biomass used in Michigan's existing wood-burning power plants and biomass-fired boilers is wood residues from commercial forest harvesting and the primary forest products industries. The electricity generation from biomass has been keeping at a flat level in the past 10 years or so, about 1% of the total generation of the state. Because of the ongoing downside pressures to the forest industry, the wood harvesting to supply to the forest products industry and the wood residues to be used in the wood-burning power plants would be difficult to experience dramatic increase in the forecast years unless there are strong policy regulations, such as RPS. To double the Michigan's existing wood-fueled power plants to fulfill a potential 10% RPS in Michigan in future years would not only require the expansion of the wood harvesting and primary forest products production, but also

Total sales. An overview of the methodology applied to forecast annual sales of electricity to Michigan consumers is briefly summarized below:

- For the Base Year of 2005, establish total retail sales in Michigan (i.e. 110,445 gigawatt-hour (GWh)).
- For the period 2006 through and including 2025, estimate the Michigan utility sales to meet the electricity demand in the state by multiplying the total gross generation by one minus the on-site usage percent and the percent losses from transmission and distribution (weighted average percent loss of Michigan[28]).
- For the period 2006 through and including 2025, compute the electricity total sales in Michigan regardless of the origin by adding the sales from imports and the sales from in-state power plants.

Combustion efficiency. An overview of the methodology applied to forecast annual heat rates at Michigan power stations is briefly summarized below:

- For the Base Year of 2005, estimate gross heat rate of Michigan power stations by dividing the plant type-specific 2005 gross generation estimate by the plant type-specific 2005 gross primary energy consumption estimate.
- For the period 2006 through and including 2025, estimate the annual average gross plant type-specific heat rate for the ECAR and MAIN regions.
- For the period 2006 through and including 2025, estimate annual average gross plant type-specific heat rate of Michigan power stations by multiplying the 2005 value of the annual average gross plant type-specific heat rate of Michigan power plants by the annual rate of improvement of gross heat rate in the ECAR and MAIN regions.

Energy use. An overview of the methodology applied to forecast annual primary energy use at Michigan power stations is briefly summarized below:

- For the Base Year of 2005, establish the actual primary energy consumption for Michigan power plants as reported by the databases used to develop the inventory.
- For the period 2006 through and including 2025, multiply annual gross generation by annual heat rate for each plant type in Michigan.

Carbon dioxide-equivalent emissions from Michigan power stations. An overview of the methodology applied to forecast annual CO_2e emissions from Michigan power stations is briefly summarized below:

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the advancement in the forest management practices. However, for the business as usual condition for Michigan in the forecast years, we choose to assume the same generation capacity from biomass as the existing capacity indicates. Therefore, we decided to use the 5-year (2001-2005) average biomass gross generation level in the forecast years through 2025.

[28] T&D loss rate data of Consumers Energy/METC, Detroit Edison/ITC, and Upper Peninsula are collected. The weighted average T&D loss rate of Michigan is computed based on the 2007 peak load on the system in each of the three regions.

- For the Base Year of 2005 through and including 2025, estimate total CO_2 emissions from Michigan power stations by multiplying total primary energy use by the CO_2 emission factor and the global warming potential.
- For the Base Year of 2005 through and including 2025, estimate total CH_4 emissions from Michigan power stations by multiplying total primary energy use by the CH_4 emission factor and the global warming potential.
- For the Base Year of 2005 through and including 2025, estimate total N_2O emissions from Michigan power stations by multiplying total primary energy use by the N_2O emission factor and the global warming potential.
- For the Base Year of 2005 through and including 2025, estimate total CO_2e emissions from Michigan power stations by adding the CO_2e of CO_2, CH_4, and N_2O.

Carbon dioxide-equivalent emissions from imported electricity. An overview of the methodology applied to forecast annual CO_2e emissions from electricity imports is briefly summarized below:

- For the Base Year of 2005 through and including 2025, estimate the average annual GHG emission intensity (i.e., metric tons of CO_2, CH_4, and N_2O per MWh of gross generation) for the ECAR and MAIN regions from the data sources described earlier.
- For the Base Year of 2005 through and including 2025, estimate total CO_2 emissions associated with imported electricity by multiplying the gross generation associated with these imports by the CO_2 emission intensity and the global warming potential.
- For the Base Year of 2005 through and including 2025, estimate total CH_4 emissions associated with imported electricity by multiplying the gross generation associated with these imports by the CH_4 emission intensity and the global warming potential.
- For the Base Year of 2005 through and including 2025, estimate total N_2O emissions associated with imported electricity by multiplying the gross generation associated with these imports by the N_2O emission intensity and the global warming potential.
- For the Base Year of 2005 through and including 2025, estimate total CO_2e emissions associated with imported electricity by adding the CO_2e of CO_2, CH_4, and N_2O.

Results

Table A2 and Figure A1 summarize the characteristics of the electric generation system in Michigan, together with a breakdown in generation and emissions for Michigan power stations for 2005. The following subsections provide an overview of the results of the GHG emissions inventory and reference case projections estimated using the methodological approach described above.

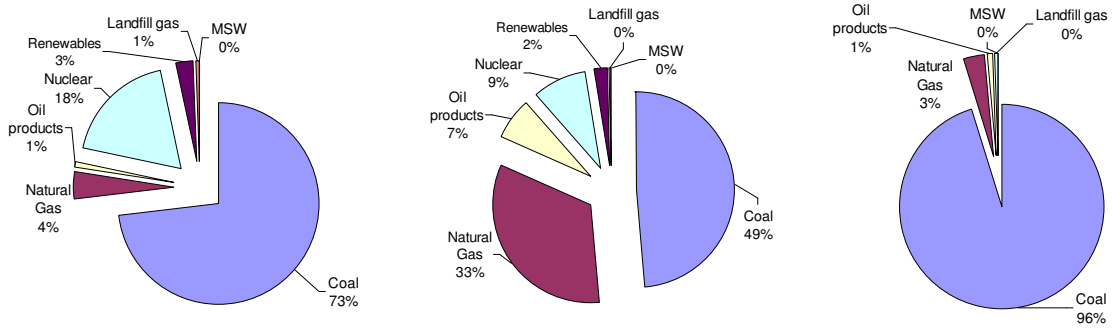
Table A2. Summary of MI Electric Generator Characteristics for the 2005 Base Year

Type	Fuel	Gross Generation (GWh)	Capacity (MW)	Fuel use (Billion Btu)	Heat rate (Btu/KWh)	Emissions ($MMtCO_2e$)
Steam plants	Non-lignite coal	69,580	12,594	713,765	10,258	67.74
	Lignite coal	0	0	0	0	0.00
	Natural Gas	1,277	2,335	15,594	12,215	0.84
	Residual oil	614	1,173	6,926	11,285	0.54
	Diesel oil	136	0	1,446	10,663	0.11
	Petroleum coke	6	0	87	13,618	0.01
	LFG	0	0	0	0	0.00
	Refuse derived fuel/MSW	0	0	0	0	0.00
	Biomass	1,046	178	15,366	14,686	0.03
	Nuclear	17,306	2,270	179,908	10,396	0.00
	Tire-derived Fuels	128	0	1,843	14,447	0.16
	Subtotal:	*90,092*	*18,549*	*934,935*		*69*
Turbines	Natural Gas	1,211	3,692	14,693	12,137	0.79
	Diesel	34	398	589	17,238	0.04
	Landfill Gas	36	7	393	10,840	0.02
	Waste oils/solvents	0	0	0	0	0.00
	Subtotal:	*1,281*	*4,097*	*15,674*		*0.86*
Combined Cycle	Natural Gas	1,747	2,350	13,727	7,857	0.74
	Diesel	0	0	0	0	0.00
	Landfill Gas	95	25	1,333	13,962	0.07
	Subtotal:	*1,843*	*2,375*	*15,060*		*0.81*
Engines	Natural Gas	8	124	124	15,000	0.01
	Diesel	2	275	128	70,891	0.01
	Landfill Gas	370	50	4,553	12,292	0.24
	LPG	0	0	0	0	0.00
	Residual Oil	0	8	3	10,441	0.00
	subtotal:	*381*	*457*	*4,807*		*0.26*
Renewable	Wind	2	2	18	9,957	0.00
	Solar PV	0	0	0	0	0.00
	Hydroelectric	1,468	383	14,616	9,957	0.00
	Subtotal:	*1,470*	*384*	*14,634*		*0.00*
Pumped Storage	Water	-1,111	1,979	0	0	0.00
	Subtotal:	*-1,111*	*1,979*	*0*		*0.00**
All	***Total***	**93,955**	**27,841**	**985,111**		**71.36**

***** Electricity has been used to pump water in Ludington. Since the emissions from electricity generation have been counted at the production site, to avoid double-counting, we assumed the emission factors of Ludington pumped storage plant are zero.

Figure A1. Breakdown of MI Generation, Capacity and CO_2 Emissions – 2005 Base Year

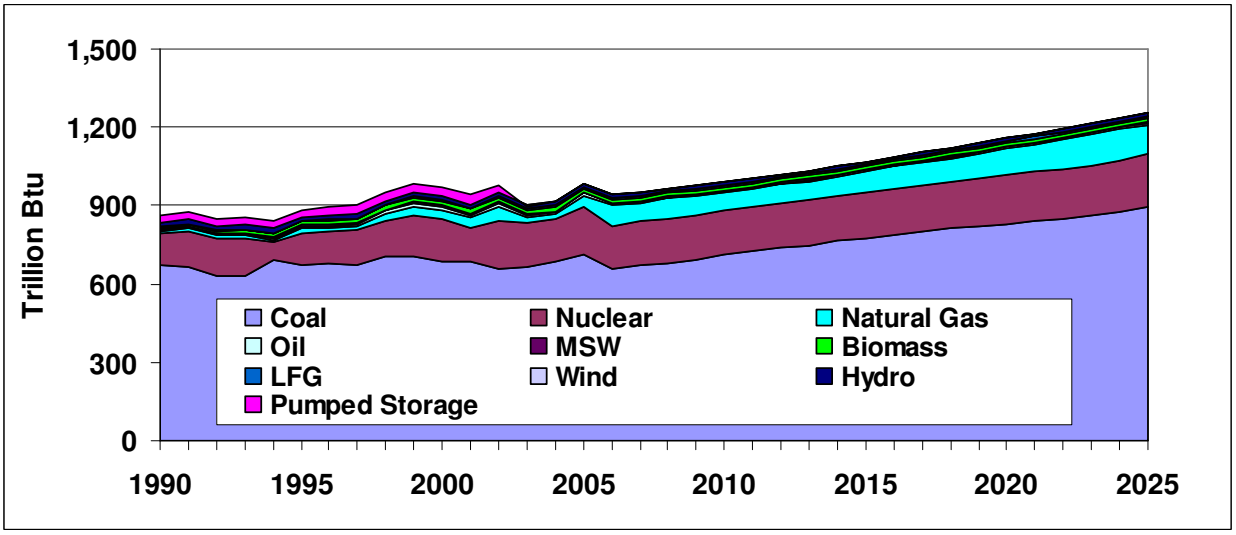
a. Gross Generation (93,955 Gigawatt-hours [GWh]) **b. Capacity (27.8 GW)** **c. Emissions (71.4 $MMtCO_2e$)**



Primary Energy Consumption

Total primary energy consumption associated with electricity generation in Michigan is summarized in Figure A2. Primary energy consumption in Michigan is dominated by coal and nuclear resources.

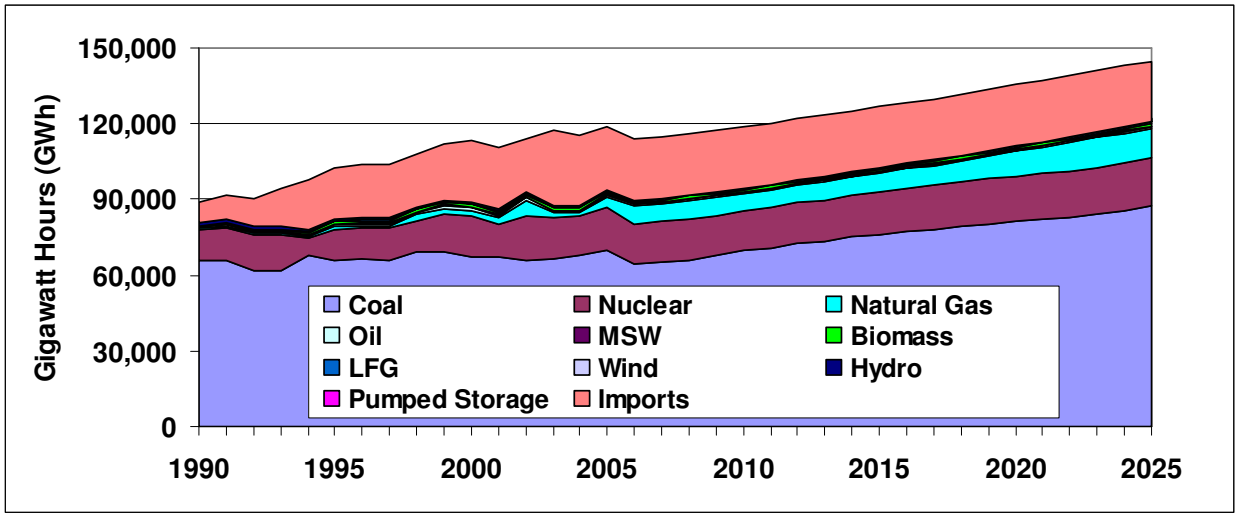
Figure A2. Gross Primary Energy Use at Michigan Power Stations



Gross Generation

Total gross generation by fuel type is summarized in Figure A3. Gross generation in Michigan is dominated by steam units, which are primarily based on coal and nuclear fuel.

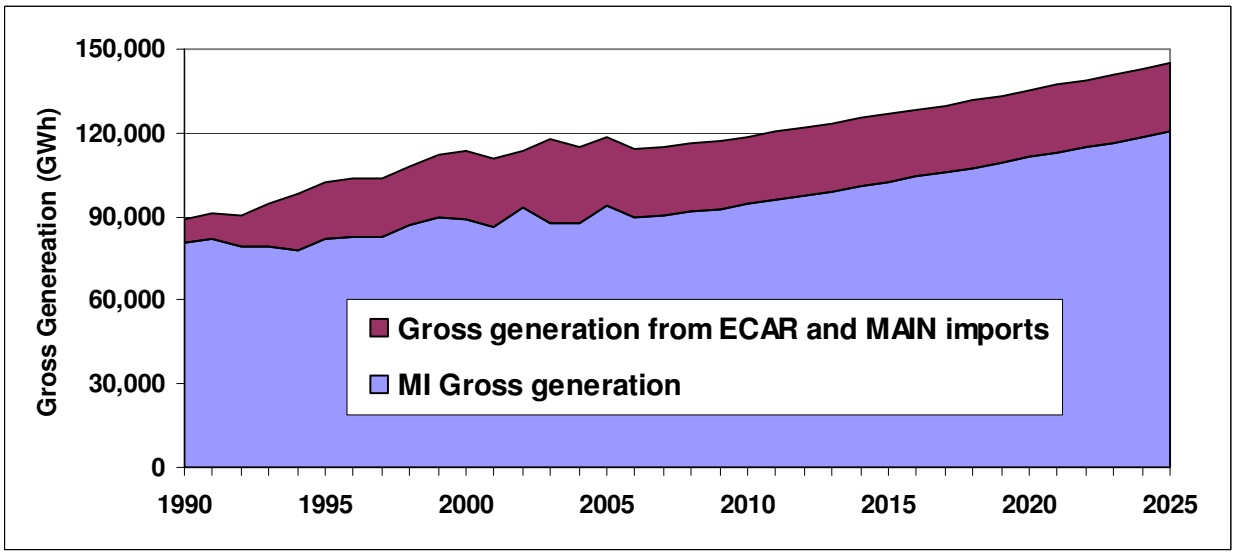
Figure A3. Gross Generation at Michigan Power Stations



Imported Electricity

To meet annual demand for electricity in Michigan, total gross generation by Michigan power plants needs to be augmented by electricity imports. As indicated earlier, it was assumed that this power is imported from the ECAR and MAIN regions. Figure A4 summarizes the gross generation within and beyond Michigan's border needed to satisfy electricity demand in Michigan.

Figure A4. Composition of Gross Generation to Meet Michigan's Electricity Demand



Source: Results in table based on approach described in text.

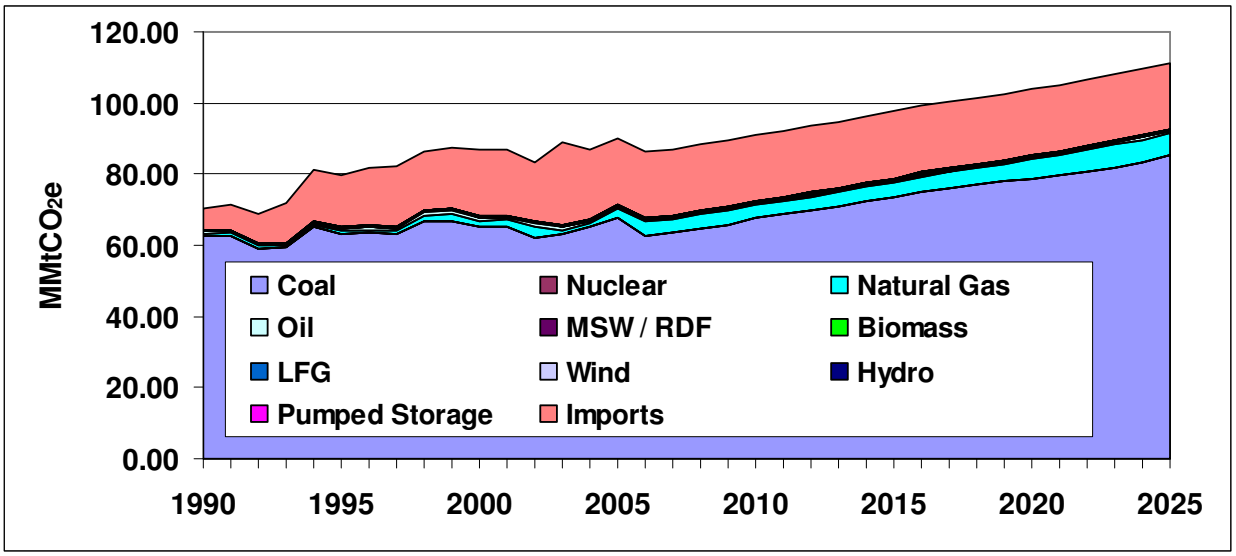
Total Gross GHG Emissions

Total emissions associated with generation by Michigan power plants as well as generation by power plants located outside Michigan to meet electricity demand within Michigan are summarized in Figure A5 by fuel type and in Figure A6 by type of plant. Figure A7 compares

emissions on a production (in-state generation) and consumption (in-state generation plus imports) basis. Figures A5, A6, and A7 were developed from the emissions data in Tables A3 and A4.

On a consumption basis, emissions were about 90.0 $MMtCO_2e$ in 2005 and are projected to increase to about 111.2 $MMtCO_2e$ in 2025, representing an overall increase of about 23.5% during this 20-year period. Michigan was a net importer of electricity since 1990 and is projected to continue to be a net importer of power through 2025.

Figure A5. Total Gross GHG Emissions Associated with MI Electric Demand by Fuel Type



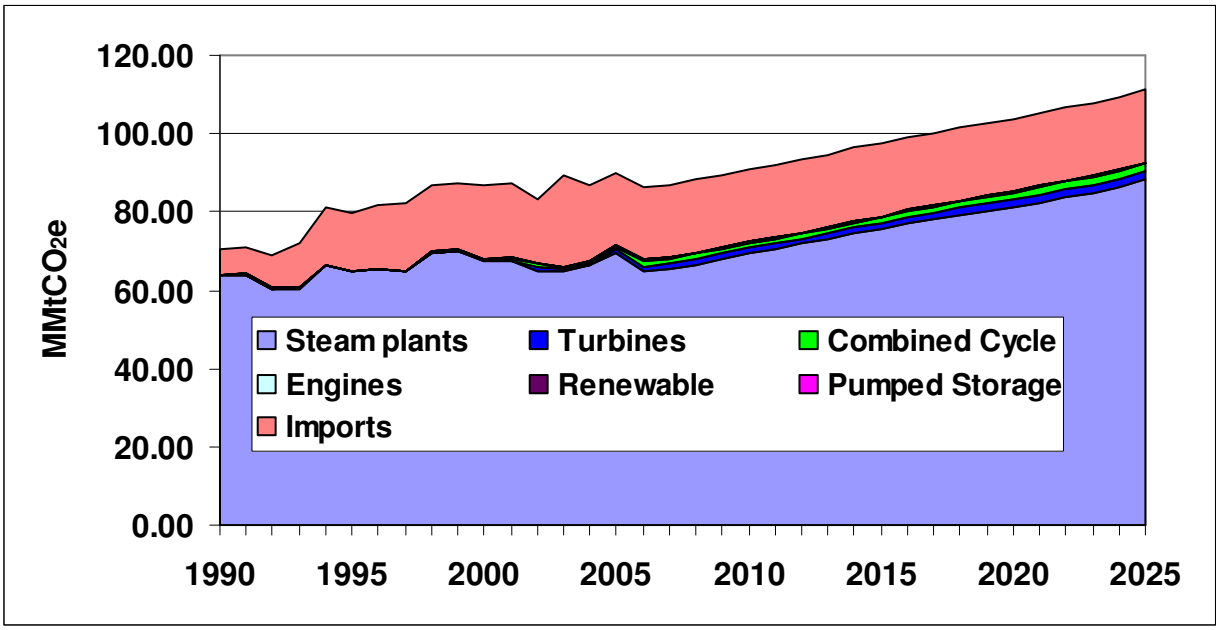
Source: Results in table based on approach described in text.
LFG = landfill gas, MSW = municipal solid waste, RDF = refuse-derived fuel.

Table A3. Total Gross GHG Emissions Associated with MI Electric Demand by Fuel Type ($MMtCO_2e$)

Fuel Type	1990	1995	2000	2005	2010	2015	2020	2025
Electricity - Consumption Based	**70.3**	**79.7**	**86.9**	**90.0**	**91.0**	**97.5**	**103.9**	**111.1**
Net Imported Electricity	6.2	14.6	18.8	18.6	18.7	18.7	18.6	18.5
Electricity - Production Based	**64.0**	**65.0**	**68.1**	**71.4**	**72.3**	**78.9**	**85.3**	**92.6**
Coal	62.8	63.1	64.9	67.7	67.6	73.5	78.8	85.3
Nuclear	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural Gas	0.46	0.83	1.77	2.38	3.67	4.34	5.40	6.06
Oil	0.66	0.67	0.99	0.71	0.48	0.41	0.48	0.57
MSW	0.07	0.18	0.21	0.16	0.19	0.19	0.21	0.22
Biomass	0.01	0.03	0.03	0.03	0.02	0.03	0.03	0.03
Landfill Gas (LFG)	0.07	0.17	0.20	0.34	0.39	0.41	0.44	0.46
Wind	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydroelectric	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pumped Storage	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Source: Results in table based on approach described in text.

Figure A6. Total Gross GHG Emissions with MI Electric Demand by Plant Type



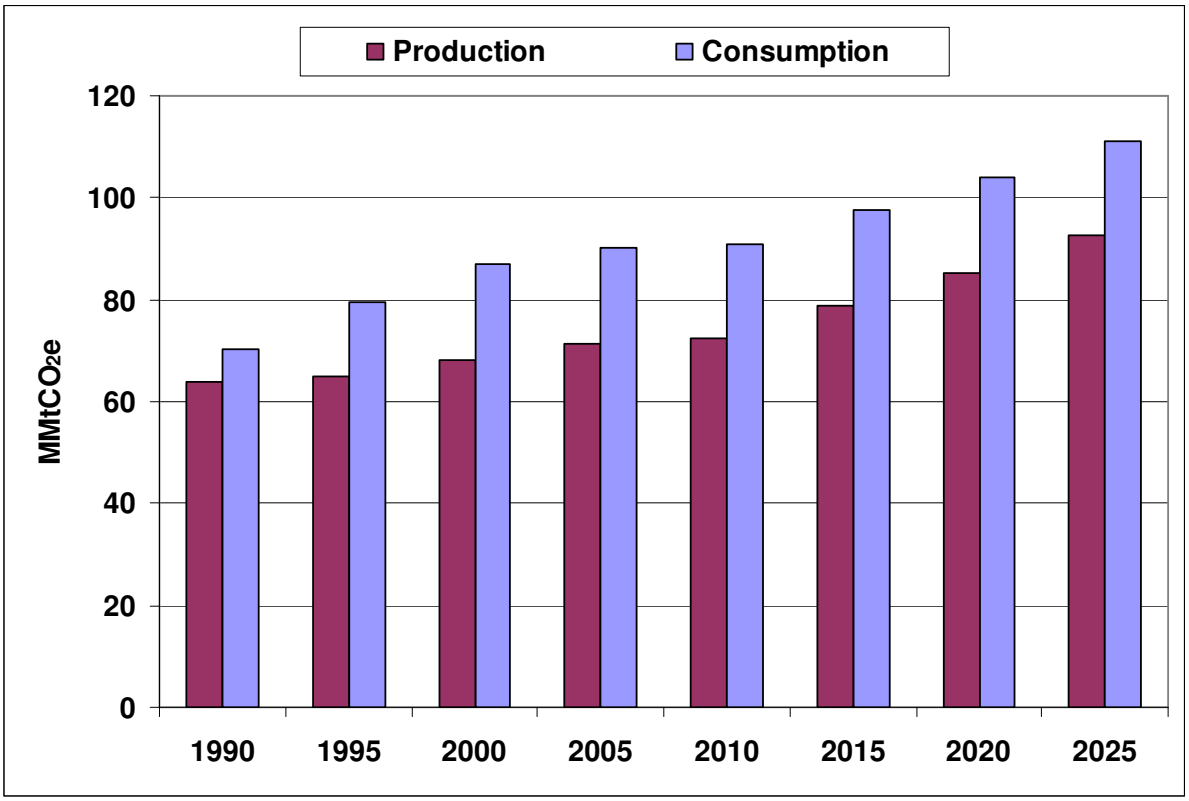
Source: Results in table based on approach described in text.

Table A4. Total Gross GHG Emissions Associated with MI Electric Demand by Plant Type ($MMtCO_2e$)

Plant Type	1990	1995	2000	2005	2010	2020	2015	2025
Electricity - Consumption Based	**70.3**	**79.7**	**86.9**	**90.0**	**91.0**	**97.5**	**103.9**	**111.1**
Net Imported Electricity	6.2	14.6	18.8	18.6	18.7	18.7	18.6	18.5
Electricity - Production Based	**64.0**	**65.0**	**68.1**	**71.4**	**72.3**	**78.9**	**85.3**	**92.6**
Steam plants[1]	63.8	64.7	67.6	69.4	69.5	75.6	81.4	88.2
Turbines[2]	0.04	0.11	0.30	0.86	1.28	1.49	1.85	2.08
Combined Cycle[3]	0.08	0.04	0.04	0.81	1.22	1.44	1.77	1.98
Engines[4]	0.08	0.17	0.17	0.26	0.30	0.31	0.34	0.36
Renewable[5]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pumped Storage	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[1] Fuels combusted by steam plants in Michigan include coal, natural gas, distillate (diesel) and residual oil, petroleum coke, landfill gas, municipal solid waste, tire-derived fuel, biomass, and nuclear.
[2] Fuels combusted by turbines in Michigan include natural gas, diesel, landfill gas, and waste oils/solvents.
[3] Fuels combusted by combined-cycle plants include natural gas, diesel, and landfill gas.
[4] Fuels combusted by internal combustion engines include natural gas, diesel, landfill gas, liquefied petroleum gas (LPG), and residual oil.
[5] Renewable fuels include wind, hydroelectric, and solar photovoltaic (PV).

Figure A7. Electricity Generation Gross GHG Emissions – Production and Consumption Basis (1990-2025)



Source: Results in table based on approach described in text.

Electricity consumption emissions are the sum of emissions associated with in-state electricity production and net imported electricity.

Key Uncertainties

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

- The methodologies used in this analysis rely on state-specific data on electricity generating units available from the EIA for the historical estimates of GHG emissions. The forecast relies primarily on EIA data available from the AEO2007 forecast for the ECAR and MAIN regions. The reference case projections do include forecasts of electric generation requirements available from *Michigan's 21st Century Electric Energy Plan.* Forecasts of GHG emissions associated with imported electricity are based on the assumption that the state will need to import the same amount of electricity from ECAR and MAIN regions in the forecast years as the average amount of the past five years (2001-2005). This approach is a top-down approach to estimating future emissions. Future work should focus on improving the forecast by compiling data that enable a bottom-up approach (unit-by-unit or contract basis) to estimating emissions for the electricity supply sector.
- Population and economic growth are the principal drivers for fuel use. The reference case projections are based on the estimates of electric generation requirements in *Michigan's*

21st Century Electric Energy Plan, which include the electric system losses (losses incurred in the transmission and distribution of electricity to retail customers). Electricity demand forecasts by the residential, commercial, and industrial sectors will help to refine the forecast for Michigan.

- Electricity on-site usage and transmission and distribution loss estimates were used to convert gross generation in the forecast to sales to meet the state demand. The estimated Michigan utility sales to the customers were less than estimates of electricity demand throughout the forecast period indicating that Michigan will need to import electricity to fulfill electricity demand that cannot be met by in-state generators. The on-site usage and transmission and distribution loss estimates are taken from the EIA AEO2007 for the ECAR and MAIN regions. Improvements to these estimates could help to get more accurate emissions associated with imported electricity.
- There are uncertainties associated with the statewide fuel mix, emission factors, and conversion factors (to convert electricity from a heat input basis to electricity output) that should be reviewed and revised with data that is specific to Michigan power generators.
- For combined heat and power facilities that generate and sell electricity to the power grid, emissions associated with the fuel they burn are included in the commercial and industrial fuel use sector (see Appendix B). The fuel use associated with these facilities is aggregated by fuel and sector and, therefore, cannot be broken out easily so that they can be reported under the electricity supply and use sector. Future work could include an assessment to determine how best to isolate emissions associated with combined heat and power facilities.
- Fuel price changes influence consumption levels and, to the extent that price trends for competing fuels differ, may encourage switching among fuels, and thereby affect emissions estimates. Although the effects of fuel price changes on the supply and demand of electricity are included in the EIA regional modeling used for this initial analysis, unanticipated events that affect fuel prices could affect the electricity forecast for Michigan.

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

Overview

Activities in the RCI[29] sectors produce carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions when fuels are combusted to provide space heating, water heating, process heating, cooking, and other energy end-uses. Carbon dioxide accounts for over 99% of these emissions on a million metric tons (MMt) of CO_2 equivalent (CO_2e) basis in Michigan. In addition, since these sectors consume electricity, one can also attribute emissions associated with electricity generation to these sectors in proportion to their electricity use.[30] Direct use of oil, natural gas, coal, and wood in the RCI sectors accounted for an estimated 59.9 $MMtCO_2e$ of gross greenhouse gas (GHG) emissions in 2005.[31]

Emissions and Reference Case Projections

Emissions from direct fuel use were estimated using the United States Environmental Protection Agency's (US EPA) State Greenhouse Gas Inventory Tool (SIT) software and the methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for RCI fossil and wood fuel combustion.[32] The default data used in SIT for Michigan are from the United States Department of Energy (US DOE) Energy Information Administration's (EIA) *State Energy Data* (SED). The SIT files were updated to include 2004 and 2005 SED information for Michigan for natural gas, petroleum, and coal for each of the RCI sectors and for residential and for wood for the commercial and industrial sectors.[33]

Note that the EIIP methods for the industrial sector exclude from CO_2 emission estimates the amount of carbon that is stored in products produced from fossil fuels for non-energy uses. For example, the methods account for carbon stored in petrochemical feedstocks, and in liquefied petroleum gases (LPG) and natural gas used as feedstocks by chemical manufacturing plants (i.e., not used as fuel), as well as carbon stored in asphalt and road oil produced from petroleum.

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[29] The industrial sector includes emissions associated with agricultural energy use and fuel used by natural gas transmission and distribution (T&D) and oil and gas production industries.

[30] Emissions associated with the electricity supply sector (presented in Appendix A) have been allocated to each of the RCI sectors for comparison of those emissions to the fuel-consumption-based emissions presented in Appendix B. Note that this comparison is provided for information purposes and that emissions estimated for the electricity supply sector are not double-counted in the total emissions for the state. One could similarly allocate GHG emissions from natural gas T&D, other fuels production, and transport-related GHG sources to the RCI sectors based on their direct use of gas and other fuels, but we have not done so here due to the difficulty of ascribing these emissions to particular end-users. Estimates of emissions associated with the transportation sector are provided in Appendix C, and estimates of emissions associated with natural gas T&D are provided in Appendix E.

[31] Emissions estimates from wood combustion include only N_2O and CH_4. Carbon dioxide emissions from biomass combustion are assumed to be "net zero", consistent with US EPA and Intergovernmental Panel on Climate Change (IPCC) methodologies, and any net loss of carbon stocks due to biomass fuel use should be accounted for in the land use and forestry analysis.

[32] GHG emissions were calculated using SIT, with reference to *EIIP, Volume VIII*: Chapter 1 "Methods for Estimating Carbon Dioxide Emissions from Combustion of Fossil Fuels", August 2004, and Chapter 2 "Methods for Estimating Methane and Nitrous Oxide Emissions from Stationary Combustion", August 2004.

[33] EIA *State Energy Data through 2005 (*http://www.eia.doe.gov/emeu/states/_seds_updates.html).

The carbon storage assumptions for these products are explained in detail in the EIIP guidance document.[34] The fossil fuel types for which the EIIP methods are applied in the SIT software to account for carbon storage include the following categories: asphalt and road oil, coking coal, distillate fuel, feedstocks (naphtha with a boiling range of less than 401 degrees Fahrenheit), feedstocks (other oils with boiling ranges greater than 401 degrees Fahrenheit), LPG, lubricants, miscellaneous petroleum products, natural gas, pentanes plus,[35] petroleum coke, residual fuel, still gas, and waxes. Data on annual consumption of the fuels in these categories as chemical industry feedstocks were obtained from the EIA SED.

Table B1 shows historical and projected growth rates for electricity sales by sector. For 2005 to 2025, the annual growth rate in the electricity sales for all of the RCI sectors combined is estimated to be 0.94%. The overall annual growth rate was developed from an annual growth rate of 1.29% obtained from data that Michigan utilities provided for gross electricity sales for 2006 through 2025.[36] The 0.94% annual growth rate is lower than the 1.29% annual growth rate for 2006 through 2025 in part because of differences in the time periods covered and in part because the 0.94% reflects only in-state generation minus losses associated with transmission and distribution of electricity and use of fuel to operate power plants. The proportion of each RCI sector's sales to total sales was used to allocate emissions associated with the electricity supply sector to each of the RCI sectors.

Table B2 shows historical and projected growth rates for energy use by sector and fuel type. Reference case emissions from direct fuel combustion were estimated based on fuel consumption forecasts from EIA's *Annual Energy Outlook 2007* (AEO2007).[37] For the RCI sectors, annual growth rates for natural gas, oil, wood, and coal were calculated from the AEO2007 regional forecast that EIA prepared for the East North Central modeling region. For the residential sector, the AEO2007 annual growth rate in fuel consumption from 2005 through 2025 was normalized using the AEO2007 population forecast and then weighted using Michigan's population forecast over this period. Michigan's rate of population growth is expected to average about 0.24% annually between 2005 and 2025.[38] Growth rates for the commercial and industrial sectors were based on the AEO2007 East North Central regional estimates of growth which reflect expected responses of the economy — as simulated by the EIA's National Energy Modeling System — to changing fuel and electricity prices and changing technologies, as well as to structural changes within each sector (such as shifts in subsectoral shares and in energy use patterns).

[34] EIIP, Volume VIII: Chapter 1 "Methods for Estimating Carbon Dioxide Emissions from Combustion of Fossil Fuels", August 2004.
[35] A mixture of hydrocarbons, mostly pentanes and heavier fractions, extracted from natural gas.
[36] See Appendix II, Table 15, page 101 of Michigan's *21st Century Electric Energy Plan* for gross electricity sales prepared by Michigan utilities (http://www.dleg.state.mi.us/mpsc/electric/capacity/energyplan/index.htm). Separate annual growth rates for each of the RCI sectors is not available.
[37] EIA AEO2007 with Projections to 2030 (http://www.eia.doe.gov/oiaf/archive.html#aeo).
[38] Michigan History, Arts, and Libraries (http://www.michigan.gov/hal/0,1607,7-160-17451_28388_28392---,00.html#STATE), Total Population and Percent Change, Michigan Counties: 1990 – 2000, "Population for Counties in Michigan: 1990 and 2000" (http://www.michigan.gov/documents/PopByCty_26001_7.pdf). Michigan projections (2006-2030) from "State Population Projections to 2030" (http://www.michigan.gov/hal/0,1607,7-160-17451_28388_28392-116118--,00.html).

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

Sector	1990-2005*	2005-2025**
Residential	2.4%	NA
Commercial	4.4%	NA
Industrial	-0.1%	NA
Total	**2.0%**	**0.94%**

* 1990-2005 compound annual growth rates calculated from Michigan electricity sales by year from EIA state electricity profiles (Table 8), http://www.eia.doe.gov/cneaf/electricity/st_profiles/e_profiles_sum.html.

** Sales by sector are not available. The overall annual growth rate was developed from an annual growth rate of 1.29% obtained from data that Michigan utilities provided for gross electricity sales for 2006 through 2025 (see Appendix II, Table 15, page 101 of the *21st Century Electric Energy Plan*). The 0.94% annual growth rate for 2005 through 2025 shown here is lower than the 1.29% annual growth rate for 2006 through 2025 in part because of differences in the time periods covered and in part because the 0.94% reflects only in-state generation minus losses associated with transmission and distribution of electricity and use of fuel to operate power plants.

Table B2. Historical and Projected Average Annual Growth in Energy Use in Michigan, by Sector and Fuel, 1990-2025

	1990-2005[a]	2005-2010[b]	2010-2015[b]	2015-2020[b]	2020-2025[b]
Residential					
natural gas	0.4%	0.5%	0.3%	-0.2%	-0.5%
petroleum	1.1%	0.03%	0.7%	0.2%	-0.1%
wood	-3.9%	1.0%	-1.4%	-0.3%	-0.6%
coal	-8.8%	-2.4%	-0.6%	-0.6%	-0.7%
Commercial					
natural gas	0.4%	0.5%	1.5%	0.8%	0.7%
petroleum	-1.0%	-0.1%	1.4%	0.3%	0.4%
wood	-0.6%	0.00%	0.00%	0.00%	0.00%
coal	-2.9%	0.00%	0.00%	0.00%	0.00%
Industrial					
natural gas	-2.0%	2.6%	1.0%	0.2%	0.6%
petroleum	-0.6%	-1.5%	0.1%	-0.1%	-0.2%
wood	-0.4%	2.2%	1.5%	1.1%	0.9%
coal	-6.1%	-4.4%	-0.9%	-0.8%	-0.4%

[a] Compound annual growth rates calculated from EIA SED historical consumption by sector and fuel type for Michigan. Latest year for which EIA SED information was available for each sector and fuel type is 2005. Petroleum includes distillate fuel, kerosene, and liquefied petroleum gases for all sectors plus residual oil for the commercial and industrial sectors.

[b] Figures for growth periods starting after 2005 are calculated from AEO2007 projections for EIA's East North Central region. Regional growth rates for the residential sector are adjusted for Michigan's projected population.

Results

Figures B1, B2, and B3 show historical and projected emissions for the RCI sectors in Michigan from 1990 through 2025. These figures show the emissions associated with the direct consumption of fossil fuels and, for comparison purposes, show the share of emissions associated with the generation of electricity consumed by each sector. During the period from

1990 through 2025, the residential sector's share of total RCI emissions from direct fuel use and electricity was 32% in 1990, increased to 35% in 2005, and is projected to remain constant at 35% in 2025. The commercial sector's share of total RCI emissions from direct fuel use and electricity use was 21% in 1990, increased to 29% in 2005, and is projected to increase slightly to 30% by 2025. The industrial sector's share of total RCI emissions from direct fuel use and electricity use was 47% in 1990, decreased to 36% in 2005, and is projected to decrease slightly to 35% in 2025. Emissions associated with the generation of electricity to meet RCI demand accounts for about 55% of the emissions for the residential sector, 72% of the emissions for the commercial sector, and 52% of the emissions for the industrial sector, on average, over the 1990 to 2025 time period. From 1990 to 2025, natural gas consumption is the next highest source of emissions for the residential and commercial sectors, accounting, on average, for about 38% and 24% of total emissions, respectively. For the industrial sector, emissions associated with the combustion of coal, natural gas, and petroleum account for about 13%, 23%, and 12% respectively, on average, from 1990 to 2025.

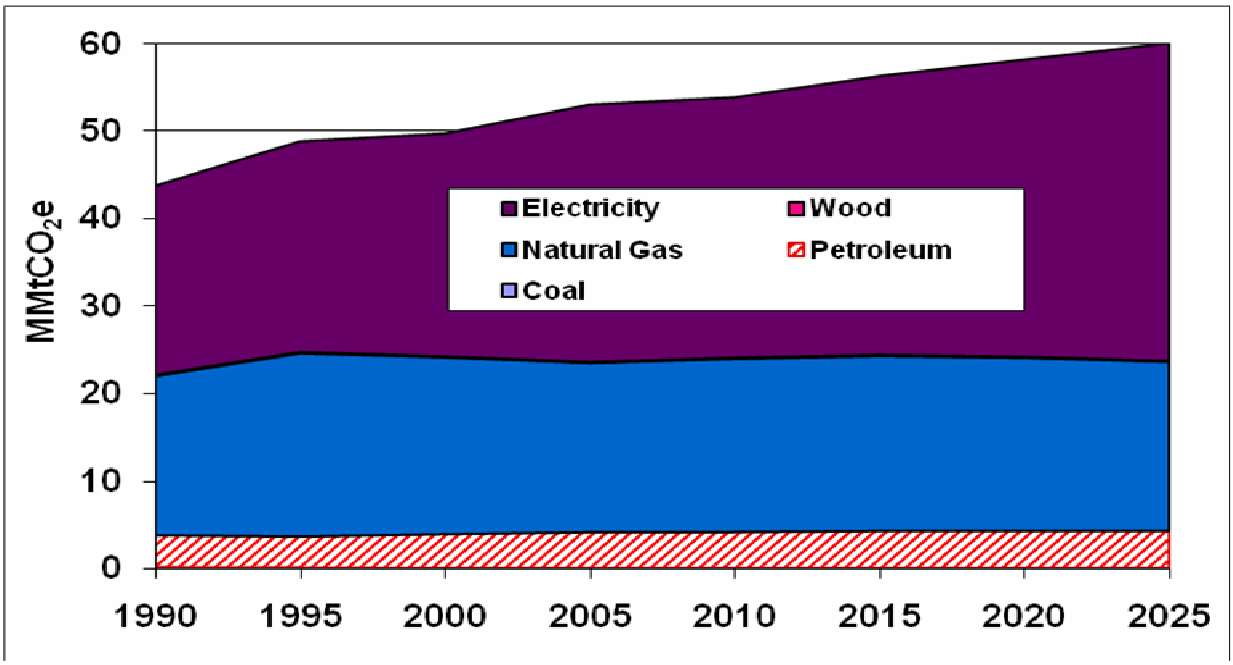
Residential Sector

Figure B1 presents the emission inventory and reference case projections for the residential sector. Figure B1 was developed from the emissions data in Table B3a. Table B3b shows the relative contributions of emissions associated with each fuel type to total residential sector emissions.

For the residential sector, emissions from electricity and direct fossil fuel use in 1990 were about 44 $MMtCO_2e$, and are estimated to increase to about 60 $MMtCO_2e$ by 2025. Emissions associated with the generation of electricity to meet residential energy consumption demand accounted for about 49% of total residential emissions in 1990, and are estimated to increase to 61% of total residential emissions by 2025. In 1990, natural gas consumption accounted for about 42% of total residential emissions, and is estimated to account for about 32% of total residential emissions by 2025. Residential-sector emissions associated with the use of coal, petroleum, and wood in 1990 were about 4.0 $MMtCO_2e$ combined, and accounted for about 9% of total residential emissions. By 2025, emissions associated with the consumption of these three fuels are estimated to increase slightly to 4.4 $MMtCO_2e$, accounting for 7% of total residential sector emissions by that year.

For the 20-year period 2005 to 2025, residential-sector GHG emissions associated with the use of electricity, and petroleum are expected to increase at average annual rates of about 1.1%and 0.2% respectively. Emissions associated with the use of natural gas, coal, and wood are expected to decline annually by about -0.01%, -1.0% and -0.4%, respectively. Total GHG emissions for this sector increase by an average of about 0.6% annually over the 20-year period.

Figure B1. Residential Sector GHG Emissions from Fuel Consumption



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

Table B3a. Residential Sector Emissions Inventory and Reference Case Projections ($MMtCO_2e$)

Fuel Type	1990	1995	2000	2005	2010	2015	2020	2025
Coal	0.13	0.08	0.00	0.03	0.03	0.03	0.03	0.03
Petroleum	3.67	3.57	3.93	4.12	4.15	4.28	4.31	4.30
Natural Gas	18.17	21.01	20.25	19.36	19.82	20.02	19.79	19.32
Wood	0.20	0.11	0.07	0.11	0.11	0.10	0.10	0.10
Electricity Consumption	21.60	24.08	25.48	29.42	29.75	31.87	33.95	36.32
Total	43.76	48.85	49.73	53.05	53.86	56.30	58.18	60.07

Source: CCS calculations based on approach described in text.

Table B3b. Residential Sector Proportions of Total Emissions by Fuel Type (%)

Fuel Type	1990	1995	2000	2005	2010	2015	2020	2025
Coal	0.3	0.2	0.0	0.1	0.1	0.1	0.0	0.0
Petroleum	8.4	7.3	7.9	7.8	7.7	7.6	7.4	7.2
Natural Gas	41.5	43.0	40.7	36.5	36.8	35.6	34.0	32.2
Wood	0.4	0.2	0.1	0.2	0.2	0.2	0.2	0.2
Electricity Consumption	49.4	49.3	51.2	55.5	55.2	56.6	58.3	60.5

Source: CCS calculations based on approach described in text.
Note: The percentages shown in this table reflect the emissions for each fuel type as a percentage of total emissions shown in Table B3a.

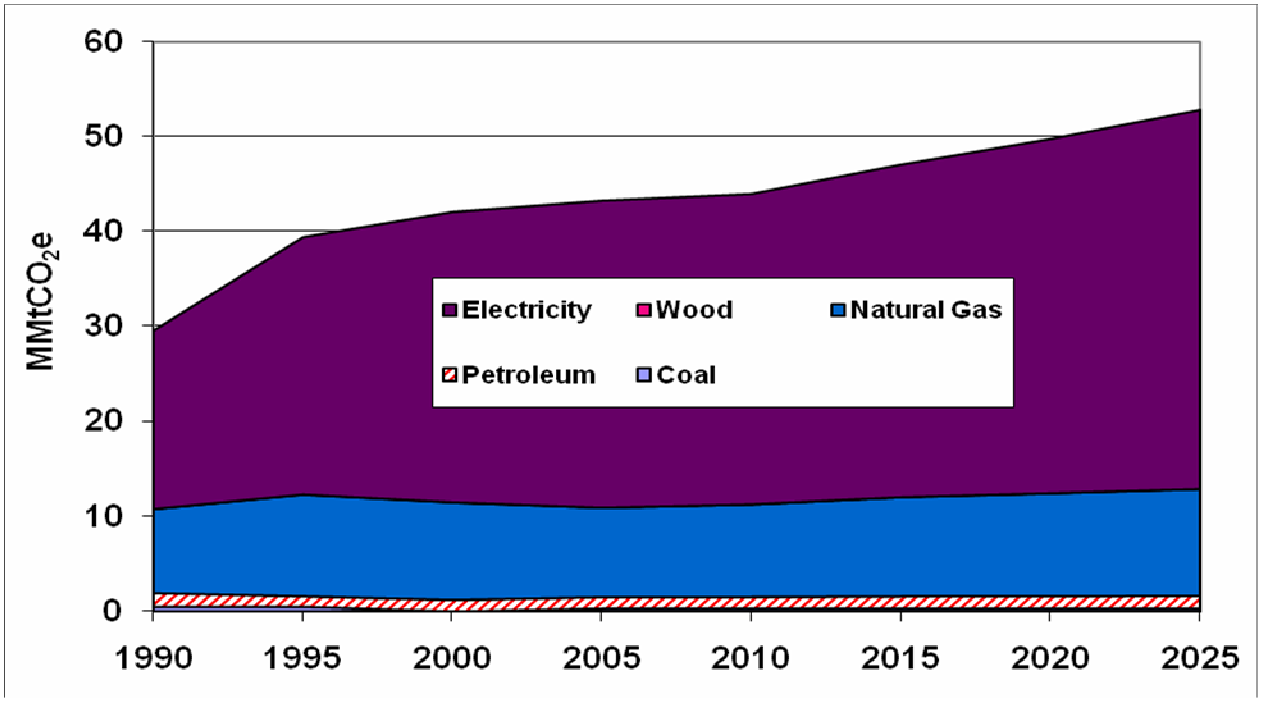
Commercial Sector

Figure B2 presents the emission inventory and reference case projections for the commercial sector. Figure B2 was developed from the emissions data in Table B4a. Table B4b show the relative contributions of emissions associated with each fuel type to total commercial sector emissions.

For the commercial sector, emissions from electricity and direct fossil fuel use in 1990 were about 30 $MMtCO_2e$, and are estimated to increase to about 53 $MMtCO_2e$ by 2025. Emissions associated with the generation of electricity to meet commercial energy consumption demand accounted for about 63% of total commercial emissions in 1990, and are estimated to increase to 75% of total commercial emissions by 2025. In 1990, natural gas consumption accounted for about 30% of total commercial emissions and is estimated to account for about 21% of total commercial emissions by 2025. Commercial-sector emissions associated with the use of coal, petroleum, and wood in 1990 were about 2.0 $MMtCO_2e$ combined, and accounted for about 6.7% of total commercial emissions. By 2025, emissions associated with the consumption of these three fuels are estimated to be 1.7 $MMtCO_2e$ and to account for 3.2% of total commercial sector emissions.

For the 20-year period 2005 to 2025, commercial-sector GHG emissions associated with the use of electricity, natural gas, and petroleum are expected to increase at average annual rates of about 1.1%, 0.9%, and 0.5% respectively. Emissions associated with the use of coal and wood are not expected to change relative to 2005. Total GHG emissions for this sector increase by an average of about 1.0% annually over the 20-year period.

Figure B2. Commercial Sector GHG Emissions from Fuel Consumption



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

Table B4a. Commercial Sector Emissions Inventory and Reference Case Projections ($MMtCO_2e$)

Fuel Type	1990	1995	2000	2005	2010	2015	2020	2025
Coal	0.50	0.51	0.03	0.32	0.32	0.32	0.32	0.32
Petroleum	1.46	1.10	1.20	1.20	1.21	1.28	1.30	1.33
Natural Gas	8.85	10.73	10.29	9.43	9.77	10.45	10.85	11.27
Wood	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02
Electricity Consumption	18.76	27.06	30.53	32.28	32.64	34.97	37.25	39.86
Total	29.58	39.41	42.06	43.25	43.96	47.04	49.73	52.79

Source: CCS calculations based on approach described in text.

Table B4b. Commercial Sector Proportions of Total Emissions by Fuel Type (%)

Fuel Type	1990	1995	2000	2005	2010	2015	2020	2025
Coal	1.7	1.3	0.1	0.7	0.7	0.7	0.6	0.6
Petroleum	4.9	2.8	2.8	2.8	2.8	2.7	2.6	2.5
Natural Gas	29.9	27.2	24.5	21.8	22.2	22.2	21.8	21.3
Wood	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electricity Consumption	63.4	68.7	72.6	74.6	74.3	74.3	74.9	75.5

Source: CCS calculations based on approach described in text.
Note: The percentages shown in this table reflect the emissions for each fuel type as a percentage of total emissions shown in Table B4a.

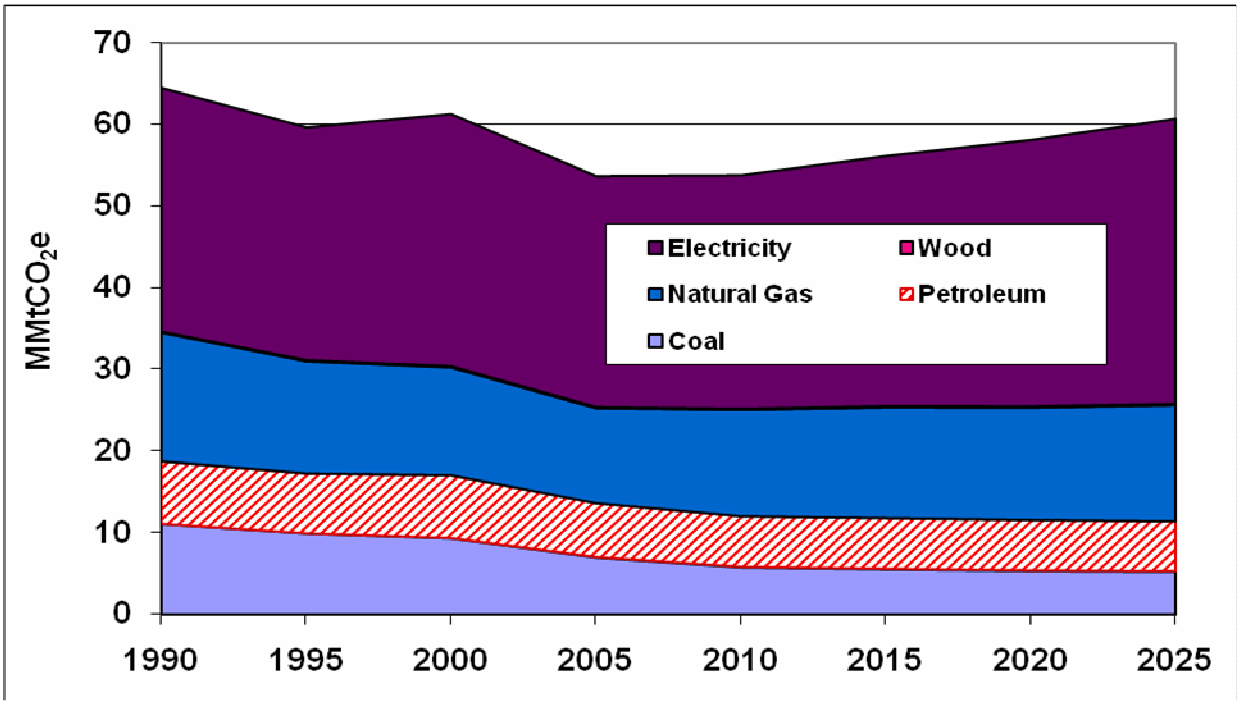
Industrial Sector

Figure B3 presents the emission inventory and reference case projections for the industrial sector. Figure B3 was developed from the emissions data in Table B5a. Table B5b show the relative contributions of emissions associated with each fuel type to total industrial sector emissions.

For the industrial sector, emissions from electricity and direct fuel use in 1990 were about 64 $MMtCO_2e$ and are estimated to decline to about 61 $MMtCO_2e$ by 2025. Emissions associated with the generation of electricity to meet industrial energy consumption demand accounted for about 46% of total industrial emissions in 1990, and are estimated to increase to about 58% of total industrial emissions by 2025. In 1990, natural gas consumption accounted for about 24% of total industrial emissions, and is estimated to decrease slightly to 23% of total industrial emissions by 2025. Coal consumption accounted for about 17% of total industrial emissions in 1990, and is estimated to decline to about 9% of total industrial emissions by 2025. In 1990, petroleum consumption accounted for about 12% of total industrial emissions, and is estimated to decline slightly to about 10% of total industrial emissions by 2025. Emissions associated with wood consumption by the industrial sector are about 0.1% of total emissions from 1990 through 2025.

For the 20-year period 2005 to 2025, industrial-sector GHG emissions associated with the use of electricity, natural gas, and wood are expected to increase at average annual rates of about 1.1%, 1.0%, and 1.4% respectively. Emissions associated with the use of petroleum and coal are expected to decrease annually by about -0.4% and -1.4%, respectively. Total GHG emissions for the industrial sector increase by an average of about 0.6% annually over the 20-year period.

Figure B3. Industrial Sector GHG Emissions from Fuel Consumption



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

Table B5a. Industrial Sector Emissions Inventory and Reference Case Projections ($MMtCO_2e$)

Fuel Type	1990	1995	2000	2005	2010	2015	2020	2025
Coal	11.05	9.90	9.30	6.97	5.77	5.52	5.33	5.21
Petroleum	7.69	7.36	7.73	6.67	6.27	6.30	6.25	6.21
Natural Gas	15.75	13.75	13.21	11.62	12.99	13.55	13.75	14.21
Wood	0.06	0.08	0.09	0.06	0.07	0.07	0.08	0.08
Electricity Consumption	29.91	28.54	30.92	28.32	28.64	30.68	32.68	34.97
Total	64.47	59.62	61.26	53.64	53.74	56.11	58.08	60.68

Source: CCS calculations based on approach described in text.

Table B5b. Industrial Sector Proportions of Total Emissions by Fuel Type (%)

Fuel Type	1990	1995	2000	2005	2010	2015	2020	2025
Coal	17.1	16.6	15.2	13.0	10.7	9.8	9.2	8.6
Petroleum	11.9	12.3	12.6	12.4	11.7	11.2	10.8	10.2
Natural Gas	24.4	23.1	21.6	21.7	24.2	24.1	23.7	23.4
Wood	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Electricity Consumption	46.4	47.9	50.5	52.8	53.3	54.7	56.3	57.6

Source: CCS calculations based on approach described in text.
Note: The percentages shown in this table reflect the emissions for each fuel type as a percentage of total emissions shown in Table B5a.

Key Uncertainties

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

- Population and economic growth are the principal drivers for electricity and fuel use. The reference case projections are based on regional fuel consumption projections for EIA's East North Central modeling region. Consequently, there are significant uncertainties associated with the projections. Future work should attempt to base projections of GHG emissions on fuel consumption estimates specific to Michigan to the extent that such data become available.
- The AEO2007 projections assume no large long-term changes in relative fuel and electricity prices, relative to current price levels and to US DOE projections for fuel prices. Price changes would influence consumption levels and, to the extent that price trends for competing fuels differ, may encourage switching among fuels, and thereby affect emissions estimates.

Appendix C. Transportation Energy Use

Overview

Transportation is one the largest GHG source sectors in Michigan. The transportation sector includes light- and heavy-duty (onroad) vehicles, aircraft, rail engines, and marine engines. Carbon dioxide (CO_2) accounts for about 97% of the transportation sector's GHG emissions in 1990 and is projected to increase to about 98% of transportation GHG emissions by 2025. Most of the remaining GHG emissions from the transportation sector are due to nitrous oxide (N_2O) emissions from gasoline engines.

Historical Emissions and Reference Case Projections

Historical GHG emissions were estimated using the United States Environmental Protection Agency's (US EPA) State Greenhouse Gas Inventory Tool (SIT) software and the methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for the sector.[39,40] For onroad vehicles, the CO_2 emission factors are in units of pounds (lb) per million British thermal unit (MMBtu) and the methane (CH_4) and N_2O emission factors are both in units of grams per vehicle mile traveled (VMT). Key assumptions in this analysis are listed in Table C1. The default fuel consumption data within SIT were used to estimate emissions, with the most recently available fuel consumption data (2004) from the United States Department of Energy (US DOE) Energy Information Administration's (EIA) *State Energy Data* (SED) added.[41] The default VMT data in SIT were replaced with annual VMT from the Michigan Department of Transportation (MDOT).[42] Default data from the Federal Highway Administration (FHWA)[43] were used to allocate the VMT by vehicle type in the State.

Onroad Vehicles

MDOT provided statewide VMT data for the years from 1994 through 2005.[44] These data were used to replace the default SIT VMT data for 1994 through 2005 for calculating CH_4 and N_2O emissions. These VMT data were distributed by vehicle type in the same proportion as the default VMT data in the SIT. The default SIT VMT data were used for the years from 1990 through 1993. The default EIA SED data were used to calculate the CO_2 emissions from onroad vehicles for the historical years. Gasoline consumption estimates for 1990-2004 were adjusted by subtracting ethanol consumption, per the methodology used in SIT. The historical EIA ethanol consumption data show that use of ethanol in Michigan began in 1990 and increased in a general trend up to 2004, with ethanol consumption ranging from about 0.32% to 2.3% of the gasoline

[39] CO_2 emissions were calculated using SIT, with reference to Emission Inventory Improvement Program, Volume VIII: Chapter. 1. "Methods for Estimating Carbon Dioxide Emissions from Combustion of Fossil Fuels", August 2004.
[40] CH_4 and N_2O emissions were calculated using SIT, with reference to Emission Inventory Improvement Program, Volume VIII: Chapter. 3. "Methods for Estimating Methane and Nitrous Oxide Emissions from Mobile Combustion", August 2004.
[41] Energy Information Administration, State Energy Consumption, Price, and Expenditure Estimates (SED), http://www.eia.doe.gov/emeu/states/_seds.html
[42] Michigan historical VMT data (1994-2006) provided by Donald Howe, Michigan Department of Transportation.
[43] Highway Statistics, Federal Highway Administration, http://www.fhwa.dot.gov/policy/ohpi/hss/index.htm.
[44] Michigan historical VMT data (1994-2006) provided by Donald Howe, Michigan Department of Transportation.

consumption on a Btu basis. For the reference case projections, ethanol consumption was assumed to remain at the 2004 level (2.3% of gasoline consumption on Btu basis).

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

Vehicle Type and Pollutants	Methods
Onroad gasoline, diesel, natural gas, and liquefied petroleum gas (LPG) vehicles – CO_2	**Inventory (1990-2004)** US EPA SIT and fuel consumption from EIA SED **Reference Case Projections (2005-2025)** Gasoline and diesel fuel use projected using Michigan Department of Transportation (MDOT) VMT projections adjusted by fuel efficiency improvement projections from AEO2007. Other onroad fuels projected using East North Central Region fuel consumption projections from EIA AEO2007 adjusted using state-to-regional ratio of population growth.
Onroad gasoline and diesel vehicles – CH_4 and N_2O	**Inventory (1990-2005)** US EPA SIT, onroad vehicle CH_4 and N_2O emission factors by vehicle type and technology type within SIT were updated to the latest factors used in the US EPA's *Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2005.* State total VMT replaced with VMT provided by MDOT, VMT allocated by vehicle type using default data in SIT. **Reference Case Projections (2006-2025)** State total VMT projections provided by MDOT and allocated to vehicle types using vehicle specific growth rates from AEO2007.
Non-highway fuel consumption (jet aircraft, gasoline-fueled piston aircraft, boats, locomotives) – CO_2, CH_4 and N_2O	**Inventory (1990-2004)** US EPA SIT and fuel consumption from EIA SED. Commercial marine based on allocation of national fuel consumption. **Reference Case Projections (2005-2025)** Aircraft projected using aircraft operations projections from Federal Aviation Administration (FAA). No growth assumed for rail diesel. Marine gasoline projected based on historical data.

Onroad vehicle gasoline and diesel emissions were projected based on statewide VMT growth rates developed from projected VMT data provided by MDOT.[45] MDOT provided projected statewide VMT for 2005-, 2010, -2015, 2020, and 2025.. From these MDOT VMT projections, CCS calculated the average annual VMT growth rates for the 2005-1010, 2010-2015, 2015-2020, and 2020-2025 time periods. Historical VMT data were used in all years prior to 2006. The resulting total annual VMT data were then allocated by vehicle type based on national VMT forecasts by vehicle type reported in EIA's *Annual Energy Outlook 2007* (AEO2007).[46] The AEO2007 data were incorporated because they indicate significantly different VMT growth rates for certain vehicle types (e.g., 56% growth between 2004 and 2025 in heavy-duty gasoline vehicle VMT versus 180% growth in light-duty diesel truck VMT over this period). The AEO2007 vehicle type-based national growth rates were applied to the 2005 Michigan estimates of VMT by vehicle type. These VMT data were then proportionally adjusted to total to the MDOT-based projected statewide VMT totals for each year. The resulting vehicle-type VMT estimates and compound annual average growth rates are displayed in Tables C2 and C3, respectively. These VMT growth rates were used to forecast the CH_4 and N_2O emissions from onroad gasoline and diesel vehicles. These VMT growth rates were also applied to natural gas vehicles.

For forecasting CO_2 emissions, growth in fuel consumption is needed. Onroad gasoline and diesel fuel consumption were forecasted by developing a set of growth factors that adjusted the VMT projections shown in Table C2 to account for improvements in vehicle fuel efficiency. Projected vehicle fuel efficiency data were obtained from AEO2007. The resulting onroad fuel consumption growth rates are shown in Table C4. Growth rates for projecting CO_2 emissions from natural gas vehicles, lubricants, and other fuel consumption were calculated by allocating the AEO2007 consumption of these fuels in the East North Central region and allocating this to Michigan based on the ratio of the State's projected population to the region's projected population.

The federal Energy Independence and Security Act (EISA) of 2007 was signed into law in December 2007. The Corporate Average Fuel Economy (CAFE) requirements will mandate that vehicle fleets will become more efficient overall. Reductions from this new legislation are shown in the Recent Actions section of this report.

Table C2. Michigan Vehicle Miles Traveled Estimates (millions)

Vehicle Type	2005	2010	2015	2020	2025
Heavy-Duty Diesel Vehicle	6,901	7,719	8,170	8,575	8,980
Heavy -Duty Gasoline Vehicle	1,019	999	989	1,005	1,038
Light-Duty Diesel Truck	1,044	1,239	1,473	1,827	2,393
Light-Duty Diesel Vehicle	313	372	443	549	719
Light-Duty Gasoline Truck	34,696	35,588	35,730	36,050	36,173
Light-Duty Gasoline Vehicle	58,834	60,346	60,586	61,129	61,338

[45] Projected Michigan VMT growth rates come from the Polly Kent at Michigan Department of Transportation, August 22, 2008. The revisions were approved by the MCAC on September 12, 2008.
[46] US Department of Energy, Energy Information Administration, *Annual Energy Outlook 2007 with Projections to 2030,* DOE/EIA-0383(2007), February 2007, available at http://www.eia.doe.gov/oiaf/aeo/index.html.

Motorcycle	352	361	363	366	367
Total	103,159	106,624	107,754	109,500	111,008

Table C3. Michigan Vehicle Miles Traveled Compound Annual Growth Rates

Vehicle Type	2005-2010	2010-2015	2015-2020	2020-2025
Heavy-Duty Diesel Vehicle	2.27	1.14	0.97	0.93
Heavy-Duty Gasoline Vehicle	-0.39	-0.20	0.32	0.65
Light-Duty Diesel Truck	3.50	3.52	4.39	5.55
Light-Duty Diesel Vehicle	3.50	3.52	4.39	5.55
Light-Duty Gasoline Truck	0.51	0.08	0.18	0.07
Light-Duty Gasoline Vehicle	0.51	0.08	0.18	0.07
Motorcycle	0.51	0.08	0.18	0.07

Table C4. Michigan Onroad Fuel Consumption Compound Annual Growth Rates

Fuel Growth Factors	2005-2010	2010-2015	2015-2020	2020-2025
Onroad gasoline	1.01%	0.20%	0.10%	0.08%
Onroad diesel	2.09%	1.33%	1.21%	1.33%

Aviation

For the aircraft sector, emission estimates for 1990 to 2004 are based on SIT methods and fuel consumption from EIA. Emissions were projected from 2005 to 2025 using general aviation and commercial aircraft operations for 2005 and 2025 from the Federal Aviation Administration's (FAA) Terminal Area Forecast System[47] and national aircraft fuel efficiency forecasts. To estimate changes in jet fuel consumption, itinerant aircraft operations from air carrier, air taxi/commuter, and military aircraft were first summed for each year of interest. The post-2004 estimates were adjusted to reflect the projected increase in national aircraft fuel efficiency (indicated by increased number of seat miles per gallon), as reported in AEO2007. Because AEO2007 does not estimate fuel efficiency changes for general aviation aircraft, forecast changes in aviation gasoline consumption were based solely on the projected number of itinerant general aviation aircraft operations in Michigan, which was obtained from the FAA source noted above. The resulting compound annual average growth rates are displayed in Table C5.

Table C5. Michigan Aviation Fuels Compound Annual Growth Rates

Fuel	2005-2010	2010-2015	2015-2020	2020-2025
Aviation Gasoline	0.66%	1.19%	0.86%	0.86%
Jet Fuel	-1.02%	0.36%	0.25%	0.19%

Rail and Marine Vehicles

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

For the rail and recreational marine sectors, 1990-2004 estimates are based on SIT methods and fuel consumption from EIA. Marine gasoline consumption was projected to 2025 based on a linear regression of the 1990 through 2004 historical data. The historical data for rail shows no significant positive or negative trend; therefore, no growth was assumed for this sector.

For the commercial marine sector (marine diesel and residual fuel), 1990-2004 emission estimates are based on SIT emission rates applied to estimates of Michigan marine vessel diesel and residual fuel consumption. Because the SIT default relies on marine vessel fuel consumption estimates that represent the State in which fuel is sold rather than consumed, an alternative method was used to estimate Michigan marine vessel fuel consumption. Michigan fuel consumption estimates were developed by allocating 1990-2004 national diesel and residual oil vessel bunkering fuel consumption estimates obtained from EIA.[48] Marine vessel fuel consumption was allocated to Michigan using the marine vessel activity allocation methods/data compiled to support the development of EPA's National Emissions Inventory (NEI).[49] In keeping with the NEI, 75% of each year's distillate fuel and 25% of each year's residual fuel were assumed to be consumed within the port area (remaining consumption was assumed to occur while ships are underway). National port area fuel consumption was allocated to Michigan based on year-specific freight tonnage data by state as reported in "Waterborne Commerce of the United States, Part 5 – Waterways and Harbors National Summaries."[50]

Nonroad Engines

It should be noted that fuel consumption data from EIA includes nonroad gasoline and diesel fuel consumption in the commercial and industrial sectors. Emissions from these nonroad engines, including nonroad vehicles such as snowmobiles and dirt bikes, are included in the inventory and forecast for the residential, commercial, and industrial (RCI) sectors. Table C6 shows how EIA divides gasoline and diesel fuel consumption between the transportation, commercial, and industrial sectors.

Table C6. EIA Classification of Gasoline and Diesel Consumption

Sector	Gasoline Consumption	Diesel Consumption
Transportation	Highway vehicles, marine	Vessel bunkering, military use, railroad, highway vehicles
Commercial	Public non-highway, miscellaneous use	Commercial use for space heating, water heating, and cooking
Industrial	Agricultural use, construction, industrial and commercial use	Industrial use, agricultural use, oil company use, off-highway vehicles

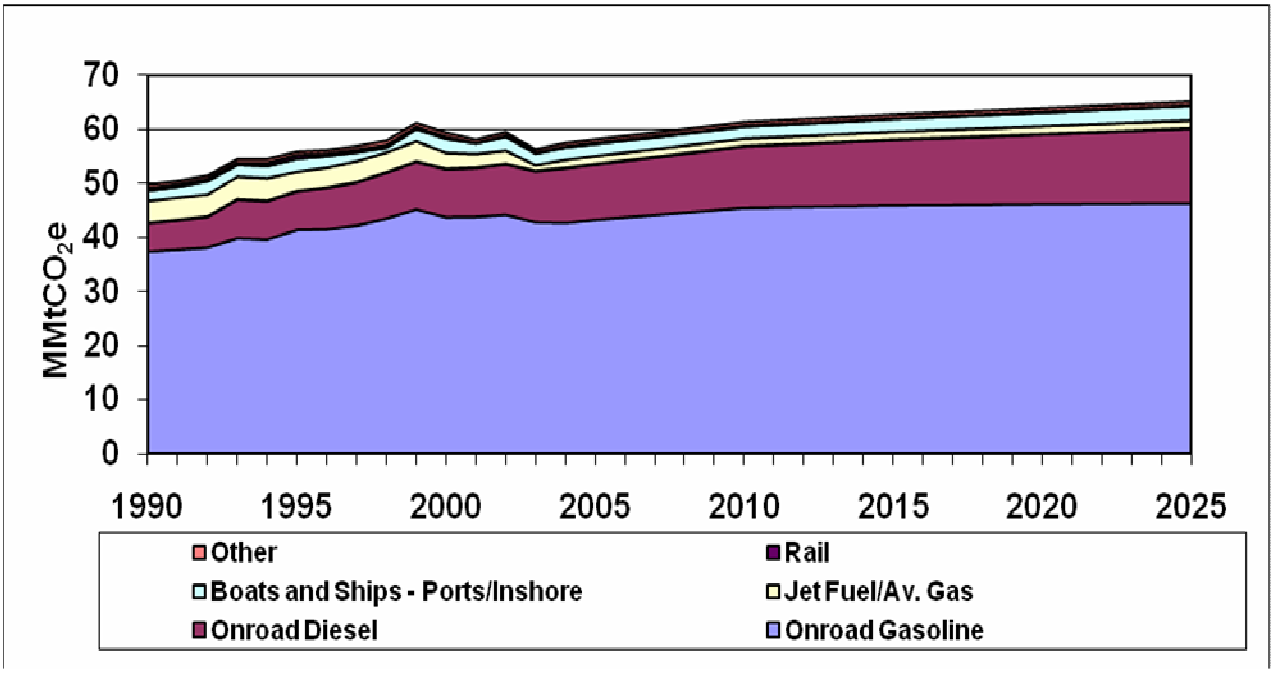
Results

[48] US Department of Energy, Energy Information Administration, "Petroleum Navigator" (diesel data obtained from http://tonto.eia.doe.gov/dnav/pet/hist/kd0vabnus1a.htm; residual data obtained from http://tonto.eia.doe.gov/dnav/pet/hist/kprvatnus1a.htm).
[49] See methods described in ftp://ftp.epa.gov/EmisInventory/2002finalnei/documentation/mobile/2002nei_mobile_nonroad_methods.pdf
[50] Note that it was necessary to estimate 1990-1996 values by applying the available 1997 MI percentage of national waterborne tonnage.

As shown in Figure C1 and in Table C7, onroad gasoline consumption accounts for the largest share of transportation GHG emissions. Emissions from onroad gasoline vehicles increased by about 16% from 1990 to 2005, accounting for 74% of total transportation emissions in 2005. GHG emissions from onroad diesel fuel consumption increased by 96% from 1990 to 2005, and by 2005 accounted for 18% of GHG emissions from the transportation sector. Emissions from boats and ships increased by 20% from 1990 to 2005 to account for 4% of transportation emissions in 2005. Emissions from all other categories combined (aviation, locomotives, natural gas and liquefied petroleum gas (LPG), and oxidation of lubricants) contributed to about 4% of total transportation emissions in 2005.

GHG emissions from onroad gasoline consumption are projected to increase by about 7%, and emissions from onroad diesel consumption are expected to increase by 34% between 2005 and 2025. The historical negative emissions growth for aviation is projected to continue, with emissions decreasing by 1% from 2005 to 2025, while marine emissions are projected to increase by 20% from 2005 to 2025.

Figure C1. Transportation Gross GHG Emissions by Fuel, 1990-2025



Source: CCS calculations based on approach described in text.

Table C7. Gross GHG Emissions from Transportation ($MMtCO_2e$)

Source	1990	1995	2000	2005	2010	2015	2020	2025
Onroad Gasoline	37.39	41.40	43.72	43.26	45.47	45.92	46.16	46.35
Onroad Diesel	5.21	7.09	8.90	10.23	11.35	12.11	12.87	13.75
Jet Fuel/Av. Gas	4.15	3.66	3.00	1.52	1.45	1.48	1.50	1.51
Boats and Ships - Ports/Inshore	1.87	2.41	2.61	2.25	2.18	2.35	2.52	2.70
Rail	0.41	0.64	0.45	0.25	0.25	0.25	0.25	0.25
Other	0.69	0.65	0.71	0.66	0.69	0.70	0.70	0.70

Total	**49.72**	**55.85**	**59.39**	**58.17**	**61.38**	**62.80**	**63.99**	**65.26**

Key Uncertainties

Uncertainties in Onroad Fuel Consumption

A major uncertainty in this analysis is the conversion of the projected VMT to fuel consumption. These are based on first allocating Michigan's total VMT by vehicle type using national vehicle type growth projections from AEO2007 modeling, which may not reflect Michigan conditions. The conversion of the VMT data to fuel consumption also includes national assumptions regarding fuel economy by vehicle type.

Uncertainties in Aviation Fuel Consumption

The jet fuel and aviation gasoline fuel consumption from EIA is actually fuel *purchased* in the State, and therefore, includes fuel consumed during state-to-state flights and international flights. The fuel consumption associated with international air flights should not be included in the State inventory; however, data were not available to subtract this consumption from total jet fuel estimates. Another uncertainty associated with aviation emissions is the use of general aviation forecasts to project aviation gasoline consumption. General aviation aircraft consume both jet fuel and aviation gasoline, but fuel specific data were not available.

Uncertainties in Marine Fuel Consumption

There are several assumptions that introduce uncertainty into the estimates of commercial marine fuel consumption. These assumptions include:

- 75% of marine diesel and 25% of residual fuel is consumed in port; and
- The proportion of freight tonnage at ports in Michigan to the total national freight tonnage reflects the proportion of national marine fuel that is consumed in Michigan.

Appendix D. Industrial Processes

Overview

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

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

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

- Nitrous oxide (N_2O) from nitric and adipic acid production;
- PFCs from aluminum production;
- CO_2 from ammonia manufacture; and
- HFCs from HCFC-22 production.

Emissions and Reference Case Projections

Greenhouse gas emissions for 1990 through 2005 were estimated using the United States Environmental Protection Agency's (US EPA) State Greenhouse Gas Inventory Tool (SIT) software, and the methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for this sector.[51] Table D1 identifies for each emissions source category the information needed for input into SIT to calculate emissions, the data sources used for the analysis described here, and the historical years for which emissions were calculated based on the availability of data. To the extent possible, information provided in the Michigan Department

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

of Environmental Quality's (MDEQ) inventory of GHG emissions for 1990 and 2002 was incorporated.[52]

Table D1. Approach to Estimating Historical Emissions

Source Category	Time Period	Required Data for SIT	Data Source
Cement Manufacture	1990 - 2005	Metric tons (Mt) of clinker produced and masonry cement produced each year.	Historical production for Michigan from USGS Minerals Yearbook, Cement Statistics and Information (http://minerals.usgs.gov/minerals/pubs/commodity/cement/index.html#myb).
Lime Manufacture	1991-2000	Mt of lime produced each year.	Historical production for Michigan from USGS Minerals Yearbook, Lime Statistics and Information. Default production data are not available in SIT for 1990 and after 2000; data for 1991 were used as a surrogate for 1990 production (http://minerals.usgs.gov/minerals/pubs/commodity/lime/index.html#myb).
Limestone and Dolomite Consumption	1994 - 2004	Mt of limestone and dolomite consumed.	Historical consumption (sales) for Michigan from USGS Minerals Yearbook, Crushed Stone Statistics and Information, (http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/). In SIT, the state's total limestone consumption (as reported by USGS) is multiplied by the ratio of national limestone consumption for industrial uses to total national limestone consumption. Additional information on these calculations, including a definition of industrial uses, is available in Chapter 6 of the EIIP guidance document. Default limestone production data are not available in SIT for 1990 – 1993 and for 2005; data for 1994 were used for 1990 – 1993 as a surrogate to fill in production data missing for these years.
Soda Ash Consumption	1990 - 2005	Mt of soda ash consumed for use in consumer products such as glass, soap and detergents, paper, textiles, and food.	Historical emissions are calculated in SIT based on the state's population and national per capita soda ash consumption from the US EPA national GHG inventory. -- National historical consumption (sales) for US from USGS Minerals Yearbook, Soda Ash Statistics and Information (http://minerals.usgs.gov/minerals/pubs/commodity/soda_ash/). -- National emissions from *US Inventory of Greenhouse Gas Emissions and Sinks: 1990-2005*, US EPA, Report #430-R-07-002, April 2007 (http://epa.gov/climatechange/emissions/usinventoryreport.html). -- US (1990-2000 and 2000-2005) and state (2000-2005) population from US Census Bureau (http://www.census.gov/popest/states/NST-ann-est.html). -- State (1990-2000) population from US Census Bureau (http://www.census.gov/popest/archives/2000s/vintage_2001/CO-EST2001-12/CO-EST2001-12-24.html).
Taconite Production	1993-2005	Short tons of taconite pellets produced and US EPA CO_2 emission factors.	MDEQ provided taconite pellet production data for 1993-2005. Emission factors for CO_2 were taken from US EPA, AP-42, Supplement C, Section 11.23 (Taconite Ore Processing), February 1997 (http://www.epa.gov/ttn/chief/ap42/ch11/related/c11s23.html).

[52] A copy of the report, *Michigan Greenhouse Gas Inventory, 1990 and 2002*, can be found at: http://www.deq.state.mi.us/documents/deq-aqd-air-aqe-greenhouse-gases.pdf.

Source Category	Time Period	Required Data for SIT	Data Source
Iron and Steel Production	1990-2007	Mt of crude steel produced by production method.	The basic activity data needed are the quantities of crude steel produced (defined as first cast product suitable for sale or further processing) by production method. Crude steel production data by production method were provided by MDEQ for 1990-2005.
Magnesium Processing	1990, 2002	Mt of magnesium metal cast	Production data for magnesium castings for 1990 and 2002 were available from MDEQ's report, *Michigan Greenhouse Gas Inventory, 1990 and 2000*. Data were not readily available for other historical years; therefore, 1990 production was used as a surrogate for production for 1995 through 1999, and 2002 production was used as a surrogate for production for 2000, 2001, and 2003 through 2005.
ODS Substitutes - Castings	1990 - 2005	Based on state's population and estimates of emissions per capita from the US EPA national GHG inventory.	References for US EPA national emissions and US Census Bureau national and state population figures are cited under the data sources for soda ash above.
Electric Power T&D Systems	1990 - 2005	Emissions from 1990 to 2005 based on the national emissions per kilowatt-hour (kWh) and state's electricity use provided in SIT.	National emissions are apportioned to the state based on the ratio of state-to-national electricity sales data provided in the Energy Information Administration's (EIA) Electric Power Annual (http://www.eia.doe.gov/cneaf/electricity/epa/epa_sum.html). Reference for US EPA national emissions is cited under the data sources for soda ash above.
Semiconductor Manufacture	1990 - 2005	State and national value of semiconductor shipments for NAICS code 334413 (Semiconductor and Related Device Manufacturing).	Method uses ratio of state-to-national value of semiconductor shipments to estimate state's proportion of national emissions for 1990–2005. Value of shipments from U.S Census Bureau's 1997 Economic Census (http://www.census.gov/econ/ census02/); 2002 Economic Census withheld value of shipments data for Michigan. Reference for US EPA national emissions is cited under the data sources for soda ash above.

Table D2 lists the data and methods that were used to estimate future activity levels related to industrial process emissions and the annual compound growth rates computed from the data/methods for the reference case projections. Because available forecast information is generally for economic sectors that are too broad to reflect trends in the specific emissions producing processes, the majority of projections are based on historical activity trends. In particular, state historical trends were analyzed for three periods: 1990-2005, 1995-2005, and 2000-2005 (or the closest available approximation of these periods). A no growth assumption was assumed when the historical periods indicated divergent activity trends (i.e., growth in certain periods and decline in other periods). In cases where the historical periods indicated either continual growth or decline, the smallest annual rate of growth/decline was selected from the values computed for each period. This conservative assumption was adopted because of the uncertainty associated with utilizing historical trends to estimate future emission activity levels.

Table D2. Approach to Estimating Projections for 2005 through 2025

Source Category	Projection Assumptions	Data Source	Annual Growth Rates (%)			
			2005 to 2010	2010 to 2015	2015 to 2020	2020 to 2025
Cement Manufacture	Smallest historical annual decline in state production from each of three periods analyzed (1995-2005)	Annual change in Michigan clinker & masonry cement production: 1990-2005 = -0.43%; 1995-2005 = -0.09%; and 2000-2005 = -1.33%	-0.09	-0.09	-0.09	-0.09
Lime Manufacture	No growth assumption based on analysis of state historical production trends	Annual change in Michigan lime production: 1991-2000 = +1.16% 1995-2000 = -4.11%	0.0	0.0	0.0	0.0
Limestone and Dolomite Consumption	No growth assumption based on analysis of state historical consumption trends	Annual change in Michigan limestone and dolomite consumption: 1994-2004 = +2.09% 1995-2005 = -1.17% 2000-2004 = +4.37%	0.0	0.0	0.0	0.0
Soda Ash Consumption	Smallest historical annual decline in state consumption from each of three periods analyzed (1990-2005)	Annual change in Michigan soda ash consumption: 1990-2005 = -0.95% 1995-2005 = -1.23% 2000-2005 = -1.30%	-0.95	-0.95	-0.95	-0.95
Taconite Production	Smallest historical annual decline in state production from each of three periods analyzed (1995-2005)	Annual change in Michigan taconite production: 1993-2005 = -8.69% 1995-2005 = -3.74% 2000-2005 = -18.67%	-3.74	-3.74	-3.74	-3.74
Iron and Steel Production	Annual growth rate computed from Primary Metal Manufacturing sector employment forecast for state	2004-2014 employment projections by Michigan Labor Market Information (http://www.milmi.org/admin/uploadedPublications/591_nac_02.htm)	-0.42	-0.42	-0.42	-0.42
Magnesium Processing - Castings	National growth in emissions estimated for the magnesium processing industry.	Annual growth rates calculated based on US national emissions projections from 2005-2020 presented in the US EPA report, *Global Anthropogenic Emissions of Non-CO_2 Greenhouse Gases 1990-2020* , EPA Report 430-R-06-003; http://www.epa.gov/nonco2/econ-inv/international.html.	10.4	5.2	5.2	5.2
ODS Substitutes	National growth in emissions associated with the use of ODS substitutes.	Annual growth rates calculated based on sum of US national emissions projections from 2005-2020 for six categories of ODS substitutes presented in Appendix D, Tables D-1 through D-6 in the US EPA report, *Global Anthropogenic Emissions of Non-CO_2 Greenhouse Gases 1990-2020*, EPA Report 430-R-06-003, http://www.epa.gov/nonco2/econ-inv/international.html	8.7	6.4	5.0	5.0
Electric Power T&D Systems	National growth rate (based on technology adoption forecast scenario reflecting industry participation in EPA voluntary stewardship program to control emissions).	Annual growth rates calculated based on US national emissions projections from 2005-2020 presented in Appendix D, Table D-10 in the US EPA report, *Global Anthropogenic Emissions of Non-CO_2 Greenhouse Gases 1990-2020* , EPA Report 430-R-06-003; http://www.epa.gov/nonco2/econ-inv/international.html.	-1.6	-0.8	-0.7	-0.7
Semiconductor Manufacturing	Ditto	Ditto	0.7	-4.2	-1.4	-1.4

Results

Figures D1 and D2 show historical and projected emissions for the industrial processes sector from 1990 to 2025. Table D3 shows the historical and projected emission values upon which Figures D1 and D2 are based. Total gross Michigan GHG emissions were about 15.3 $MMtCO_2e$ in 1990, 18.4 $MMtCO_2e$ in 2005, and are projected to increase to about 26.4 $MMtCO_2e$ in 2025. Emissions from the overall industrial processes category are expected to grow by about 1.8% annually from 2005 through 2025, as shown in Figures D1 and D2, with emissions growth primarily associated with increasing magnesium production and the increasing use of HFCs and PFCs in refrigeration and air conditioning equipment.

Cement Manufacture

Michigan has five cement plants (Essroc Italcementi Company, Lafarge Corporation, Holcim, Inc, and St Marys Cement Inc.) that produce clinker and masonry cement. Clinker is an intermediate product from which finished Portland and masonry cement are made. Clinker production releases CO_2 when calcium carbonate ($CaCO_3$) is heated in a cement kiln to form lime (calcium oxide) and CO_2 (see Chapter 6 of EIIP guidance document). Emissions are calculated by multiplying annual clinker production by emission factors to estimate emissions associated with the clinker production process (0.507 metric ton (Mt) of CO_2 emitted per Mt of clinker produced) and cement kiln dust (0.020 $MtCO_2$ emitted per Mt of clinker CO_2 emitted).

Masonry cement requires additional lime, over and above the lime used in the clinker. During the production of masonry cement, non-plasticizer additives such as lime, slag, and shale are added to the cement, increasing its weight by 5%. Lime accounts for approximately 60% of the added substances. About 0.0224 $MtCO_2$ is emitted for every Mt of masonry cement produced, relative to the CO_2 emitted during the production of a Mt of clinker (see Chapter 6 of EIIP guidance document).

As shown in Figure D2 (see black line) and Table D3, emissions from this source are estimated to be about 2.3 $MMtCO_2e$ in 1990 and are projected to decline to about 2.1 $MMtCO_2e$ by 2025. Historical clinker and masonry cement production data for Michigan obtained from the USGS (see Table D1) and the default emission factors in SIT were used to calculate CO_2 emissions for 1990-2005. The annual rate of decrease in Michigan clinker/masonry cement production over the 1995-2005 period (-0.09% per year) was used to project emissions from 2006 to 2025.

Lime Manufacture

Lime is a manufactured product that is used in many chemical, industrial, and environmental applications including steel making, construction, pulp and paper manufacturing, and water and sewage treatment. Lime is manufactured by heating limestone (mostly $CaCO_3$) in a kiln, creating calcium oxide and CO_2. The CO_2 is driven off as a gas and is normally emitted to the atmosphere, leaving behind a product known as quicklime. Some of this quicklime undergoes slaking (combining with water), which produces hydrated lime. The consumption of lime for certain uses, specifically the production of precipitated $CaCO_3$ and refined sugar, results in the reabsorption of some airborne CO_2 (see Chapter 6 of EIIP guidance document.).

Figure D1. GHG Emissions from Industrial Processes, 1990-2025

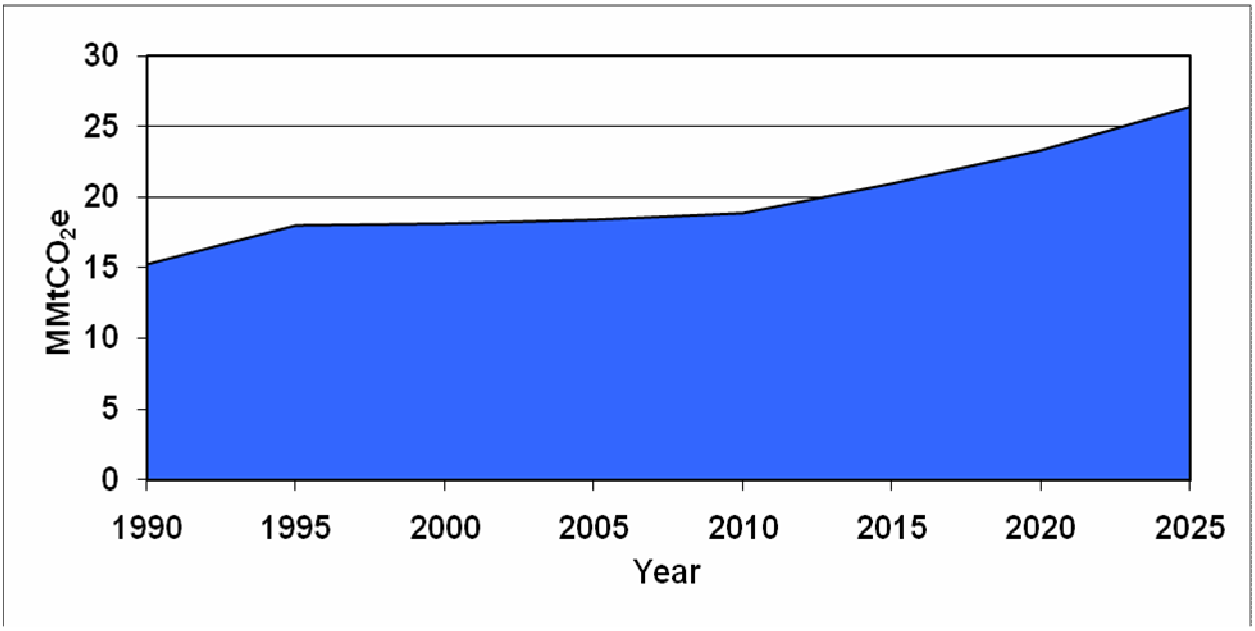


Figure D2. GHG Emissions from Industrial Processes, 1990-2025, by Source

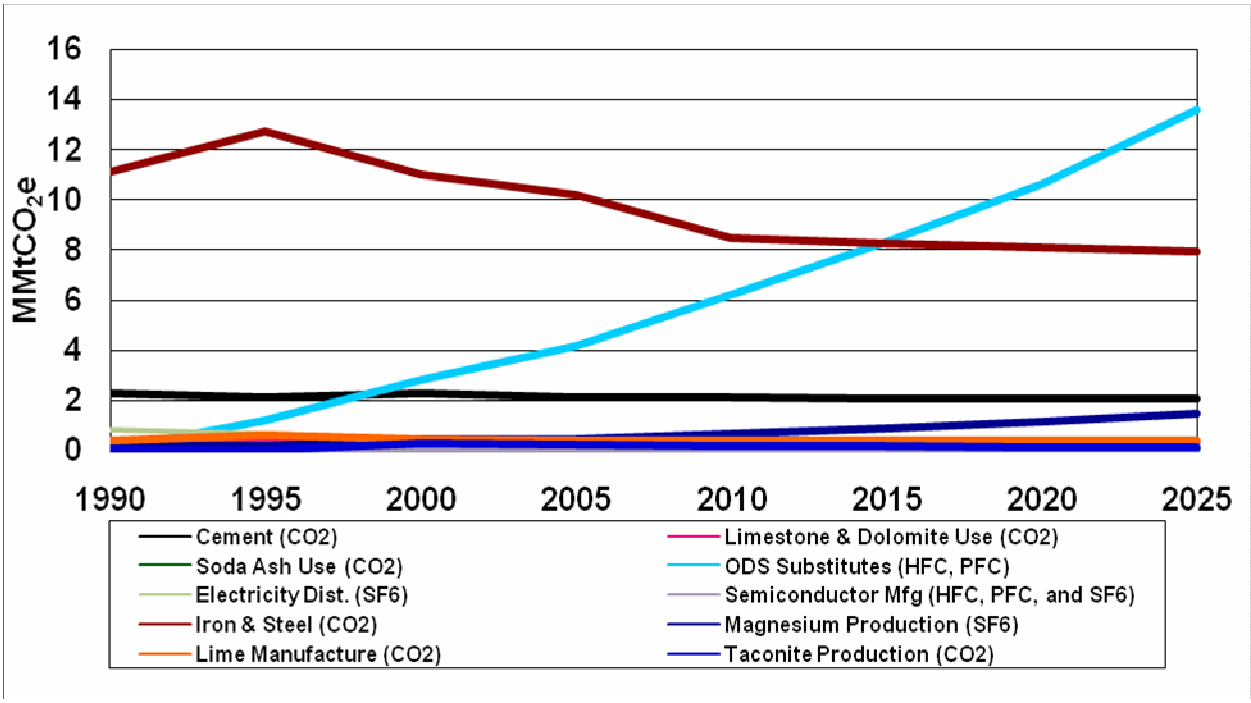


Table D3. Historical and Projected Emissions for the Industrial Processes Sector ($MMtCO_2e$)

Industry / Pollutant	1990	1995	2000	2005	2010	2015	2020	2025

Cement (CO2)	2.27	2.15	2.26	2.13	2.12	2.11	2.10	2.09
Lime Manufacture (CO2)	0.43	0.59	0.48	0.41	0.41	0.41	0.41	0.41
Limestone & Dolomite Use (CO2)	0.24	0.33	0.25	0.31	0.31	0.31	0.31	0.31
Soda Ash Use (CO2)	0.10	0.10	0.09	0.09	0.08	0.08	0.08	0.07
Iron & Steel (CO2)	11.15	12.76	11.01	10.20	8.47	8.29	8.12	7.95
Taconite Production (CO2)	0.04	0.02	0.28	0.25	0.20	0.17	0.14	0.11
Magnesium Production (SF6)	0.18	0.18	0.45	0.45	0.70	0.90	1.16	1.50
ODS Substitutes (HFC, PFC)	0.01	1.19	2.84	4.16	6.18	8.31	10.63	13.58
Electricity Dist. (SF6)	0.82	0.69	0.47	0.40	0.37	0.36	0.34	0.33
Semiconductor Manufacturing (HFC, PFC, and SF6)	0.001	0.002	0.004	0.004	0.004	0.003	0.003	0.003
Total	**15.25**	**18.00**	**18.12**	**18.39**	**18.86**	**20.95**	**23.30**	**26.37**

Emissions associated with lime manufacture were estimated for 1991 through 2000 using the amount of lime produced and an emission factor of 0.75 $MtCO_2$ per ton high-calcium lime and 0.87 $MtCO_2$ per ton dolomitic lime produced. Lime production for 1990 was not available for Michigan; therefore, production for 1991 was used as a surrogate to estimate emissions for 1990. Lime production data for 2001-2005 were not available; emissions for these years were estimated using an annual growth rate applied to year 2000 emissions. The annual growth rate was developed from Michigan's Lime and Gypsum Manufacturing sector employment data which reflected an annual decline in employment of -3% for the 2001-2005 period. Post-2005 production and emissions were held constant at 2005 levels. This assumption was adopted because of conflicting production trends observed over the historical periods analyzed. Relative to total industrial non-combustion process emissions, CO_2 emissions from lime production are low (about 0.43 $MMtCO_2e$ in 1990, 0.59 $MMtCO_2e$ in 1995, 0.48 $MMtCO_2e$ in 2000, and 0.41 $MMtCO_2e$ in 2005 through 2025), and therefore, appear at the bottom of the graph because of scaling effects (see orange line at the bottom of Figure D2).

Limestone and Dolomite Consumption

Limestone and dolomite are basic raw materials used by a wide variety of industries, including the construction, agriculture, chemical, glass manufacturing, and environmental pollution control industries, as well as in metallurgical industries such as magnesium production. Emissions associated with the use of limestone and dolomite to manufacture steel and glass and for use in flue-gas desulfurization scrubbers to control sulfur dioxide emissions from the combustion of coal in boilers are included in the industrial processes sector.[53]

[53] In accordance with EIIP Chapter 6 methods, emissions associated with the following uses of limestone and dolomite are not included in this category: (1) crushed limestone consumed for road construction or similar uses (because these uses do not result in CO_2 emissions), (2) limestone used for agricultural purposes (which is counted under the methods for the agricultural sector), and (3) limestone used in cement production (which is counted in the methods for cement production).

Historical limestone and dolomite consumption (sales) data for Michigan obtained from the USGS (see Table D1) and the default emission factors in SIT were used to calculate CO_2 emissions for 1990-2005. Emission projections from 2005 to 2025 are held constant at 2005 levels, reflecting the conflicting trends observed for the historical periods analyzed. Relative to total industrial non-combustion process emissions, CO_2 emissions from limestone and dolomite consumption are low (about 0.24 $MMtCO_2e$ in 1990, 0.33 $MMtCO_2e$ in 1995, 0.25 $MMtCO_2e$ in 2000, and 0.31 $MMtCO_2e$ in 2005 through 2025), and therefore, appear at the bottom of the graph because of scaling effects (see pink line at the bottom of Figure D2).

Soda Ash Consumption

Commercial soda ash (sodium carbonate) is used in many consumer products such as glass, soap and detergents, paper, textiles, and food. Carbon dioxide is also released when soda ash is consumed (see Chapter 6 of EIIP guidance document). SIT estimates historical emissions (see green line in Figure D2) based on the state's population and national per capita soda ash consumption from the US EPA national GHG inventory. A no growth assumption was adopted for this category based on the conflicting consumption trends observed over the historical periods analyzed. Relative to total industrial non-combustion process emissions, CO_2 emissions from soda ash consumption are low (about 0.1 $MMtCO_2e$ per year from 1990 through 1995, 0.09 $MMtCO_2e$ per year from 1996 through 2005, and decreases to 0.07 $MMtCO_2e$ by 2025), and therefore, appear at the bottom of the graph because of scaling effects.

Taconite Production

Michigan is only one of two states in the US that process taconite iron ore. This industry produces usable concentrations of iron-bearing material by removing nonferrous rock (gangue) from low-grade ore. Processing of taconite consists of crushing and grinding the ore to free iron-bearing particles, concentrating the ore by separating the particles from the waste material (gangue), and pelletizing the iron ore concentrate. The pellets are hardened by a procedure called induration, which involves the use of a furnace or kiln to harden the pellets and then processing in a separate "cooler" unit. These pelletizing processes release CO_2 emissions. Acid pellets are produced from iron ore and a binder only, and flux pellets are produced by adding between 1% and 10% limestone to the ore and binder before pelletization.

The CO_2 emissions for 1993 through 2005 are estimated using production data provided by MDEQ and emission factors published by US EPA.[54] Production data for 1990-1992 were not available; data for these years are based on 1993 production levels. As shown in Table D3, CO_2 emissions associated with pellet production from 1990 to 2000 increased by about 600% (from 0.04 to 0.28 $MMtCO_2e$) and have leveled off since 2000. This dramatic increase in emissions was due to the addition of acid pellet production in 1998. In the past seven years (1998 through 2005), the majority of pellets have been produced using the acid pellet process. Flux pellet production from 1998 to 2005 decreased at an average annual rate of about 23%. For the purpose of this forecast, future emissions were projected using an assumed annual decrease of -3.74% in total taconite ore production, which was computed from 1995-2005 production data for Michigan. Relative to total industrial non-combustion process emissions, CO_2 emissions from

[54] US EPA, AP-42, Supplement C, Section 11.23 (Taconite Ore Processing), February 1997 (http://www.epa.gov/ttn/chief/ap42/ch11/related/c11s23.html).

taconite pelletizing processes are low (about 0.04 $MMtCO_2e$ in 1990, 0.02 $MMtCO_2e$ in 1995, 0.28 $MMtCO_2e$ in 2000, 0.25 $MMtCO_2e$ in 2005, and 0.11 $MMtCO_2e$ in 2025), and therefore, appear at the bottom of the graph because of scaling effects (see blue line at the bottom of Figure D2).

Iron and Steel Production

Michigan had three iron and steel production facilities from 1990 to 2005: US Steel Corporation, located in Ecorse, Michigan, is the largest producer of steel; Severstal North America, which purchased Rouge Steel in 2004, is located in Dearborn; and McLouth Steel, a former integrated steel mill that hasn't been operating since 1996, is located in Trenton. The production of iron and steel generate process-related CO_2 emissions. Iron is produced by reducing iron ore with metallurgical coke in a blast furnace to produce pig iron; this process emits CO_2 emissions. Pig iron is used as a raw material in the production of steel. The production of metallurgical coke from coking coal produces CO_2 emissions as well.

The EPA SIT methodology was used to estimate Michigan's CO_2 emissions from steel production (see Table D1). The basic activity data needed are the quantities of crude steel produced (defined as first cast product suitable for sale or further processing) by production method. Plant-specific production data by the Electric Arc Furnace (EAF), Basic Oxygen Furnace (BOF) with and without coke ovens, and the Direct Reduced Iron (DRI) production methods were provided by MDEQ for the years 1990 to 2005. Default SIT emission factors of 0.08 $MtCO_2$ per Mt, 1.46 $MtCO_2$ per Mt, and 1.72 $MtCO_2$ per Mt production were used for EAF steel production from scrap metal, BOF production without coke ovens, and BOF production with coke ovens, respectively. IPCC emission factor of 0.7 $MtCO_2$ per Mt iron production were used for the DRI method. As shown in Figure D2 (see dark red line) and Table D3, emissions in 1990 were 11.2 $MMtCO_2e$ and are projected to decline to about 8 $MMtCO_2e$ in 2025. Emissions are projected to decrease at a rate of 0.42% per year based on Primary Metal Manufacturing sector employment projections available from the State of Michigan (note that these projections are available for 2014—in lieu of other information, the same rate of decrease was used throughout the forecast period to 2025).

Magnesium Casting

The magnesium (Mg) casting industry uses SF_6 as a cover gas to prevent the violent oxidation of molten Mg in the presence of air. A gas mixture consisting of CO_2, air, and a small concentration of SF_6 is blown over the molten Mg metal to induce the formation of a protective crust. Because of the high cost of SF_6, firms in the industry are voluntarily seeking to reduce their use of the gas. Emissions were estimated using EPA emission factors and production data for magnesium castings for 1990 and 2002 from MDEQ's GHG report. Data were not readily available for other historical years; therefore, 1990 production was used as a surrogate for production for 1995 through 1999, and 2002 production was used as a surrogate for production for 2000, 2001, and 2003 through 2005. The projected rate of increase for these emissions is based on projections for national emissions from the US EPA report referenced in Table D2. As shown in Figure D2 (see purple line) and Table D3, emissions in 1990 were 0.18 $MMtCO_2e$ and are projected to increase to about 1.50 $MMtCO_2e$ in 2025.

Substitutes for Ozone-Depleting Substances (ODS)

HFCs and PFCs are used as substitutes for ODS, most notably CFCs (CFCs are also potent warming gases, with global warming potentials on the order of thousands of times that of CO_2 per unit of emissions) in compliance with the *Montreal Protocol* and the *Clean Air Act Amendments of 1990*.[55] Even low amounts of HFC and PFC emissions, for example, from leaks and other releases associated with normal use of the products, can lead to high GHG emissions on a CO_2e basis. Emissions have increased from 0.01 $MMtCO_2e$ in 1990 to about 4.16 $MMtCO_2e$ in 2005, and are expected to increase at an average rate of 6.1% per year from 2005 to 2025 due to increased substitutions of these gases for ODS (see sky-blue line in Figure D2). The projected rate of increase for these emissions is based on projections for national emissions from the US EPA report referenced in Table D2.

Electric Power Transmission and Distribution

Emissions of SF_6 from electrical equipment have experienced declines since the mid nineties (see pale green line in Figure D2), mostly due to voluntary action by industry. Sulfur hexafluoride is used as an electrical insulator and interrupter in the electric power T&D system. The largest use for SF_6 is as an electrical insulator in electricity T&D equipment, such as gas-insulated high-voltage circuit breakers, substations, transformers, and transmission lines, because of its high dielectric strength and arc-quenching abilities. Not all of the electric utilities in the US use SF_6; use of the gas is more common in urban areas where the space occupied by electric power T&D facilities is more valuable.[56]

As shown in Figure D2 and Table D3, SF_6 emissions from electric power T&D are about 0.82 $MMtCO_2e$ in 1990 and 0.33 $MMtCO_2e$ in 2025. Emissions in Michigan from 1990 to 2005 were estimated based on the estimates of emissions per kilowatt-hour (kWh) of electricity consumed from the US EPA GHG inventory, and the ratio of Michigan's to the US electricity consumption (sales) estimates available from the Energy Information Administration's (EIA) Electric Power Annual and provided in SIT (see Table D1). The national trend in US emissions estimated for 2005-2025 for the technology-adoption scenario shows expected decreases in these emissions at the national level (see Table D2), and the same rate of decline is assumed for emissions in Michigan. The decline in SF_6 emissions in the future reflects expectations of future actions by the electric power industry to reduce these emissions.

Semiconductor Manufacture

The semiconductor industry uses fluorinated gases (PFCs [CF_4, C_2F_6, and C_3F_8]; HFC-23; and SF_6) in plasma etching and chemical vapor deposition processes. Emissions of SF_6 and HFCs

[55] As noted in EIIP Chapter 6, ODS substitutes are primarily associated with refrigeration and air conditioning, but also many other uses including as fire control agents, cleaning solvents, aerosols, foam blowing agents, and in sterilization applications. The applications, stocks, and emissions of ODS substitutes depend on technology characteristics in a range of equipment types. For the US national inventory, a detailed stock vintaging model was used to track ODS substitutes uses and emissions, but this modeling approach has not been completed at the state level.

[56] US EPA, Draft User's Guide for Estimating Carbon Dioxide, Nitrous Oxide, HFC, PFC, and SF_6 Emissions from Industrial Processes Using the State Inventory Tool, prepared by ICF International, March 2007.

from the manufacture of semiconductors have experienced declines since 2000. Emissions for Michigan from 1990 to 2005 were estimated based on the default estimates provided in SIT, which uses the ratio of the state-to-national value of semiconductor shipments to estimate the state's proportion of national emissions from the US EPA GHG inventory (see Table D1). The national trend in US emissions estimated for 2005-2025 for the technology-adoption scenario shows expected decreases in these emissions at the national level (see Table D2), and the same rate of decline is assumed for emissions in Michigan. The decline in emissions in the future reflects expectations of future actions by the semiconductor industry to reduce these emissions. Relative to total industrial non-combustion process emissions, estimated emissions associated with semiconductor manufacturing are low (about 0.001 $MMtCO_2e$ in 1990, 0.004 $MMtCO_2e$ in 2005, and 0.003 $MMtCO_2e$ in 2025), and therefore, cannot be seen in Figure D2 due to scaling effects.

Key Uncertainties

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

- Since emissions from industrial processes are determined by the level of production and the production processes of a few key industries—and in some cases, a few key plants—there is relatively high uncertainty regarding future emissions from the industrial processes category as a whole. Future emissions depend on the competitiveness of Michigan manufacturers in these industries, and the specific nature of the production processes used in Michigan.
- The projected largest source of future industrial emissions, HFCs and PFCs used in cooling applications, is subject to several uncertainties as well. Emissions through 2025 and beyond will be driven by future choices regarding mobile and stationary air conditioning technologies and the use of refrigerants in commercial applications, for which several options currently exist.
- Due to the lack of reasonably specific projection surrogates, historical trend data were used to project emission activity level changes for multiple industrial processes. There is significant uncertainty associated with any projection, including a projection that assumes that past historical trends will continue in future periods. Reflecting this uncertainty, the lowest historical annual rate of increase/decrease was selected as a conservative assumption for use in projecting future activity level changes. These assumptions on growth should be reviewed by industry experts and revised to reflect their expertise on future trends especially for the cement and lime manufacture, iron and steel production, magnesium casting, and taconite production industries.
- For the industries for which EPA default activity data and methods were used to estimate historical emissions, future work should include efforts to obtain state-specific data to replace the default assumptions. For example, historical production data for magnesium casting were available for only 1990 and 2002, and the activity for other years were estimated based on the use of either 1990 or 2002 production data. Future work should include efforts to obtain plant-specific production data for 1991 through 2001 and 2003 through 2005 to improve the historical emission estimates for this industry. For limestone and dolomite consumption, 1994 activity data were used as a surrogate to estimate emissions for 1990 through 1993.

- For the electricity T&D and semiconductor industries, future efforts should include a survey of companies within these industries to determine the extent to which they are implementing techniques to minimize emissions to improve the emission projections for these industries.

Appendix E. Fossil Fuel Industries

Overview

The inventory for this subsector of the Energy Supply sector includes includes methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) emissions associated with the production, processing, transmission, and distribution of fossil fuels in Michigan.[57] There is no coal mining in Michigan. In 2005, emissions from the subsector accounted for an estimated 6.64 million metric tons (MMt) of CO_2 equivalent (CO_2e) of total gross greenhouse gas (GHG) emissions in Michigan, and are estimated to increase to about 9.66 $MMtCO_2e$ by 2025.

Emissions and Reference Case Projections

Oil and Gas Production

Michigan crude oil production totals 15,000 barrels (bbls) per day and accounts for about 0.3% of US production.[58] Proved crude oil reserves sit at 62 million bbls, which is similarly about 0.3% of US totals. The peak year of oil production in Michigan was 1981 (89,000 bbls per day), which was the first year that the Energy Information Administration (EIA) of the United States (US) Department of Energy (DOE) reported production data for Michigan. Production has steadily declined for more than two decades.[59] Michigan has one operating petroleum refinery, with a crude oil distillation capacity of 100,000 bbls per day.[60]

Michigan has more natural gas reserves than any other state in the Great Lakes region, and the Antrim natural gas fields in the northern Lower Peninsula, are among the largest in the Nation. State natural gas production supplies nearly 30% of state demand.[60] In 2005, Michigan consumed about 914 billion cubic feet (Bcf) of natural gas while it produced about 261 billion Bcf.[60]

Oil and Gas Industry Emissions

Emissions of CH_4 and entrained CO_2 can occur at several stages of production, processing, transmission, and distribution of oil and gas. Based on the information provided in the Emission Inventory Improvement Program (EIIP) guidance[61] for estimating emissions for this sector, transmission pipelines are large diameter, high-pressure lines that transport gas from production fields, processing plants, storage facilities, and other sources of supply over long distances to local distribution companies or to large volume customers. Sources of CH_4 emissions from transmission pipelines include leaks, compressor fugitives, vents, and pneumatic devices. Distribution pipelines are extensive networks of generally small diameter, low-pressure pipelines

[57] Note that emissions from natural gas consumed as lease fuel (used in well, field, and lease operations) and plant fuel (used in natural gas processing plants) are included in Appendix B in the industrial fuel combustion category
[58] "Crude Oil Production", US DOE Energy Information Administration website, November 2007, Accessed at < http://tonto.eia.doe.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_a.htm >
[59] "Petroleum Navigator", US DOE Energy Information Administration website, November 2007, Accessed at < http://tonto.eia.doe.gov/dnav/pet/hist/mcrfp_smi_2a.htm >
[60] "State Energy Profiles: Michigan", US DOE Energy Information Administration website, November 2007, Accessed at < http://tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=MI >
[61] Emission Inventory Improvement Program, Volume VIII: Chapter 5. "Methods for Estimating Methane Emissions from Natural Gas and Oil Systems," August 2004.

that distribute gas within cities or towns. Sources of CH_4 emissions from distribution pipelines are leaks, meters, regulators, and mishaps. Carbon dioxide, CH_4, and N_2O emissions occur as the result of the combustion of natural gas by internal combustion engines used to operate compressor stations.

With 12,000 active oil and gas wells in the state, 22 operational gas processing plants, and nearly 64,000 miles of gas pipelines,[62] there are significant uncertainties associated with estimates of Michigan's GHG emissions from this sector. This is compounded by the fact that there are no regulatory requirements to track GHG emissions.

However, the EPA's State Greenhouse Gas Inventory Tool (SIT) facilitates the development of state-level GHG emissions estimates.[63] Methane and CO_2 emission estimates are calculated by multiplying emissions-related activity levels (e.g., miles of pipeline, number of compressor stations) by aggregate industry-average emission factors. Key information sources for the activity data are the US Department of Energy's Energy Information Administration (EIA)[64] and the US Department of Transportation's Office of Pipeline Safety (OPS).[62] It was necessary to make two revisions to the OPS' data for Michigan. All year 2003 distribution pipeline mileage and service count values were interpolated from the OPS' 2002 and 2004 values because Consumers Energy Company, which accounts for a significant portion of total distribution mileage/service counts, was missing from the OPS data set in 2003. In addition, the pre-1994 service counts for Michigan Consolidated Gas Company (MICHCON) were revised from the protected steel category to the unprotected steel category because all post-1993 years show that the steel service counts for MICHCON represent unprotected steel. Emissions were estimated using SIT, with reference to the EIIP guidance document for natural gas and oil systems. Emissions of CO_2, CH_4, and N_2O associated with pipeline natural gas combustion are estimated using SIT emission factors[65] and Michigan 1990-2005 natural gas data from EIA for the "consumed as pipeline fuel" category.[66]

Because available forecast information is generally for a broad region that may not reflect Michigan-specific trends (e.g., US DOE EIA *Annual Energy Outlook* forecasts of natural gas production for the Northeast Region, which includes more than 20 states in addition to Michigan), the majority of oil and gas system projections are based on state-level historical activity/emissions trends. In particular, state historical trends were analyzed for three periods: 1990-2005, 1995-2005, and 2000-2005. A no growth assumption was assumed when the historical periods indicated divergent activity trends (i.e., growth in certain periods and decline in

[62] US Department of Transportation, Office of Pipeline Safety, "Distribution and Transmission Annuals Data: 1990 to 2005," accessed from http://ops.dot.gov/stats/DT98.htm, November 2007.
[63] Methane and CO_2 emissions were calculated using SIT, with reference to Emission Inventory Improvement Program, Volume VIII: Chapter. 5. "Methods for Estimating Methane Emissions from Natural Gas and Oil Systems", August 2004.
[64] "Petroleum Navigator" and "Natural Gas Navigator," US DOE Energy Information Administration website, November 2007, Accessed at http://www.eia.doe.gov.
[65] GHG emissions were calculated using SIT, with reference to *EIIP, Volume VIII*: Chapter 1 "Methods for Estimating Carbon Dioxide Emissions from Combustion of Fossil Fuels," August 2004, and Chapter 2 "Methods for Estimating Methane and Nitrous Oxide Emissions from Stationary Combustion," August 2004.
[66] US DOE, Energy Information Administration, *State Energy Consumption, Price, and Expenditure Estimates (SEDS)*, (http://www.eia.doe.gov/emeu/states/_seds.html).

other periods). In cases where the historical periods indicated either continual growth or decline, the smallest annual rate of growth/decline was selected from the values computed for each period. This conservative assumption was adopted because of the uncertainty associated with utilizing historical trends to estimate future emission activity levels. Note that potential improvements to production, processing, and pipeline technologies resulting in GHG emissions reductions are generally not accounted for in this analysis.

Table E1 provides an overview of data sources and approaches used to develop historical and projected natural gas and oil system emission estimates for Michigan.

Coal Production Emissions

Because there are no operating coal mines in Michigan, no coal production emissions are estimated for Michigan.[67]

[67] EIA coal data, November 2007, Accessed at < http://www.eia.doe.gov/cneaf/coal/page/acr/table1.html >

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

Activity	**Approach to Estimating Historical Emissions**		**Approach to Estimating Projections**
	Required Data for SIT	***Data Source***	***Projection Assumptions***
Natural Gas Drilling and Field Production	Number wells	EIA[68]	Emissions estimated based on smallest annualized growth rate in the number of gas wells in the state (+4.72%) from each of 3 periods analyzed (2000-2005).
	Miles of gathering pipeline	Office of Pipeline Safety[69]	Emissions estimated based on smallest annualized growth in state gathering/transmission emissions (+3.49%) from each of 3 periods analyzed (1990-2005).
Natural Gas Processing	Number gas processing plants	*Oil and Gas Journal*[70]	Emissions estimated based on smallest annualized decline in the number of gas processing plants in the state (-0.89%) from each of 3 periods analyzed (2000-2005).
	Venting of Entrained Gas	EIA[71]	No change based on trend of nearly constant activity throughout historical period.
Natural Gas Transmission	Miles of transmission pipeline	Office of Pipeline Safety	Emissions estimated based on smallest annualized growth in state gathering/transmission emissions (+3.49%) from each of 3 periods analyzed (1990-2005).
	Number of gas transmission compressor stations	EIIP[72]	
	Number of gas storage compressor stations	EIIP[73]	Emissions estimated based on smallest annualized growth in state gathering/transmission emissions (+3.49%) from each of 3 periods analyzed (1990-2005).
	Number of LNG storage compressor stations	UM and EIA[74]	No projected emissions for this category (no activity in Michigan)

[68] US Department of Energy, Energy Information Administration, "Natural Gas Navigator - Michigan Natural Gas Number of Gas and Gas Condensate Wells," accessed from http://tonto.eia.doe.gov/dnav/ng/hist/na1170_smi_8a.htm, November 2007.
[69] US Department of Transportation, Office of Pipeline Safety, "Distribution and Transmission Annuals Data: 1990 to 2005," accessed from http://ops.dot.gov/stats/DT98.htm, November 2007.
[70] PennWell Corporation, "Worldwide Gas Processing," *Oil and Gas Journal* (1990-2005 June/July issues).
[71] US Department of Energy, Energy Information Administration, "Natural Gas Navigator - Michigan Natural Gas Vented and Flared," accessed from http://tonto.eia.doe.gov/dnav/ng/hist/n9040mi2A.htm, November 2007.
[72] Number of gas transmission compressor stations = miles of transmission pipeline x 0.006 – EIIP, Volume VIII: Chapter 5, March 2005.
[73] Number of gas storage compressor stations = miles of transmission pipeline x 0.0015 EIIP. Volume VIII: Chapter 5, March 2005.
[74] University of Michigan, "Michigan Greenhouse Gas Inventory 1990 and 2002," Prepared for Michigan Department of Environmental Quality, April 2005, and US Department of Energy, Energy Information Administration, "Table 48. Summary Statistics for Natural Gas – Michigan, 2002-2006," *Natural Gas Annual 2006,* DOE/EIA-0131(06), October 2007.

Activity	**Approach to Estimating Historical Emissions**		**Approach to Estimating Projections**
	Required Data for SIT	***Data Source***	***Projection Assumptions***
Natural Gas Distribution	Miles of distribution pipeline Total number of services Number of unprotected steel services Number of protected steel services	Office of Pipeline Safety	Emissions estimated based on smallest annualized growth in the state distribution emissions (+0.45%) from each of 3 periods analyzed (2000-2005).
Natural Gas Pipeline Fuel Use (CO_2, CH_4, N_2O)	Natural gas consumption by pipeline compressor stations	EIA	Used AEO 2007 projected regional pipeline natural gas fuel energy consumption growth rates since they are in-line with long-term historical MI trends.
Oil Production	Annual production	EIA[75]	Emissions estimated based on smallest annualized decline in state oil production (-6.84%) from each of 3 periods analyzed (2000-2005).
Oil Refining	Annual amount refined	EIA[76]	No growth assumption based on conflicting state historical refining trends across 3 periods analyzed.(declines in 2 periods, increase in other period)
Oil Transport	Annual oil transported	Unavailable, per SIT, assumed oil refined = oil transported	Same as Oil Refining noted above.

Results

Table E2 displays the estimated emissions from the fossil fuel industry in Michigan for select years over the period 1990 to 2025. Emissions from this sector grew by 34% from 1990 to 2005 and are projected to increase by a further 45% between 2005 and 2025. The natural gas industry is the major contributor to both historical emissions and emissions growth.

[75] US Department of Energy, Energy Information Administration, "Petroleum Navigator - Michigan Crude Oil Production," accessed from http://tonto.eia.doe.gov/dnav/pet/hist/mcrfp_smi_1a.htm, November 2007.

[76] Refining is assumed to be equal to the total input of crude oil into PADD II times the ratio of Michigan's refining capacity to PADD II's total refining capacity. No data for 1996 and 1998, so linear interpolation used to estimate values in these years. Data are from US Department of Energy, Energy Information Administration, "Petroleum Navigator." PADD capacity data accessed from http://tonto.eia.doe.gov/dnav/pet/hist/moclep22A.htm. PADD crude input data accessed from http://tonto.eia.doe.gov/dnav/pet/hist/mgirip22A.htm. State capacity data accessed from http://tonto.eia.doe.gov/dnav/pet/hist/8_na_8do_smi_4a.htm, November 2007.

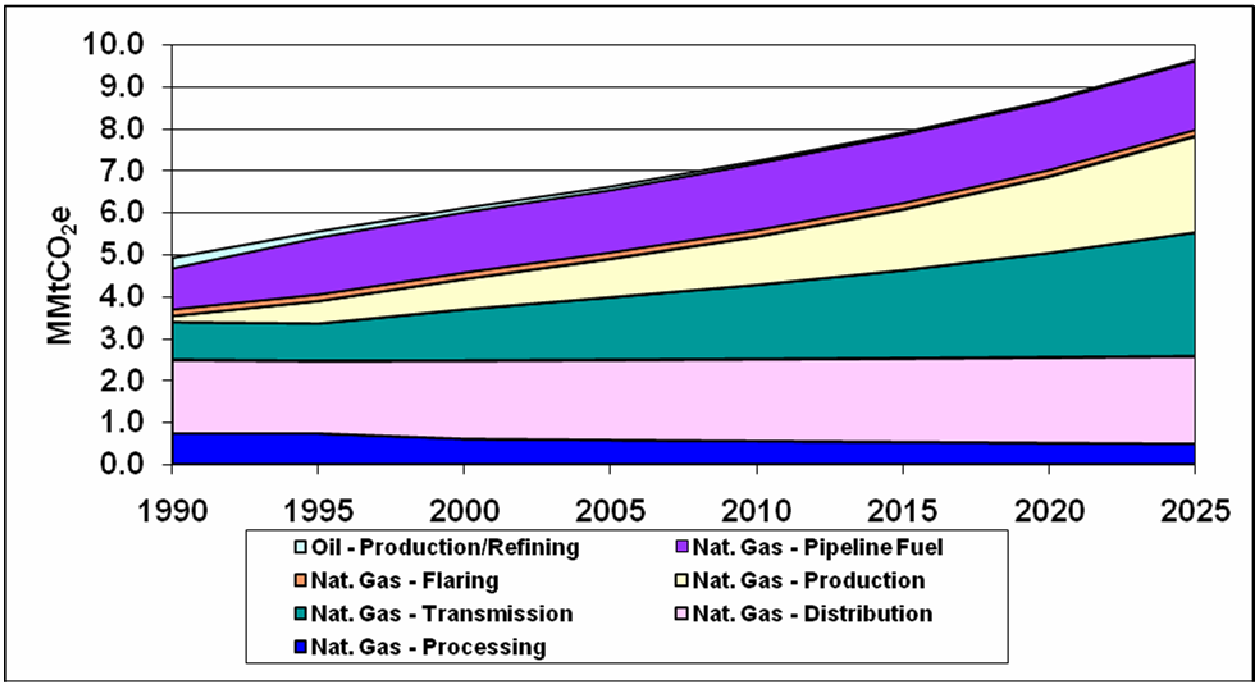
Table E2. Historical and Projected Emissions for the Fossil Fuel Industry

(Million Metric Tons CO_2e)	1990	1995	2000	2005	2010	2015	2020	2025
Fossil Fuel Industry	4.94	5.57	6.13	6.64	7.25	7.93	8.70	9.66
Natural Gas Industry	4.69	5.42	6.03	6.55	7.19	7.88	8.67	9.64
Production	0.14	0.53	0.72	0.91	1.15	1.45	1.82	2.29
Processing	0.73	0.73	0.60	0.58	0.55	0.53	0.51	0.48
Transmission	0.89	0.88	1.21	1.49	1.76	2.09	2.49	2.95
Distribution	1.77	1.74	1.88	1.92	1.96	2.01	2.05	2.10
Flaring	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Pipeline Fuel	0.99	1.37	1.45	1.50	1.60	1.64	1.64	1.65
Oil Industry								
Production	0.25	0.15	0.10	0.09	0.06	0.04	0.03	0.02
Refining	0.25	0.14	0.10	0.08	0.06	0.04	0.03	0.02

Note: Does not include energy combustion emissions from this sector (see Appendix B).

Figure E1 displays process-level emission trends from natural gas and oil systems, on an $MMtCO_2e$ basis.

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



Source: CCS calculations based on approach described in text.

Key Uncertainties

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

- Current levels of fugitive emissions. These are based on industry-wide averages, and until estimates are available for local facilities some level of uncertainty will remain.

- Projections of future production of fossil fuels. Forecasts are not readily available for the specific emission processes. The assumptions used for the projections, which are based on recent trends, do not reflect potential significant future changes in energy prices. Large price swings, resource limitations, or changes in regulations could significantly change future production and associated GHG emissions.
- Other uncertainties include the potential emissions-reducing improvements in oil and gas production, processing, and pipeline technologies.
- For the natural gas T&D sector, there are limitations to the OPS data and emissions for Michigan. The OPS has revised its forms such that operators must now report their activity data by state starting in 2001 for transmission pipelines and 2004 for distribution pipelines and service connections. Prior to 2001 for transmission pipelines and 2004 for distribution pipelines and service connections, operators in Michigan have been allowed to report on the OPS form their pipeline system information as a total across multiple states. Thus, for these years the activity data for operators that included multi-state data in their reporting forms cannot be disaggregated to the state level without the assistance of the operators. Because of this constraint, pipeline activity data were included only when Michigan was reported as the only state of record. To the extent that operators of Michigan pipelines reported their mileage/service connections from 1990 to 2000 for transmission pipelines and 1990 to 2003 for distribution pipelines as multi-state totals, this inventory is under-reporting activity/emissions in these years. In addition, the OPS has noted that the reporting of activity data by individual operators may not be consistent between years over which an ownership transfer occurs, thus causing one operator's mileage to decrease while another operator's mileage increases. This issue can be associated with transfers in ownership, which may cause one operator's mileage to decrease while another operator's mileage increases. Future work should ask that operators in Michigan review and correct the historical data to ensure that T&D pipeline mileage and service connections exclude data for other states.

Appendix F. Agriculture

Overview

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

There are two livestock sources of greenhouse gas (GHG) emissions: enteric fermentation and manure management. Methane emissions from enteric fermentation are the result of normal digestive processes in ruminant and non-ruminant livestock. Microbes in the animal digestive system break down food and emit CH_4 as a by-product. More CH_4 is produced in ruminant livestock because of digestive activity in the large fore-stomach. Methane and N_2O emissions from the storage and treatment of livestock manure (e.g., in compost piles or anaerobic treatment lagoons) occur as a result of manure decomposition. The environmental conditions of decomposition drive the relative magnitude of emissions. In general, the more anaerobic the conditions are, the more CH_4 is produced because decomposition is aided by CH_4 producing bacteria that thrive in oxygen-limited conditions. Under aerobic conditions, N_2O emissions are dominant. Emissions estimates from manure management are based on manure that is stored and treated on livestock operations. Emissions from manure that is applied to agricultural soils as an amendment or deposited directly to pasture and grazing land by grazing animals are accounted for in the agricultural soils emissions.

The management of agricultural soils can result in N_2O emissions and net fluxes of carbon dioxide (CO_2) causing emissions or sinks. In general, soil amendments that add nitrogen to soils can also result in N_2O emissions. Nitrogen additions drive underlying soil nitrification and de-nitrification cycles, which produce N_2O as a by-product. The emissions estimation methodologies used in this inventory account for several sources of N_2O emissions from agricultural soils, including decomposition of crop residues, synthetic and organic fertilizer application, manure application, sewage sludge, nitrogen fixation, and histosols (high organic soils, such as wetlands or peatlands) cultivation. Both direct and indirect emissions of N_2O occur from the application of manure, fertilizer, and sewage sludge to agricultural soils. Direct emissions occur at the site of application and indirect emissions occur when nitrogen leaches to groundwater or in surface runoff and is transported off-site before entering the nitrification/denitrification cycle. Methane and N_2O emissions also result when crop residues are burned. Methane emissions occur during rice cultivation; however, rice is not grown in Michigan.

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

the practice of adding limestone and dolomite to agricultural soils (for neutralizing acidic soil conditions) results in CO_2 emissions.

Emissions and Reference Case Projections

Methane and Nitrous Oxide

GHG emissions for 1990 through 2005 were estimated using the United States Environmental Protection Agency's (US EPA) State Greenhouse Gas Inventory Tool (SIT) software and the methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for the sector.[77] In general, the SIT methodology applies emission factors developed for the US to activity data for the agriculture sector. Activity data include livestock population statistics, crop production statistics, amounts of fertilizer applied to crops, and trends in manure management practices. Climate factors like average temperature and moisture are also factored into the SIT analysis. The amount of manure methane captured through anaerobic digestion was assumed to follow current trends. The SIT methodology is based on international guidelines developed by sector experts for preparing GHG emissions inventories.

Data on crop production in Michigan from 1990 to 2005 and the number of animals in the state from 1990 to 2005 were obtained from the United States Department of Agriculture (USDA) National Agriculture Statistical Service (NASS) and incorporated as defaults in SIT.[78] The default SIT manure management system assumptions for each livestock category were used for this inventory.[79] SIT data on fertilizer usage came from *Commercial Fertilizers*, a report from the Fertilizer Institute. Activity data for fertilizer includes all potential uses in addition to agriculture, such as residential and commercial (e.g., golf courses). The estimates are reported in the agriculture sector but they represent emissions occurring on other land uses.[80]

Crop production data from USDA NASS were available through 2005; therefore, N_2O emissions from crop residues and crops that use nitrogen (i.e., nitrogen fixation) and N_2O and CH_4 emissions from agricultural residue burning were calculated through 2005. Emissions for the other agricultural crop production categories (i.e., synthetic and organic fertilizers) were also calculated through 2005. Data were not available to estimate nitrogen released by the cultivation of histosols (i.e., the number of acres of high organic content soils). Given that cultivation of organic soils is a source of CO_2 emissions in Michigan (see below), N_2O emissions are also probably occurring.

[77] GHG emissions were calculated using SIT, with reference to EIIP, Volume VIII: Chapter 8. "Methods for Estimating Greenhouse Gas Emissions from Livestock Manure Management", August 2004; Chapter 10. "Methods for Estimating Greenhouse Gas Emissions from Agricultural Soil Management", August 2004; and Chapter 11. "Methods for Estimating Greenhouse Gas Emissions from Field Burning of Agricultural Residues", August 2004.
[78] USDA, NASS (http://www.nass.usda.gov/Statistics_by_State/Michigan/index.asp).
[79] In calculating methane emissions for different livestock production systems, SIT uses a Methane Conversion Factor (MCF) developed by EPA that represents the extent to which the potential for emitting CH4 from volatile solids in the manure is realized (expressed as a percent). The MCF values used by SIT are specific to each state. Climate factors like higher temperature and moisture, as well as different manure management practices, impact a state's MCF.
[80] There is an issue of potential double-counting of N2O emissions from settlement soils. CCS has communicated this issue to EPA, who will assess changes in the next version of the SIT module to avoid any double-counting.

There is some agricultural residue burning conducted in Michigan; however, emissions are estimated to be relatively small (<0.03 $MMtCO_2e$). The default SIT method was used to calculate emissions. The SIT methodology calculates emissions by multiplying the amount (e.g., bushels or tons) of each crop produced by a series of factors to calculate the amount of crop residue produced and burned, the resultant dry matter, and the carbon/nitrogen content of the dry matter.

Emissions from enteric fermentation and manure management were projected based on forecasted animal populations. Dairy cattle forecasts were based on state-level projections of dairy cows from the Food and Agricultural Policy Research Institute (FAPRI).[81] Projections for all other livestock categories, except poultry, were estimated based on logarithmic forecasts of the historical 1990-2005 populations. Poultry populations were held at 2005 levels based on input from the poultry industry.[82] Livestock population growth rates are shown in Table F1.

Table F1. Growth Rates Applied for the Enteric Fermentation And Manure Management Categories

Livestock Category	2005-2025 Annual Growth
Dairy Cattle	0.14%
Beef Cattle	-1.48%
Swine	-2.69%
Sheep	-3.76%
Goats	-2.06%
Horses	0.75%
Turkeys	0.00%
Broilers	0.00%
Layers	0.00%

Projections for agricultural burning and agricultural soils were based on linear extrapolation of the 1990-2005 historical data. Table F2 shows the 2005-2025 annual growth rates estimated for each category.

Soil Carbon

Net carbon fluxes from agricultural soils have been estimated by researchers at the Natural Resources Ecology Laboratory at Colorado State University and are reported in the US Inventory of Greenhouse Gas Emissions and Sinks[83] and the US Agriculture and Forestry Greenhouse Gas Inventory. The estimates are based on the Intergovernmental Panel on Climate Change (IPCC) methodology for soil carbon adapted to conditions in the US. Preliminary state-level estimates of CO_2 fluxes from mineral soils and emissions from the cultivation of organic soils were reported in the US Agriculture and Forestry Greenhouse Gas Inventory. The inventory also reports

[81] FAPRI Agricultural Outlook 2006, Food and Agricultural Policy Research Institute, http://www.fapri.iastate.edu/outlook2006.
[82] C. Vollmer-Sanders, MI Farm Bureau, communicated to R. Anderson, CCS, via telephone, May 2008.
[83] US Inventory of Greenhouse Gas Emissions and Sinks: 1990-2005 (and earlier editions), US Environmental Protection Agency, Report # 430-R-07-002, April 2007. Available at: http://www.epa.gov/climatechange/emissions/usinventoryreport.html.

national estimates of CO_2 emissions from limestone and dolomite applications from the United States Geological Survey (USGS).[84] Currently, these are the best available data at the state-level for this category.

Table F2. Growth Rates Applied for the Agricultural Soils and Burning

Agricultural Category	2005-2025 Growth Rate
Agricultural Burning	1.37%
Liming of Agricultural Soils	-2.10%
Agricultural Soils – Direct Emissions	
Fertilizers	-2.65%
Crop Residues	0.22%
Nitrogen-Fixing Crops	-2%
Histosols	0%
Livestock	-3.96%
Agricultural Soils – Indirect Emissions	
Fertilizers	-1.89%
Livestock	-5.80%
Leaching/Runoff	-2.66%

Carbon dioxide fluxes resulting from specific management practices were reported. These practices include: conversions of cropland resulting in either higher or lower soil carbon levels; additions of manure; participation in the Federal Conservation Reserve Program (CRP); and cultivation of organic soils (with high organic carbon levels). For Michigan, Table F3 shows a summary of the latest estimates available from the USDA, which are for 1997.[85] These data show that changes in agricultural practices are estimated to result in net emission of 2.14 million metric tons (MMt) of CO_2 equivalent (CO_2e) per year in Michigan; this is driven largely by the cultivation of organic soils and the plowout of grassland to annual cropland in Michigan. Since data are not yet available from USDA to make a determination of whether the emissions are increasing or decreasing, emissions of 2.14 $MMtCO_2e$ per year are assumed to remain constant.

Note that emissions from agricultural soils estimated using the SIT were multiplied by a national adjustment factor to reconcile differences between methodologies used in the National Inventory of Greenhouse Gas Emissions and the SIT.

[84] State-level annual application rates of limestone and dolomite to agricultural purposes were provided from the Minerals Yearbook "Crushed Stone" from the USGS website: http://minerals.er.usgs.gov/minerals/pubs/commodity/stone_crushed/.

[85] US Agriculture and Forestry Greenhouse Gas Inventory: 1990-2001. Global Change Program Office, Office of the Chief Economist, US Department of Agriculture. Technical Bulletin No. 1907, 164 pp. March 2004. http://www.usda.gov/oce/global_change/gg_inventory.htm; the data are in appendix B table B-11. The table contains two separate IPCC categories: "carbon stock fluxes in mineral soils" and "cultivation of organic soils." The latter is shown in the second to last column of Table F3. The sum of the first nine columns is equivalent to the mineral soils category.

Table F3. GHG Emissions from Soil Carbon Changes Due to Cultivation Practices ($MMtCO_2e$)

Changes in cropland			Changes in Hayland				Other			Total[4]
Plowout of grassland to annual cropland[1]	Cropland manage-ment	Other cropland[2]	Cropland converted to hayland[3]	Hayland manage-ment	Cropland converted to grazing land[3]	Grazing land manage-ment	CRP	Manure application	Cultivation of organic soils	Net soil carbon emissions
2.09	(0.07)	(0.07)	(1.72)	(0.07)	(0.51)	(0.00)	(0.15)	(0.46)	3.12	2.14

Parentheses indicate net sequestration. Based on USDA 1997 estimates: US Agriculture and Forestry Greenhouse Gas Inventory: 1990-2001. Global Change Program Office, Office of the Chief Economist, US Department of Agriculture. Technical Bulletin No. 1907, 164 pp. March 2004. http://www.usda.gov/oce/global_change/gg_inventory.htm; the data are in appendix B table B-11. The table contains two separate IPCC categories: "carbon stock fluxes in mineral soils" and "cultivation of organic soils." The latter is shown in the second to last column of Table F3. The sum of the first nine columns is equivalent to the mineral soils category. [1] Losses from annual cropping systems due to plow-out of pastures, rangeland, hayland, set-aside lands, and perennial/horticultural cropland (annual cropping systems on mineral soils, e.g., corn, soybean, cotton, and wheat).
[2] Perennial/horticultural cropland and rice cultivation.
[3] Gains in soil carbon sequestration due to land conversions from annual cropland into hay or grazing land.
[4] Total does not include change in soil organic carbon storage on federal lands, including those that were previously under private ownership, and does not include carbon storage due to sewage sludge applications.

Results

Figure F1 and Table F4 show gross GHG emissions associated with the agricultural sector from 1990 through 2025. In 1990, enteric fermentation accounted for about 18.3% (1.53 $MMtCO_2e$) of total agricultural emissions. Enteric fermentation emissions decreased slightly to 1.40 $MMtCO_2e$ between 1990 and 2005 due to the decline in livestock populations in this time period. While the dairy cattle population is projected to remain relatively constant, there is a decrease in the projected beef cattle population, and enteric fermentation emissions are estimated to decrease to 1.29 $MMtCO_2e$ in 2025.

The manure management category accounted for 11.1% (0.92 $MMtCO_2e$) of total agricultural emissions in 1990 and increased to 13.5% (1.09 $MMtCO_2e$) in 2005. Manure management is projected to remain relatively constant at 13.8% (0.99 $MMtCO_2e$) in 2025. This is largely due to the projection that the dairy cow population was to stay relatively unchanged between 2005 and 2025.

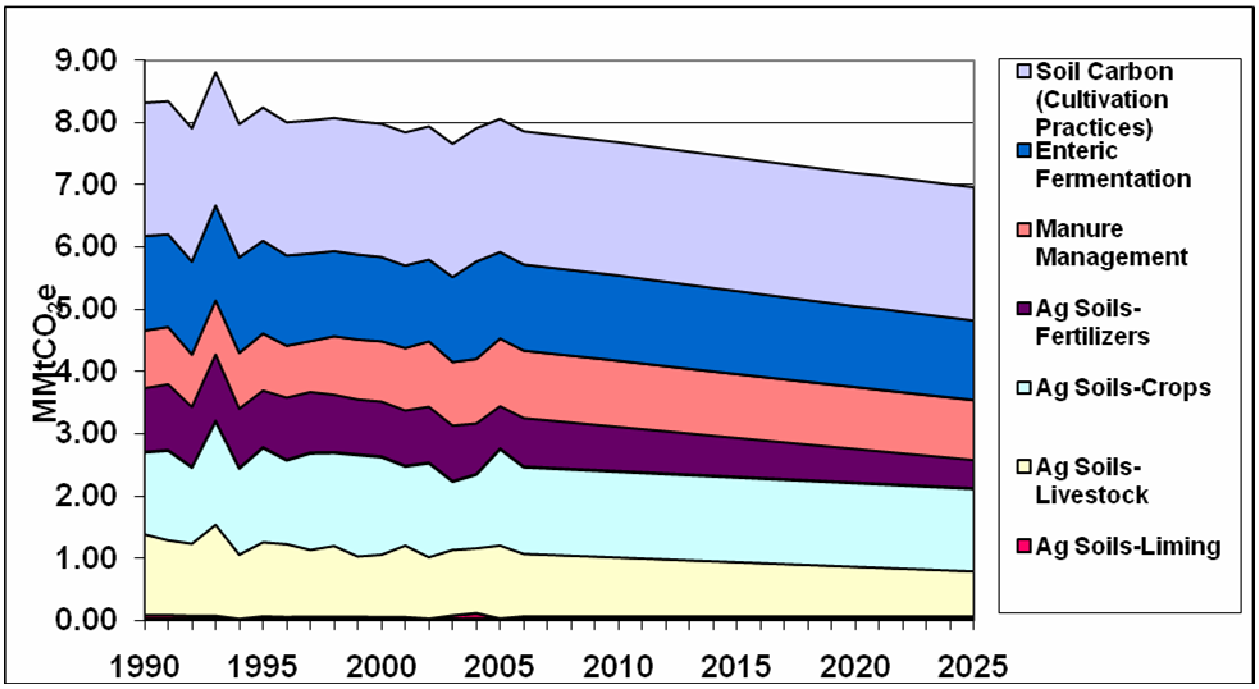
The largest source of emissions in the agricultural sector is the agricultural soils category, which includes crops (legumes and crop residues), fertilizer, manure application, application of limestone and dolomite, and indirect sources (leaching, runoff, and atmospheric deposition). Agricultural soils is projected to decrease from 1990 to 2025, with 1990 emissions accounting for 44.6% (3.71 $MMtCO_2e$) of total agricultural emissions and 2025 emissions estimated to be about 36.6% (2.55 $MMtCO_2e$) of total agricultural emissions.

As noted previously, cultivation of soils is estimated to be a net emissions source in Michigan. The emissions for this category are estimated to account for 25.7% of total agricultural emissions in 1990 and about 30.7% of total emissions in 2025. Since data are not yet available from USDA

to determine if emissions are increasing or decreasing, emissions of 2.14 $MMtCO_2e$ per year are assumed to remain constant throughout the inventory and forecast period.

The only standard IPCC source category missing from this report is N_2O emissions from the cultivation of histosols; there were no activity data available for Michigan.

Figure F1. Gross GHG Emissions from Agriculture, 1990-2025



Source: CCS calculations based on approach described in text.
Notes: Ag Soils – Crops category includes: incorporation of crop residues and nitrogen fixing crops (no cultivation of histosols estimated); emissions for agricultural residue burning are too small to be seen in this chart.

Table F4. Gross GHG Emissions from Agriculture in Michigan

Source	1990	1995	2000	2005	2010	2015	2020	2025
Enteric Fermentation	1.53	1.50	1.36	1.40	1.38	1.36	1.33	1.31
Manure Management	0.92	0.92	0.97	1.09	1.07	1.04	1.01	0.99
Ag Soils-Fertilizers	1.03	0.92	0.89	0.69	0.72	0.64	0.55	0.47
Ag Soils-Crops	1.32	1.52	1.57	1.55	1.38	1.36	1.35	1.33
Ag Soils-Livestock	1.30	1.19	1.01	1.18	0.95	0.87	0.80	0.73
Ag Soils-Liming	0.06	0.04	0.02	0.00	0.03	0.03	0.03	0.03
Agricultural Burning	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.04
Soil Carbon (Cultivation Practices)	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14
TOTAL	**8.33**	**8.25**	**7.99**	**8.07**	**7.71**	**7.47**	**7.25**	**7.03**

Key Uncertainties

Emissions from enteric fermentation and manure management are dependent on the estimates of animal populations and the various factors used to estimate emissions for each animal type and manure management system (i.e., emission factors which are derived from several variables including manure production levels, volatile solids content, and CH_4 formation potential). Each of these factors has some level of uncertainty. Also, animal populations fluctuate throughout the year, and thus using point estimates introduces uncertainty into the average annual estimates of these populations. In addition, there is uncertainty associated with the original population survey methods employed by USDA. The largest contributors to uncertainty in emissions from manure management are the emission factors, which are derived from limited data sets.

As mentioned above, for emissions associated with changes in agricultural soil carbon levels, the only data currently available are for 1997. When newer data are released by the USDA, these should be reviewed to represent current conditions as well as to assess trends. In particular, given the potential for some CRP acreage to retire and possibly return to active cultivation prior to 2025, the emissions could be appreciably affected.

Uncertainties in the estimates of emissions from liming result from both the emission factors and the activity data. It is uncertain what fraction of agricultural lime is dissolved by nitric acid – a process that releases CO_2 – and what portion reacts with carbonic acid (H_2CO_3), resulting in the uptake of CO_2. Also, there is uncertainty in the limestone and dolomite data (reported to USGS) as some producers do not distinguish between them, and report them both as limestone.

Another contributor to the uncertainty in the emission estimates is the forecast assumptions. The growth rates for most categories are assumed to continue growing at historical 1990-2005 growth rates. These historical trends may not reflect future projections.

Appendix G. Waste Management

Overview

Greenhouse gas (GHG) emissions from waste management include:

- Solid waste management – methane (CH_4) emissions from municipal and industrial solid waste landfills (LFs), accounting for CH_4 that is flared or captured for energy production (this includes both open and closed landfills) [86];
- Solid waste combustion – CH_4, carbon dioxide (CO_2), and nitrous oxide (N_2O) emissions from the combustion of solid waste in incinerators or waste to energy plants; and
- Wastewater management – CH_4 and N_2O from municipal wastewater (WW) and CH_4 from industrial wastewater treatment facilities.

Inventory and Reference Case Projections

Solid Waste Management

For solid waste management, the United States Environmental Protection Agency's (US EPA) State Inventory Tool (SIT) software was used to estimate emissions. Landfill emplacement and emissions control data were obtained from the Michigan Department of Environmental Quality (MDEQ).[87] MDEQ reports indicate that a significant fraction of waste disposed of in Michigan originated from other states or Canada [88] CCS did not apply the SIT assumption that 10% of CH_4 is oxidized as it travels through the surface layers of the landfill due to a lack of information to support this assumption.

Emissions for industrial solid waste landfills were estimated using the SIT default activity data and emission factors. The activity data are based on national data indicating that industrial landfilled waste is emplaced at approximately 7% of the rate of municipal solid waste (MSW) emplacement. It was assumed that this additional industrial waste emplacement occurs beyond that already addressed in the emplacement rates for MSW sites described above.

The amount of CH_4 captured for flaring and use in landfill gas-to-energy (LFGTE) plants was calculated based on waste emplacement data for controlled landfills and date of emission capture equipment installation. Information on controlled landfills was obtained from MDEQ and a database of landfill gas-to-energy (LFGTE) projects compiled by the EPA. Emissions factors and landfill control efficiencies (quantity methane captured vs. escaped) were obtained from EPA's SIT. The amount of landfill gas captured in Michigan may be underestimated if MI flaring and LFGTE controls have been underreported to MDEQ and EPA. CO_2 released upon thermal destruction of methane is not included in the inventory since it would be considered biogenic (originating from organic materials in the landfills).

[86] CCS acknowledges that N_2O and CH_4 emissions are also produced from the combustion of landfill gas; however, these emissions tend to be negligible for the purposes of developing a state-level inventory for policy analysis.
[87] Communicated to CCS by Timothy Unseld, MI DEQ, via email, January 2008.
[88] Annual Reports of Solid Waste Landfilled, Michigan Department of Environmental Quality, http://www.michigan.gov/deq/0,1607,7-135-3312-47581--,00.html.

Growth rates were estimated by using the historical (1999-2005) growth rates of total net emissions from landfills. The annual growth rates are 3.0% for MSW landfills and 3.3% for industrial landfills. The years 1999 through 2005 were used to calculate these growth rates since previous to that many flaring and LFGTE controls were not in place.

Solid Waste Combustion

SIT defaults were used to estimate emissions from solid waste combustion. The default volumes of waste combusted correlated well with a limited dataset provided by MDEQ .

Open burning of MSW at residential sites (e.g. backyard burn barrels) also contributes to GHG emissions. The US EPA's 2002 National Emissions Inventory estimates the quantity of waste burned at residential sites in Michigan.[89] Emissions from open burning were calculated using SIT emissions factors and waste characteristics for municipal waste combustion. The historical (2000-2005) growth rate of 0.95% for combined municipal and residential waste combustion was used to estimate future growth rates.

Wastewater Management

GHG emissions from municipal wastewater treatment were also estimated. For municipal wastewater treatment, emissions are calculated in EPA's SIT based on state population, assumed biochemical oxygen demand (BOD) and protein consumption per capita, and emission factors for N_2O and CH_4. The key SIT default values are shown in Table G1 below. Municipal wastewater emissions were projected based on the historical growth rate for 1990-2005 for a growth rate of 0.76% per year.

Table G1. SIT Key Default Values for Municipal Wastewater Treatment

Variable	Default Value
BOD	0.09 kilogram (kg) /day-person
Amount of BOD anaerobically treated	16.25%
CH_4 emission factor	0.6 kg/kg BOD
Michigan residents not on septic	75%
Water treatment N_2O emission factor	4.0 g N_2O/person-yr
Biosolids emission factor	0.01 kg N_2O-N/kg sewage-N

Source: US EPA State Greenhouse Gas Inventory Tool (SIT) – Wastewater Module.

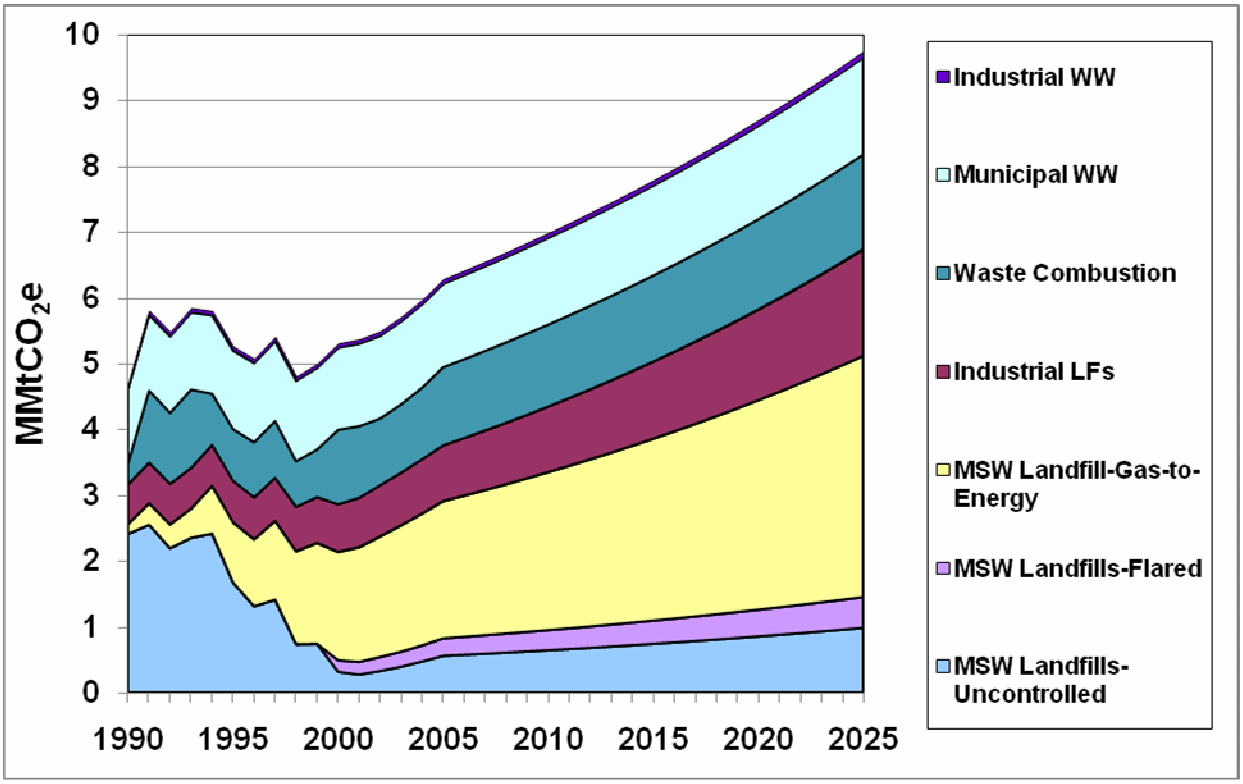
For industrial wastewater emissions, SIT provides default assumptions and emission factors for three industrial sectors: Fruits & Vegetables, Red Meat & Poultry, and Pulp & Paper. The SIT default activity data were used to estimate emissions for red meat production; however, default data were not available for the other sectors. Emissions were projected to 2025 based on the 1990-2005 annual growth rate (1.9%).

[89] EPA, ftp://ftp.epa.gov/EmisInventory/2002finalnei/documentation/nonpoint/2002nei_final_nonpoint_documentation0206version.pdf

Results

Figure G1 and Table G2 show the emission estimates for the waste management sector. Overall, the sector accounts for 6.28 $MMtCO_2e$ in 2005, and emissions are estimated to be 9.74 $MMtCO_2e$/yr in 2025.

Figure G1. Michigan GHG Emissions from Waste Management, 1990-2025



Source: Based on approach described in text.

Table G2. Michigan GHG Emissions from Waste Management ($MMtCO_2e$)

Source	1990	1995	2000	2005	2010	2015	2020	2025
MSW Landfills - Gas-to-Energy	0.15	0.91	1.64	2.08	2.40	2.76	3.18	3.67
MSW Landfills - Flared	0.00	0.00	0.17	0.27	0.31	0.35	0.41	0.47
MSW Landfills - Uncontrolled	2.41	1.67	0.32	0.56	0.64	0.74	0.85	0.98
Industrial Landfills	0.60	0.63	0.73	0.85	1.00	1.17	1.38	1.62
Waste Combustion	0.33	0.80	1.14	1.20	1.26	1.32	1.38	1.45
Municipal Wastewater	1.13	1.19	1.25	1.27	1.32	1.37	1.42	1.47
Industrial Wastewater	0.04	0.05	0.05	0.06	0.06	0.07	0.08	0.09
Total	**4.67**	**5.26**	**5.30**	**6.28**	**6.98**	**7.78**	**8.70**	**9.74**

The largest contributor to waste management emissions is the solid waste sector, in particular, municipal landfills. In 2005, municipal landfills accounted for 46% of total waste management emissions. In 2005, 72% of municipal landfill emissions are from escaped from LFGTE landfills, 9% are escaped emissions from flared landfills, and the remaining 19% are from uncontrolled

landfills. By 2025, the contribution from municipal landfills is expected to increase slightly to about 53%. Industrial landfills accounted for about 14% of waste management emissions in 2005, and 17% in 2025.

In 2005, about 20% of the waste management sector emissions were contributed by municipal wastewater treatment systems and 1% of emissions were contributed by the industrial wastewater subsector. Note that these estimates are based on the default parameters listed in Table G1 above, and might not adequately account for emissions, existing controls, or management practices (e.g. anaerobic digesters served by a flare or other combustion device). By 2025, municipal and industrial wastewater treatment subsectors are expected to contribute about 15% and 1%, respectively of the waste management sector emissions.

Emissions from waste combustion accounted for 19% of total waste management emissions in 2005 and are projected to account for 15% in 2025.

Key Uncertainties

For municipal waste landfills, the modeling also does not account for uncontrolled landfills that will need to apply controls during the period of analysis due to triggering requirements of the federal New Source Performance Standards/Emission Guidelines.

The inventory and forecast accounts for all waste emplaced in MI, regardless of state or country of origin. Although MDEQ reports indicate that a significant percentage of waste emplaced in Michigan is imported from other states and Canada (approximately 29% in FY 2005), insufficient historical data is available to simultaneously account for imported waste and landfill controls. Estimates of waste emissions whose origin is imported can be calculated but will be overestimated because they will not include landfill control information. To the extent that any waste is exported out of state for management, the inventory and forecast should attempt to capture these emissions as well. This additional detail on waste exports will be incorporated based on available data from MDEQ.

For industrial landfills, emissions were estimated using national defaults (with industrial landfill emissions approximately 7% of MSW emissions). MDEQ has provided waste emplacement data for industrial landfills. However, emissions factors for industrial waste are not currently available in the EPA SIT.

Open burning of waste at residential sites was estimated using a US EPA NEI methodology and SIT emissions factors and waste composition defaults. Depending on actual burn rates and waste composition, this could be an over- or underestimate. Emissions from open burning of yard waste were not estimated but are expected to be small (only the CH_4 and N_2O emissions would be of interest here, since the CO_2 would be considered to be biogenic).

For the wastewater sector, the key uncertainties are associated with the application of SIT default values for the parameters listed in Table G1 above (e.g. fraction of the Michigan population on septic; fraction of BOD which is anaerobically decomposed). The SIT defaults were derived from national data.

For industrial wastewater, emissions were only estimated for the red meat industry using default data; default data for fruits and vegetables, poultry, and pulp and paper were not available. Therefore, emissions from industrial wastewater are likely to be underestimated. MDEQ has been contacted to provide wastewater data.

This emission inventory for the waste management sector will be revised to address the issues discussed above. In addition, the MCAC and the agriculture, forestry, and waste technical work group will be asked to provide additional data, where available, that can be used to refine this waste management inventory.

Appendix H. Forestry & Land Use

Overview

Forestland emissions refer to the net carbon dioxide (CO_2) flux[90] from forested lands in Michigan, which account for about 53% of the state's land area.[91] The dominant forest type in Michigan is Maple-beech-birch which makes up about 38% of forested lands. Other common forest types are Aspen-birch at 17% of forested land, Spruce-fir at 15%, White-red-jack pine at 11%, Oak-hickory at 10%, and Elm-ash-cottonwood at 9% of forested land.

Through photosynthesis, CO_2 is taken up by trees and plants and converted to carbon in biomass within the forests. Carbon dioxide emissions occur from respiration in live trees, decay of dead biomass, and combustion (both wildfires and biomass removed from forests for energy use). In addition, carbon is stored for long time periods when forest biomass is harvested for use in durable wood products. Carbon dioxide flux is the net balance of CO_2 removals from and emissions to the atmosphere from the processes described above.

The forestry sector CO_2 flux is categorized into two primary subsectors:

- *Forested Landscape:* this consists of carbon flux occurring on lands that are not part of the urban landscape. Fluxes covered include net carbon sequestration, carbon stored in harvested wood products (HWP) or landfills, and emissions from forest fires.
- *Urban Forestry and Land Use:* this covers carbon sequestration in urban trees, flux associated with carbon storage from landscape waste and food scraps in landfills, and nitrous oxide (N_2O) emissions from settlement soils (those occurring as a result of application of synthetic fertilizers).

Inventory and Reference Case Projections

Forested Landscape

For over a decade, the United States Forest Service (USFS) has been developing and refining a forest carbon modeling system for the purposes of estimating forest carbon inventories. The methodology is used to develop national forest CO_2 fluxes for the official *US Inventory of Greenhouse Gas Emissions and Sinks*. The national estimates are compiled from state-level data. The Michigan forest CO_2 flux data in this report come from the national analysis and are provided by the USFS. See the footnotes below for the most current documentation for the forest carbon modeling.[92] Additional forest carbon information is in the form of specific carbon conversion factors.[93]

[90] "Flux" refers to both emissions of CO_2 to the atmosphere and removal (sinks) of CO_2 from the atmosphere.
[91] Total forested acreage is 19.3 million acres in 1997. Acreage by forest type available from the USFS at: http://www.fs.fed.us/ne/global/pubs/books/epa/states/MI.htm. The total land area in Michigan is 36 million acres (http://www.50states.com/Michigan.htm).
[92] The most current citation for an overview of how the USFS calculates the inventory based forest carbon estimates as well as carbon in harvested wood products is from the US Inventory of Greenhouse Gas Emissions and Sinks: 1990-2005 (and earlier editions), US Environmental Protection Agency, Report # USEPA #430-R-07-002, April 2007, available at: http://epa.gov/climatechange/emissions/usinventoryreport.html. Both Annex 3.12 and Chapter 7

The forest CO_2 flux methodology relies on input data in the form of plot-level forest volume statistics from the Forest Inventory Analysis (FIA). FIA data on forest volumes are converted to values for ecosystem carbon stocks (i.e., the amount of carbon stored in forest carbon pools) using the FORCARB2 modeling system. Coefficients from FORCARB2 are applied to the plot level survey data to give estimates of C density [megagrams (Mg) per hectare] for a number of separate C pools. Additional background on the FORCARB system is provided in a number of publications.[94]

Carbon dioxide flux is estimated as the change in carbon mass for each carbon pool over a specified time-frame. Forest biomass data from at least two points in time are required. The change in carbon stocks between time intervals is estimated for specific carbon pools (Live Tree, Standing Dead Wood, Understory, Down & Dead Wood, Forest Floor, and Soil Organic Carbon) and divided by the number of years between inventory samples. Annual increases in carbon density reflect carbon sequestration in a specific pool; decreases in carbon density reveal CO_2 emissions or carbon transfers out of that pool (e.g., death of a standing tree transfers carbon from the live tree to standing dead wood pool). The amount of carbon in each pool is also influenced by changes in forest area (e.g., an increase in area could lead to an increase in the associated forest carbon pools and the estimated flux). The sum of carbon stock changes for all forest carbon pools yields a total net CO_2 flux for forest ecosystems.

In preparing these estimates, USFS estimates the amount of forest carbon in different forest types as well as different carbon pools. The different forests also include differences in ownership class: those in the national forest (NF) system and those that are not federally-owned (private and other public forests). Additional details on the forest carbon inventory methods can be found in Annex 3 to the US EPA's 2007 GHG inventory for the US.[95]

Carbon pool data for four FIA cycles to estimate flux for three different periods were available for Michigan. The carbon pool data for three points are shown in Table H1 below. Note that prior to 1993, FIA had a variable schedule for taking Michigan forest inventory samples. Beginning in 2000, Michigan transitioned from periodic to annual inventories as modifications to the FIA program were applied. The annual inventories are on a 5-year cycle and sample 20% of the state forests each year. Michigan completed its first annual inventory cycle in 2004. The

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LULUCF are useful sources of reference. See also Smith, J.E., L.S. Heath, and M.C. Nichols (in press), *US Forest Carbon Calculation Tool User's Guide: Forestland Carbon Stocks and Net Annual Stock Change*, Gen Tech Report, Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station.

[93] Smith, J.E., and L.S. Heath (2002). "A model of forest floor carbon mass for United States forest types," Res. Pap. NE-722. Newtown Square, PA: US Department of Agriculture, Forest Service, Northeastern Research Station. 37 p., or Jenkins, J.C., D.C. Chojnacky, L.S. Heath, R.A. Birdsey (2003), "National-scale biomass estimators for United States tree species", *Forest Science*, 49:12-35.

[94] Smith, J.E., L.S. Heath, and P.B. Woodbury (2004). "How to estimate forest carbon for large areas from inventory data", *Journal of Forestry*, 102: 25-31; Heath, L.S., J.E. Smith, and R.A. Birdsey (2003), "Carbon trends in US forest lands: A context for the role of soils in forest carbon sequestration", In J. M. Kimble, L. S. Heath, R. A. Birdsey, and R. Lal, editors. *The Potential of US Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect.* CRC Press, New York; and Woodbury, Peter B.; Smith, James E.; Heath, Linda S. 2007, "Carbon sequestration in the US forest sector from 1990 to 2010", *Forest Ecology and Management*, 241:14-27.

[95] Annex 3 to EPA's 2007 report, which contains estimates for calendar year 2005, can be downloaded at: http://www.epa.gov/climatechange/emissions/downloads06/07Annex3.pdf.

2005 carbon pool data represents 20% of the next 5-year inventory cycle that is yet to be completed.

The underlying FIA data, as shown in Table H1, display a net increase in forested area for all sample years: 912 thousand acres between 1980 and 1993, and 58 thousand acres between 1993 and 2005. This results in a net increase in forested area of 970 thousand acres in the 1980-2005 period. Most of the forested lands in Michigan are considered timberland, meaning they are unreserved productive forest land producing, or capable of producing, crops of industrial wood. The timberland area is shown to have increased by 1.1 million acres between 1980 and 1993, while it only increased 191 thousand acres between 1993 and 2005. This increase in timberland area resulted in the tremendous increase in carbon (177 million metric tons) from forested areas between 1980 and 1993. The decrease in carbon stocks between 1993 and 2005 may possibly be due to the slower growth in timberland area during this period. It is also important to note that the 1993 data included modeled plots, and there are other changes in inventory sampling methods between the 1993 and 2005 FIA reporting years, which could lead to bias or error in the estimates.

Table H1. USFS Forest Carbon Pool Data for Michigan

Forest Pool	1980 (MMtC)	1993 (MMtC)	2005 (MMtC)
Live Tree – Above Ground	384	475	472
Live Tree – Below Ground	76.3	93.8	93.4
Understory	12.8	13.1	13.4
Standing Dead	33.4	36.2	35.3
Down Dead	35.5	43.6	43.2
Forest Floor	145	160	153
Soil Carbon	1,160	1,202	1,166
Totals	**1,847**	**2,024**	**1,976**
Totals (without soil carbon)	**687**	**822**	**810**
Forest Area	**1980 (10^3 acres)**	**1993 (10^3 acres)**	**2005 (10^3 acres)**
All Forests	18,369	19,281	19,339
Timberland	17,493	18,616	18,807

MMtC = million metric tons of carbon. Positive numbers indicate net emission. Multiply MMtC by 3.667 (44/12) to convert to $MMtCO_2$.

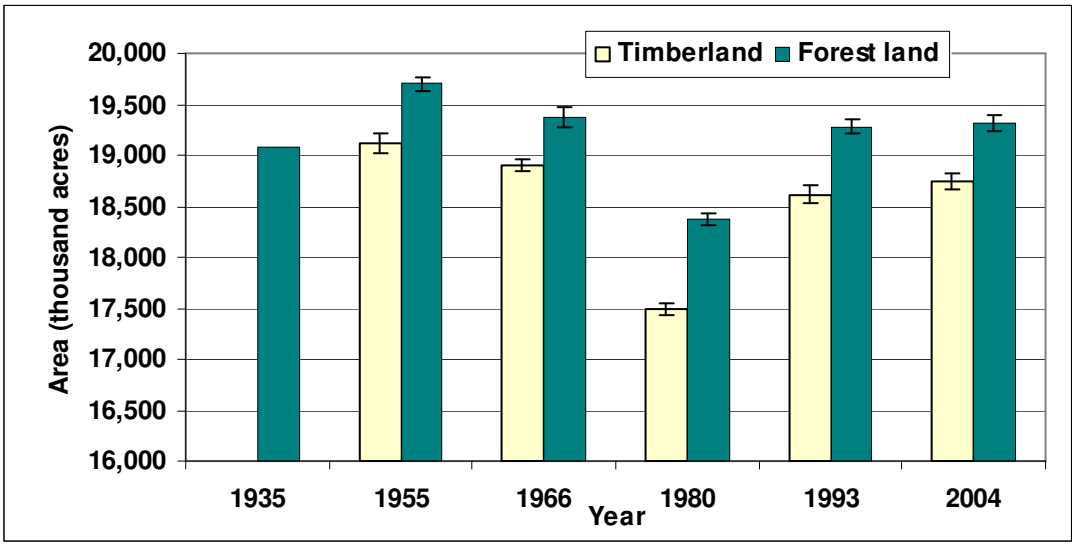
Totals may not sum exactly due to independent rounding.

Data source: Smith, James, et al. *US Forest Carbon Calculation Tool: Forest-Land Carbon Stocks and Net Annual Stock Change* (http://www.nrs.fs.fed.us/pubs/2394), November 2007.

To further illustrate the historical changes in both timberland and all forested lands, Figure H1 provides additional data back to 1935. This chart clearly shows the losses of acreage from the mid-1950's and 1980, followed by the fairly rapid expansion of acreage into the early 1990's.[96]

[96] Provided by L. Pedersen, MIDNR Forest, Mineral and Fire Management, to S. Roe, CCS, April 30, 2008.

Figure H1. USFS Forest Carbon Pool Data for Michigan



In addition to the forest carbon pools, additional carbon is stored in biomass removed from the forest for the production of HWP. Carbon remains stored in the durable wood products pool or is transferred to landfills where much of the carbon remains stored over a long period of time. The USFS uses a model referred to as WOODCARB2 for the purposes of modeling national HWP carbon storage.[97] State-level information for Michigan was provided to CCS by USFS[98].

As shown in Table H2, about 2.6 million metric tons (MMt) of CO_2 per year (yr) is estimated by the USFS to be sequestered annually (1980-2005) in wood products. Also, as shown in this table, the total flux estimate including all forest pools fluctuates between -33 $MMtCO_2e/yr$ and 6.9 $MMtCO_2e/yr$ between 1980 and 2005.[99] This fluctuation is largely due to significant differences in forest carbon pools from each cycle period as well as the increase in soil organic carbon source. Note that from 1980 to 1993, soil carbon was estimated to be a net sink.

Based on discussions with the USFS, CCS recommends excluding the soil carbon pool from the overall forest flux estimates due to a high level of uncertainty associated with these estimates. The forest carbon flux estimates provided in the summary tables at the front of this report are those without the soil carbon pool. The resulting estimates provided at the bottom of Table H2 are in line with the observed changes in forest area during this time period (i.e. large increases in the early period, followed by smaller increases since the mid-1990's).[100]

[97] Skog, K.E., and G.A. Nicholson (1998), "Carbon cycling through wood products: the role of wood and paper products in carbon sequestration", *Forest Products Journal*, 48(7/8):75-83; or Skog, K.E., K. Pingoud, and J.E. Smith (2004), "A method countries can use to estimate changes in carbon stored in harvested wood products and the uncertainty of such estimates", *Environmental Management*, 33(Suppl. 1): S65-S73.
[98] Obtained from the Harvested Wood Product model developed by Ken Skog, USFS
[99] Jim Smith, USFS, *US. Forest Carbon Calculation Tool: Forest-Land Carbon Stocks and Net Annual Stock Change* (http://www.nrs.fs.fed.us/pubs/2394), November 2007.
[100] Note that the data on carbon stocks in shown in Table H1 show a slightly smaller carbon pool in 2005 as compared to 1993, suggesting a net positive flux over this period. CCS used the average flux during each year estimated using CCT to generate the forest carbon flux estimates shown in Table H2, thereby minimizing the influence of estimates in individual years and shifts between FIA measurements.

Table H2. USFS Annual Forest CO_2 Fluxes for Michigan

Forest Pool	1980-1993 Flux ($MMtCO_2$/yr)	1994-2005 Flux ($MMtCO_2$/yr)
Forest Carbon Pools (non-soil)	-25.2	-6.17
Soil Organic Carbon	-4.84	15.6
Harvested Wood Products	-2.60	-2.60
Totals	**-32.7**	**6.86**
Totals (excluding soil carbon)	**-27.8**	**-8.77**

Totals may not sum exactly due to independent rounding.
Data source: Smith, James, et al. US Forest Carbon Calculation Tool: Forest-Land Carbon Stocks and Net Annual Stock Change (http://www.nrs.fs.fed.us/pubs/2394), USFS, November 2007.

For historical emission estimates, CCS used the 1980-1993 and 1994-2005 carbon fluxes to represent forest carbon flux prior to 2005. Current flux estimates (1994-2005) are those based on the average calculated flux during this period using the Carbon Calculation Tool. For the reference case projections (2005-2025), the forest area and carbon densities of forestlands were assumed to remain at the same levels as in 2005. Information is not available on the near term effects of climate change and their impacts on forest productivity. Nor were data readily-available on projected losses in forested area.

Biomass burned in forest fires emits CO_2, methane (CH_4), and N_2O, in addition to many other gases and pollutants. Since CO_2 emissions are captured under total carbon flux calculations, CCS used the United States Environmental Protection Agency's (US EPA) StateInventory Tool (SIT) to estimate CH_4 and N_2O emissions. No default data were available for area burned by forest type, so CCS used available state data (1992-2005) from Michigan Department of Natural Resources (MDNR).[101] An average of the wildfire acres burned data was used for the years 1990-2005 and the forest type of "other temperate forests" was assumed in the SIT to calculate historical emissions. Projected emissions for 2005-2025 were assumed to be held constant at 2005 emissions.

Urban Forestry & Land Use

GHG emissions from urban forestry and land use for 1990 through 2005 were estimated using the EPA SIT software and the methods provided in the Emission Inventory Improvement Program (EIIP) guidance document for this sector.[102] In general, the SIT methodology applies emission factors developed for the US to activity data for the urban forestry sector. Activity data include urban area, urban area with tree cover, amount of landfilled yard trimmings and food scraps, and the total amount of synthetic fertilizer applied to settlement soils (e.g., parks, yards,

[101] Wildfire acres burned data obtained from personal communication with Donald Johnson of Michigan Department of Natural Resources, Forest, Mineral, & Fire Management Division.
[102] GHG emissions were calculated using SIT, with reference to EIIP, Volume VIII: Chapter 8.

etc.). This methodology is based on international guidelines developed by sector experts for preparing GHG emissions inventories.[103] Table H3 displays the emissions and reference case projections for Michigan.

Table H3. Urban Forestry Emissions and Reference Case Projections ($MMtCO_2e$)

	1990	2000	2005	2010	2020	2025
Urban Trees	-1.67	-2.03	-2.20	-2.20	-2.20	-2.20
Landfilled Yard Trimmings and Food Scraps	-8.49	-1.76	-1.81	-1.81	-1.81	-1.81
N_2O from Settlement Soils	0.10	0.10	0.11	0.11	0.11	0.11
Total	**-10.1**	**-3.69**	**-3.91**	**-3.91**	**-3.91**	**-3.91**

*Data for settlement soils was obtained from AAPFCO (2006) Commercial Fertilizers 2005. Association of American Plant Food Control Officials and The Fertilizer Institute. University of Kentucky, Lexington, KY.

Changes in carbon stocks in urban trees are equivalent to tree growth minus biomass losses resulting from pruning and mortality. Net carbon sequestration was calculated using data on crown cover area. The default urban area data in SIT (which varied from 7,272 square kilometers [km^2] to 9,590 km^2 between 1990 and 2005) was multiplied by the state estimate of the percent of urban area with tree cover (30% for Michigan) to estimate the total area of urban tree cover. These default SIT urban area tree cover data represent area estimates taken from the US Census and coverage for years 1990 and 2000.[104] Estimates of urban area in the intervening years (1990-1999) and subsequent years (2001-2005) are interpolated and extrapolated, respectively.

Estimates of net carbon flux of landfilled yard trimmings and food scraps were calculated by estimating the change in landfill carbon stocks between inventory years. The SIT estimates for the amount of landfilled yard trimmings decreased significantly during the 1990's. CCS believes that this is consistent with changes in the waste management industry during this period. Therefore, the forecast was based on an extrapolation of the flux from 2000-2005, which show relatively constant rates of landfilling these materials.

Settlement soils include all developed land, transportation infrastructure, and human settlements of any size. Projections for urban trees and settlement soils were kept constant at 2005 levels. Table H4 provides a summary of the estimated flux for the entire forestry and land use sector.

Table H4. Forestry and Land Use Flux and Reference Case Projections ($MMtCO_2e$)

	1990	2000	2005	2010	2020	2025

[103] Revised 1996 1ntergovermental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, published by the National Greenhouse Gas Inventory Program of the IPCC, available at (http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm; and Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, published in 2000 by the National Greenhouse Gas Inventory Program of the IPCC, available at: (http://www.ipcc-nggip.iges.or.jp/public/gp/english/).

[104] Dwyer, John F.; Nowak, David J.; Noble, Mary Heather; Sisinni, Susan M. 2000. Connecting people with ecosystems in the 21st century: an assessment of our nation's urban forests. Gen. Tech. Rep. PNW-GTR-490

Forested Landscape (excluding soil carbon)	-27.8	-8.77	-8.77	-8.77	-8.77	-8.77
Urban Forestry and Land Use	-10.1	-3.69	-3.91	-3.91	-3.91	-3.91
Forest Wildfires	0.02	0.02	0.02	0.02	0.02	0.02
Sector Total	**-37.9**	**-12.4**	**-12.7**	**-12.7**	**-12.7**	**-12.7**

Key Uncertainties

Emissions from wildfires in Michigan were estimated based on State acres burned data from 1992-2005. 1990 and 1991 acres burned data were not available so the emissions were based on the average of 1992-2005 emissions. Future forecasts are hard to estimate given the large swings in fire activity from year to year. Emissions from wildfires in Michigan are very small and they do not impact the estimated flux significantly.

It is important to note that there were methodological differences in the four FIA cycles (used to calculate carbon pools and flux) that can produce different estimates of forested area and carbon density. For example, the FIA program modified the definition of forest cover for the woodlands class of forestland (considered to be non-productive forests). Earlier FIA cycles defined woodlands as having a tree cover of at least 10%, while the newer sampling methods used a woodlands definition of tree cover of at least 5% (leading to more area being defined as woodland). In woodland areas, the earlier FIA surveys might not have inventoried trees of certain species or with certain tree form characteristics (leading to differences in both carbon density and forested acreage). Given that the forested land in Michigan is dominated by timberlands (productive forests), CCS does not believe that the definitional differences noted above have had a significant impact on the forest flux estimates provided in this report.

Also, FIA surveys since 1999 include all dead trees on the plots, but data prior to that are variable in terms of these data. The modifications to FIA surveys are a result of an expanded focus in the FIA program, which historically was only concerned with timber resources, while more recent surveys have aimed at a more comprehensive gathering of forest biomass data. In addition, the FIA program has moved from periodic to annual inventory methods – FIA now has Michigan on a continuous 5-year cycle. The effect of these changes in survey methods has not been estimated by the USFS.

Regarding the forecast for the forested landscape, potentially the largest source of uncertainty relates to the influence that future changes in climate will have on Michigan's forests to sequester carbon. Regarding future land use change, FIA data indicate that forested acreage is increasing at the state-level. It is unclear whether these trends will continue. Land use change to developed use could be coming more from uses other than forestry. For example, a recent study by University of Michigan researchers in northeast MI indicated that agriculture was the land use type most impacted by development.[105]

[105] Bergen, K.M. et al, "Development of a Method for Remote Sensing of Land-Cover Change 1980-2000 in the USFS North Central Region Using Heterogeneous USGS LUDA and NOAA AVHRR 1 km Data", http://www.ncrs.fs.fed.us/4153/deltawest/landcover/LandCover.pdf, accessed June 23, 2008.

Much of the urban forestry & land use emission estimates rely on national default data and could be improved with state-specific information.

Appendix I. Greenhouse Gases and Global Warming Potential Values: Excerpts from the Inventory of US Greenhouse Emissions and Sinks: 1990-2000

Original Reference: Material for this Appendix is taken from the *Inventory of US Greenhouse Gas Emissions and Sinks: 1990 - 2000*, US Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-02-003, April 2002 www.epa.gov/globalwarming/publications/emissions. Michael Gillenwater directed the preparation of this appendix.

Introduction

The *Inventory of US Greenhouse Gas Emissions and Sinks* presents estimates by the United States government of US anthropogenic greenhouse gas emissions and removals for the years 1990 through 2000. The estimates are presented on both a full molecular mass basis and on a Global Warming Potential (GWP) weighted basis in order to show the relative contribution of each gas to global average radiative forcing.

The Intergovernmental Panel on Climate Change (IPCC) has recently updated the specific global warming potentials for most greenhouse gases in their Third Assessment Report (TAR, IPCC 2001). Although the GWPs have been updated, estimates of emissions presented in the US *Inventory* continue to use the GWPs from the Second Assessment Report (SAR). The guidelines under which the *Inventory* is developed, the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines for national inventories[106] were developed prior to the publication of the TAR. Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. This excerpt of the US *Inventory* addresses in detail the differences between emission estimates using these two sets of GWPs. Overall, these revisions to GWP values do not have a significant effect on US emission trends.

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

What is Climate Change?

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

The Earth naturally absorbs and reflects incoming solar radiation and emits longer wavelength terrestrial (thermal) radiation back into space. On average, the absorbed solar radiation is balanced by the outgoing terrestrial radiation emitted to space. A portion of this terrestrial radiation, though, is itself absorbed by gases in the atmosphere. The energy from this absorbed terrestrial radiation warms the Earth's surface and atmosphere, creating what is known as the

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

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

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

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

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

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

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

Greenhouse Gases

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

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

Naturally occurring greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that

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

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

Carbon dioxide, methane, and nitrous oxide are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities, however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes—except when directly or indirectly perturbed out of equilibrium by anthropogenic activities—generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table I1.

Table I1. Global Atmospheric Concentration (ppm Unless Otherwise Specified), Rate of Concentration Change (ppb/year) and Atmospheric Lifetime (Years) of Selected Greenhouse Gases

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

Source: IPCC (2001)
[a] Concentrations in parts per trillion (ppt) and rate of concentration change in ppt/year.
[b] Rate is calculated over the period 1990 to 1999.
[c] Rate has fluctuated between 0.9 and 2.8 ppm per year for CO_2 and between 0 and 0.013 ppm per year for CH_4 over the period 1990 to 1999.
[d] No single lifetime can be defined for CO_2 because of the different rates of uptake by different removal processes.
[e] This lifetime has been defined as an "adjustment time" that takes into account the indirect effect of the gas on its own residence time.

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

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

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

some non-energy production processes (e.g., cement production) also emit notable quantities of carbon dioxide.

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

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

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

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

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

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

in the category referred to as "criteria pollutants" in the United States under the Clean Air Act and its subsequent amendments. The tropospheric concentrations of ozone and these other pollutants are short-lived and, therefore, spatially variable.

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

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

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

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

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

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

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

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

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

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

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

Global Warming Potentials

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

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

Tg CO_2 Eq. = Teragrams of Carbon Dioxide Equivalents
Gg = Gigagrams (equivalent to a thousand metric tons)
GWP = Global Warming Potential
Tg = Teragrams

GWP values allow policy makers to compare the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of roughly ±35 percent, though some GWPs have larger uncertainty than others, especially those in which lifetimes have not yet been ascertained. In the following decision, the parties to the UNFCCC have agreed to use consistent GWPs from the IPCC Second Assessment Report (SAR), based upon a 100 year time horizon, although other time horizon values are available (see Table I2).

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

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

Table I2. Global Warming Potentials (GWP) and Atmospheric Lifetimes (Years) Used in the Inventory

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

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

Table I3 presents direct and net (i.e., direct and indirect) GWPs for ozone-depleting substances (ODSs). Ozone-depleting substances directly absorb infrared radiation and contribute to positive radiative forcing; however, their effect as ozone-depleters also leads to a negative radiative forcing because ozone itself is a potent greenhouse gas. There is considerable uncertainty regarding this indirect effect; therefore, a range of net GWPs is provided for ozone depleting substances.

Table I3. Net 100-year Global Warming Potentials for Select Ozone Depleting Substances*

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

Source: IPCC (2001)
* Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as ozone depleting substances (ODSs). However, they are also potent greenhouse gases. Recognizing the

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

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

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

References

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