Energy, Industry, and Waste Management Activities: An Introduction to CO_2 Emissions From Fossil Fuels

Coordinating Lead Author: Gregg Marland, ORNL and Mid Sweden Univ. (Östersund)

Contributing Authors: Robert J. Andres, Univ. N. Dak.; T.J. Blasing, ORNL; Thomas A. Boden, ORNL; Christine T. Broniak, Oreg. State Univ.; Jay S. Gregg, Univ. Md.; London M. Losey, Univ. N. Dak.; Karen Treanton, IEA (Paris)

II.1 THE CONTEXT

Fossil fuels (coal, oil, and natural gas) are used primarily for their concentration of chemical energy, energy that is released as heat when the fuels are burned. Fossil fuels are composed primarily of compounds of hydrogen and carbon, and when the fuels are burned, the hydrogen and carbon oxidize to water and carbon dioxide (CO_2) and heat is released. If the water and CO_2 are released to the atmosphere, the water will soon fall out as rain or snow. The CO_2, however, will increase the concentration of CO_2 in the atmosphere and join the active cycling of carbon that takes place among the atmosphere, biosphere, and hydrosphere. Since humans began taking advantage of fossil-fuel resources for energy, we have been releasing to the atmosphere, over a very short period of time, carbon that was stored deep in the Earth over millions of years. We have been introducing a large perturbation to the active cycling of carbon.

Estimates of fossil-fuel use globally show that there have been significant emissions of CO_2 dating back at least to 1750, and from North America, back at least to 1785. However, this human perturbation of the active carbon cycle is largely a recent process, with the magnitude of the perturbation growing as population grows and demand for energy grows. Over half of the CO_2 released from fossil-fuel burning globally has occurred since 1980 (Figure II.1).

Some CO_2 is also released to the atmosphere during the manufacture of cement. Limestone ($CaCO_3$) is heated to release CO_2 and produce the calcium oxide (CaO) used to manufacture cement. In North America, cement manufacture now releases less than 1% of the mass of CO_2 released by fossil-fuel combustion. However, cement manufacture is the third largest human-caused (anthropogenic) source of CO_2 (after fossil-fuel use and the clearing and oxidation of forests and soils; see Part III this report). The CO_2 emissions from cement manufacture are often included with the accounting of anthropogenic CO_2 emissions from fossil fuels.

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Part II of this report addresses the magnitude and pattern of CO_2 emissions from fossil-fuel consumption and cement manufacture in North America. This introductory section addresses some general issues associated with CO_2 emissions and the annual and cumulative magnitude of total emissions. It looks at the temporal and spatial dis-

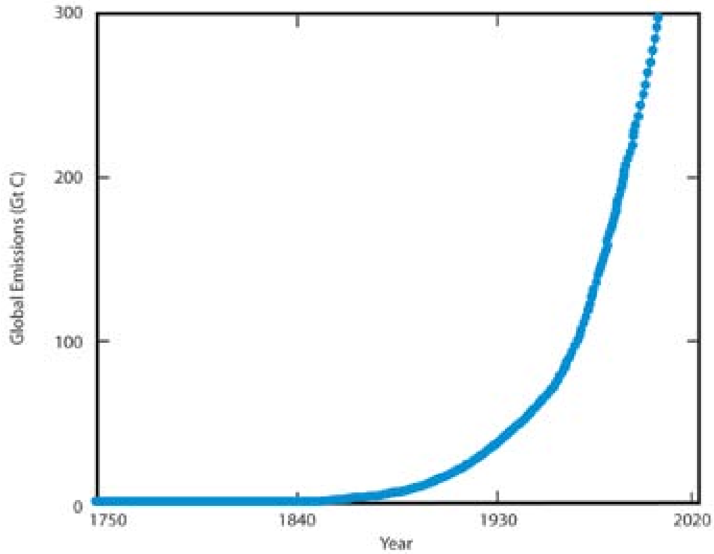

Figure II.1 Cumulative global emmissions of CO_2 from fossil-fuel combustion and cement manufacture from 1751 to 2002. *Source data:* Marland *et al.* (2005).

tribution of emissions and other data likely to be of interest. The following four chapters delve into the sectoral details of emissions so that we can understand the forces that have driven the growth in emissions to date and the possibilities for the magnitude and pattern of emissions in the future. These chapters reveal, for example, that 38% of CO_2 emissions from North America come from enterprises whose primary business is to provide electricity and heat and another 31% come from the transport of passengers and freight. This introduction focuses on the total emissions from the use of fossil fuels and the subsequent chapters provide insight into how these fuels are used and the economic and human factors motivating their use.

II.1.1 Estimating Carbon Dioxide Emissions

It is relatively straightforward to estimate the amount of CO_2 released to the atmosphere when fossil fuels are consumed. Because CO_2 is the equilibrium product of oxidizing the carbon in fossil fuels, we need to know only the amount of fuel used and its carbon content. For greater accuracy, we adjust this estimate to take into consideration the small amount of carbon that is left as ash or soot and is not actually oxidized. We also consider the fraction of fossil fuels that are used for things like asphalt, lubricants, waxes, solvents, and plastics and may not be soon converted to CO_2. Some of these long-lived, carbon-containing products will release their contained carbon to the atmosphere as CO_2 during use or during processing of waste. Other products will hold the carbon in use or in landfills for decades or longer. One of the differences among the various estimates of CO_2 emissions is the way they deal with the carbon in these products.

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Fossil-fuel consumption is often measured in mass or volume units and, in these terms, the carbon content of fossil fuels is quite variable. However, when we measure the amount of fuel consumed in terms of its energy content, we find that for each of the primary fuel types (coal, oil, and natural gas) there is a strong correlation between the energy content and the carbon content. The rate of CO_2 emitted per unit of useful energy released depends on the ratio of hydrogen to carbon and on the details of the organic compounds in the fuels; but, roughly speaking, the numerical conversion from energy released to carbon released as CO_2 is about 25 kg C per 10^9 joules for coal, 20 kg C per 10^9 joules for petroleum, and 15 kg C per 10^9 joules for natural gas. Figure PII.2 shows details of the correlation between energy content and carbon content for more than 1000 coal samples. Detailed analysis of the data suggests that hard coal contains 25.16 ± 2.09% kg C per 10^9 joules of coal (measured on a net heating value basis[1]). The value is slightly higher for lignite and brown coal (26.23 kg C ±

Table II.1 A sample of the coefficients used for estimating CO_2 emissions from the amount of fuel burned.

Fuel	Emissions coefficient (kg C/10^9 J net heating value)
Lignite	27.6
Anthracite	26.8
Bituminous coal	25.8
Crude oil	20.0
Residual fuel oil	21.1
Diesel oil	20.2
Jet kerosene	19.5
Gasoline	18.9
Natural gas	15.3

Source: IPCC (1997).

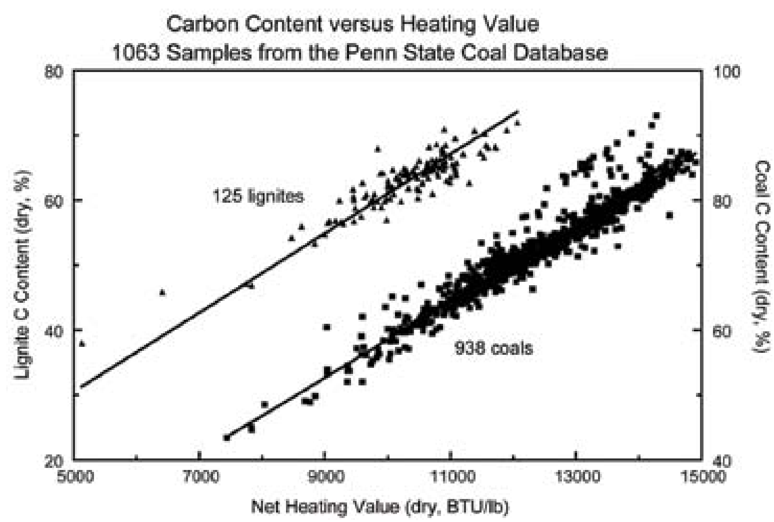

Figure II.2 The carbon content of coal varies with the heat content, shown here as the net heating value. To make them easier to distinguish, data for lignites and brown coals are shown on the left axis, while data for hard coals are offset by 20% and shown on the right axis. Heating value is plotted in the units at which it was originally reported, Btu/lb, where 1 Btu/lb = 2324 J/kg. *Source:* Marland *et al.* (1995).

[1] Net heating value (NHV) is the heat release measured when fuel is burned at constant pressure so that the water (H_2O) is released as H_2O vapor. This is distinguished from the gross heating value (GHV), the heat release measured when the fuel is burned at constant volume so that the H_2O is released as liquid H_2O. The difference is essentially the heat of vaporization of the H_2O and is related to the hydrogen content of the fuel.

2.33% per 10^9 joules (also shown in Figure II.2). Similar correlations exist for all fuels and Table PII.1 shows some of the coefficients reported by the Intergovernmental Panel on Climate Change (IPCC) for estimating CO_2 emissions. The differences between the values in Table II.1 and those in Figure II.2 are small, but they begin to explain how different data compilations can end up with different estimates of CO_2 emissions.

Data on fossil-fuel production, trade, consumption, *etc.* are generally collected at the level of some political entity, such as a country, and over some time interval, typically a year. Estimates of national, annual fuel consumption can be based on estimates of fuel production and trade, estimates of actual final consumption, data for fuel sales or some other activity that is clearly related to fuel use, or on estimates and models of the activities that consume fuel (such as vehicle miles driven). In the discussion that follows, some estimates of national, annual CO_2 emissions are based on "apparent consumption" (defined as production + imports – exports +/– changes in stocks), while others are based on more direct estimates of fuel consumption. All of the emissions estimates in this chapter are as the mass of carbon released[2].

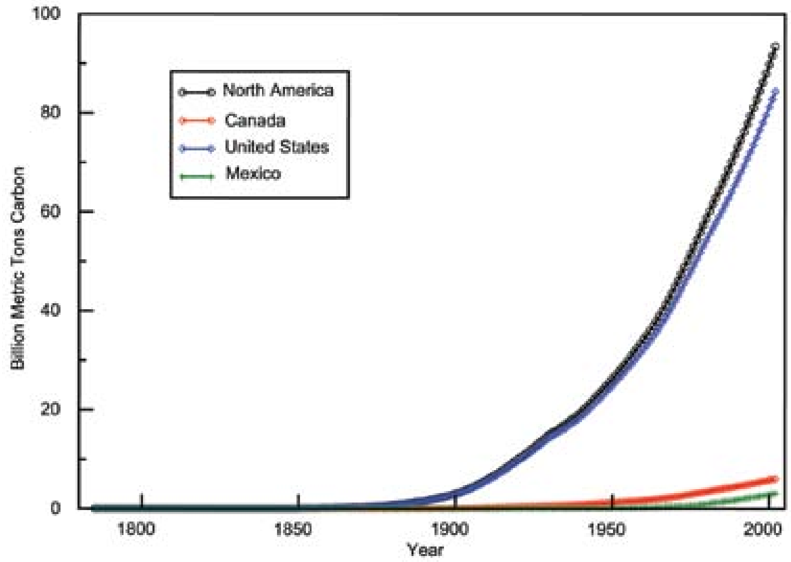

Figure II.3 The cumulative total of CO_2 emissions from fossil-fuel consumption and cement manufacture, as a function of time, for the three countries of North America and for the sum of the three. *Source:* Marland *et al.* (2005).

The uncertainty in estimates of CO_2 emissions will thus depend on the variability in the chemistry of the fuels, the quality of the data or models of fuel consumption, and on uncertainties in the amount of carbon that is used for non-fuel purposes (such as asphalt and plastics) or is otherwise not burned. For countries like the United States—with good data on fuel production, trade, and consumption—the uncertainty in national emissions of CO_2 is on the order of ±5% or less. In fact, the U.S. Environmental Protection Agency (USEPA, 2005) suggests that their estimates of CO_2 emissions from energy use in the United States are accurate, at the 95% confidence level, within –1 to +6% and Environment Canada (2005) suggests that their estimates for Canada are within –4 to 0%. The Mexican National Report (Mexico, 2001) does not provide estimates of uncertainty, but our analyses with the Mexican data suggest that uncertainty is larger than for the United States and Canada. Emissions estimates for these same three countries, as reported by the Carbon Dioxide Information Analysis Center (CDIAC) and the International Energy Agency (IEA) (see the following section), will have larger uncertainty because these groups are making estimates for all countries. Because they work with data from all countries, they use global average values for things like the emissions coefficients, whereas agencies within the individual countries use values that are more specific to the particular country. When national emissions are calculated by consistent methods it is likely that year-to-year changes can be estimated more accurately than would be suggested by the uncertainties of the individual annual values.

II.1.2 The Magnitude of National and Regional Carbon Dioxide Emissions

Figure II.3 shows that from the beginning of the fossil-fuel era (1751 in these graphs) to the end of 2002, there were 93.5 billion tons of carbon (Gt C) released as CO_2 from fossil-fuel consumption (and cement manufacture) in North America: 84.4 Gt C from the United States, 6.0 from Canada, and 3.1 from Mexico. All three countries of North America are major users of fossil fuels and this 93.5 Gt C was 31.5% of the global total. Among all countries, the United States, Canada, and Mexico ranked as the first, eighth, and eleventh largest emitters of CO_2 from fossil-fuel consumption, respectively (for 2002) (Marland *et al*., 2005). Figure II.4 shows, for each of these countries and for the sum of the three, the annual total of emissions and the contributions from the different fossil fuels.

The long time series of emissions estimates in Figures II.1, II.3, and II.4 are from the CDIAC (Marland *et al*., 2005). These estimates are derived from the "apparent consumption" of fuels and are based on data from the United Nations Statistics Office back to 1950 and on data from a mixture of sources for the earlier years (Andres *et al*., 1999). There are other published estimates (with shorter time series) of national, annual CO_2 emissions. Most notably the IEA (2005) has reported estimates of emissions for many coun-

[2] The carbon is actually released to the atmosphere as CO_2 and it is accurate to report (as is often done) either the amount of CO_2 emitted or the amount of C in the CO_2. The numbers can be easily converted back and forth using the ratio of the molecular masses, *i.e.* (mass of C) x (44/12) = (mass of CO_2).

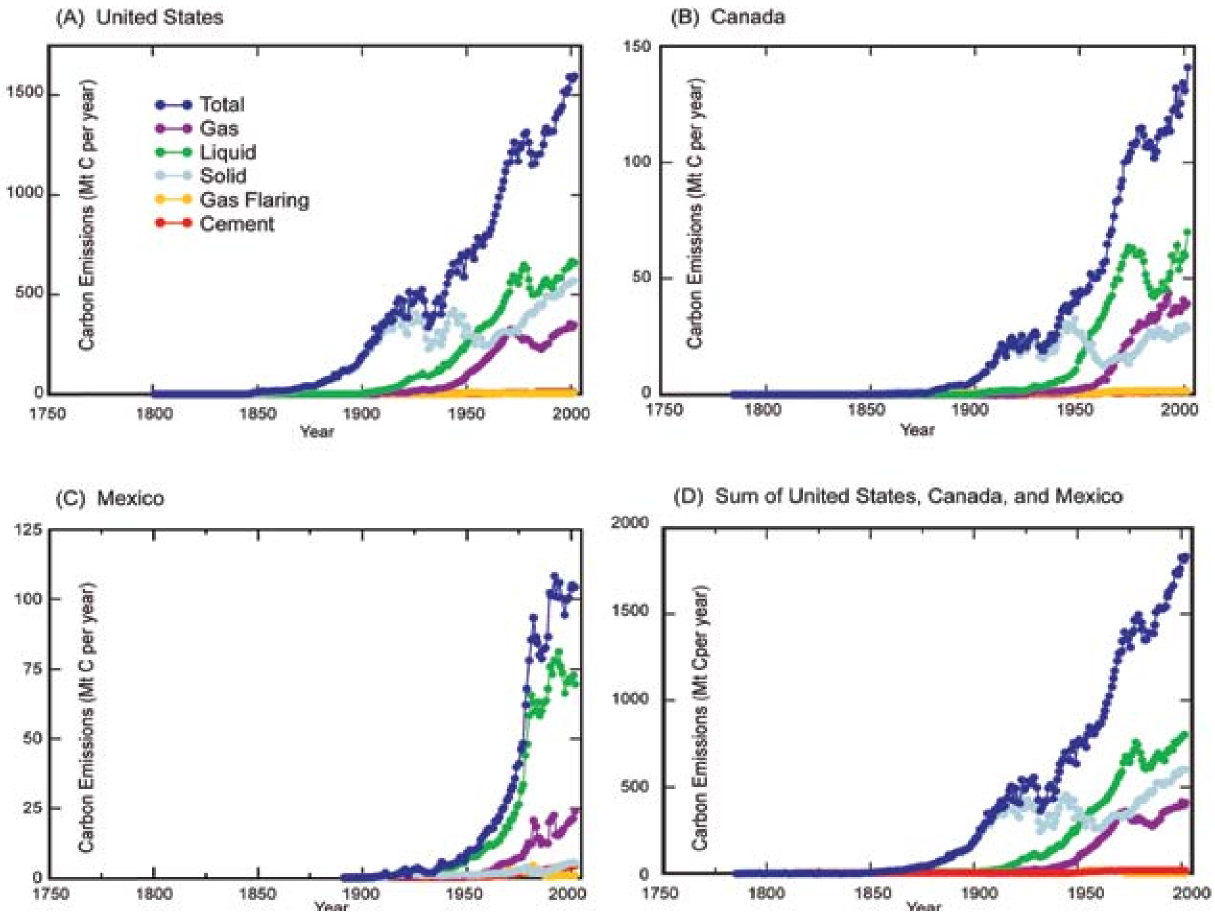

Figure II.4 Annual emissions of CO_2 from fossil-fuel use by fuel type for (A) the United States, (B) Canada, (C) Mexico, and (D) North America, as the sum of the data shown in the other three panels. *Note* that in order to illustrate the contributions of the different fuels, the four plots are not to the same vertical scale. *Source*: Marland *et al.* (2005).

tries for all years back to 1971, and most countries have now provided some estimates of their own emissions as part of their national obligations under the United Nations Framework Convention on Climate Change (UNFCCC, see http://unfccc.int). These latter two sets of estimates are based on data on actual fuel consumption and thus are able to provide details as to the sector of the economy where fuel use is taking place[3].

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Comparing the data from multiple sources can give us some insight into the reliability of the estimates, generally. These different estimates of CO_2 emissions are not, of course, truly independent because they all rely, ultimately, on national data on fuel use; but they do represent different manipulations of this primary data and in many countries there are multiple potential sources of energy data. Many developing countries do not collect or do not report all of the data necessary to precisely estimate CO_2 emissions and in these cases differences can be introduced by how the various agencies derive the basic data on fuel production and use. Because of the way data are collected, there are statistical differences between "consumption" and "apparent consumption" as defined above.

To make comparisons of different estimates of CO_2 emissions we would like to be sure that we are indeed comparing estimates of the same thing. For example, emissions from cement manufacture are not available from all of the sources, so they are not included in the comparisons in Table II.2. All of the estimates in Table II.2, except those from the IEA, include emissions from flaring natural gas at oil production facilities. It is not easy to identify the exact reason the estimates differ, but the differences are generally small. The differences have mostly to do with the statistical difference between consumption and apparent consumption, the way in which correction is made for non-fuel usage of fossil-fuel resources, the conversion from mass or volume to energy

[3] The International Energy Agency provides estimates based on both the reference approach (estimates of apparent consumption) and the sectoral approach (estimates of actual consumption) as described by the IPCC (IPCC, 1997). In the comparison here, we use the numbers that they believe to be the most accurate, those based on the sectoral approach.

Table II.2 Different estimates (in MtC) of CO2 emissions from fossil-fuel consumption for the United States, Canada, and Mexico.

Country	1990		1998		2002	
United States	CDIAC	1305	CDIAC	1501	CDIAC	1580
	IEA	1320	IEA	1497	IEA	1545
	USEPA	1316	USEPA	1478	USEPA	1534
Canada	CDIAC	112	CDIAC	119	CDIAC	139
	IEA	117	IEA	136	IEA	145
	Canada	117	Canada	133	Canada	144
Mexico	CDIAC	99	CDIAC	96	CDIAC	100
	IEA	80	IEA	96	IEA	100
	Mexico	81	Mexico	96	Mexico	NA

Notes:
Many of these data were published in terms of the mass of CO_2, and these data have been multiplied by 12/44 to get the mass of carbon for the comparison here.
All data except CDIAC include oxidation of non-fuel hydrocarbons.
All data except IEA include flaring of gas at oil and gas processing facilities.
Sources: CDIAC (Marland *et al.*, 2005), IEA (2005), USEPA (2005), Canada (Environment Canada, 2005), and Mexico (2001).

units, and/or the way in which estimates of carbon content are derived. Because the national estimates from CDIAC do not include emissions from the non-fuel uses of petroleum products, we expect them to be slightly smaller than the other estimates shown here, all of which do include these emissions[4]. The comparisons in Table II.2 reveal one number for which there is a notable relative difference among the multiple sources, emissions from Mexico in 1990. Losey (2004) has suggested, based on other criteria, that there is a problem in the United Nations energy data set with the Mexican natural gas data for the three years 1990-1992, and these kinds of analyses result in re-examination of some of the fundamental data.

The IEA (2005, p. 1.4) has systematically compared their estimates with those reported to the UNFCCC by the different countries and they find that the differences for most developed countries are within 5%. The IEA attributes most of the differences to the following: use of the IPCC Tier 1 method that does not take into account different technologies, use of energy data that may have come from different "official" sources within a country, use of average values for net heating value of secondary oil products, use of average emissions values, use of incomplete data on non-fuel uses, different treatment of military emissions, and a different split between what is identified as emissions from energy and emissions from industrial processes.

II.1.3 Emissions by Month and/or State

With increasing interest in the details of the global carbon cycle there is increasing interest in knowing emissions at spatial and temporal scales finer than countries and years. For the United States, energy data have been collected for many years at the level of states and months and thus estimates of CO_2 emissions can be made by state or by month. Figure II.5 shows the variation in United States' emissions by month and preliminary analyses by Gurney *et al.* (2005) reveal that proper recognition of this variability can be very important in some exercises to model the details of the global carbon cycle.

Because of differences in the way energy data are collected and aggregated, it is not obvious that an estimate of emissions from the United States will be identical to the sum of estimates for the 50 United States' states. Figure II.6 shows that estimates of total annual CO_2 emissions are slightly different if we use data directly from the U.S. Department of Energy (DOE) and sum the estimates for the 50 states or if we sum the estimates for the 12 months of a given year, or if we take United States' energy data as aggregated by the United Nations Statistics Office and calculate the annual total of CO_2 emissions directly. Again,

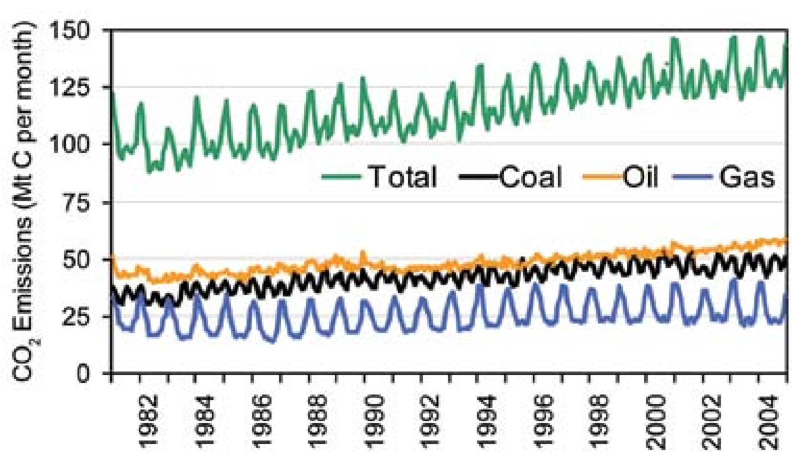


Figure. II.5 Emissions of CO_2 from fossil-fuel consumption in the United States, by month. Emissions from cement manufacturing are not included. *Source:* Blasing *et al.* (2005a).

[4] The CDIAC estimate of global total emissions does include estimates of emissions from oxidation from non-fuel use of hydrocarbons.

the state and monthly emissions data are based on estimates of fuel consumption while the national emissions estimates calculated using United Nations' data result from estimates of "apparent consumption." There is a difference between annual values for consumption and annual values of "apparent consumption" (the IEA calls this difference simply "statistical difference") that is related to the way statistics are collected and aggregated. There are also differences in the way values for fuel chemistry and non-fuel usage are averaged at different spatial and temporal scales, but the differences in CO_2 estimates are seen to be within the error bounds generally expected.

Data from DOE permit us to estimate emissions by state or by month (Blasing *et al*., 2005a and 2005b), but they do not permit us to estimate CO_2 emissions for each state by month directly from the published energy data. Nor do we have sufficiently complete data to estimate emissions from Canada and Mexico by month or province. Andres *et al*. (2005), Gregg (2005), and Losey (2004) have shown that we can disaggregate national total emissions by month or by some national subdivision (such as states or provinces) if we have data on some large fraction of fuel use. Because this approach relies on determining the fractional distribution of an otherwise-determined total, it can be done with incomplete data on fuel use. The estimates will, of course, improve as the fraction of the total fuel use is increased. Figure II.7 is based on sales data for most fossil-fuel commodities and the CDIAC estimates of total national emissions and shows how

To understand the trends and the driving forces behind the growth in fossil-fuel emissions, and the opportunities for controlling emissions, it is necessary to look in detail at how the fuels are used.

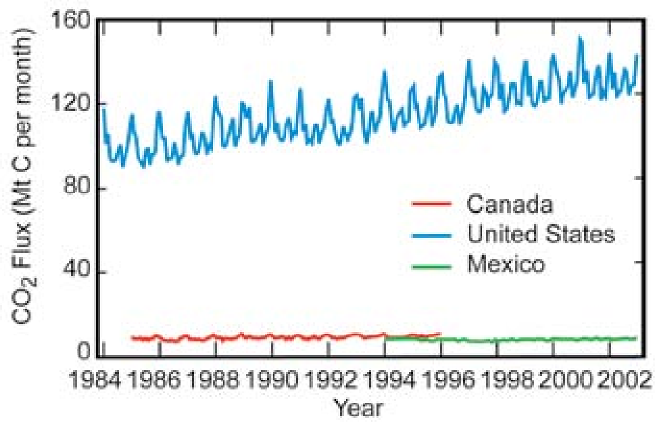


Figure II.7 Carbon dioxide emissions from fossil-fuel consumption in North America, by month. Monthly values are shown where estimates are justified by the availability of monthly data on fuel consumption or sales. *Source:* Andres *et al.*, (2005).

the CO_2 emissions from North America vary at a monthly time scale.

.II.1.4 Emissions by Economic Sector

To understand how CO_2 emissions from fossil-fuel use interact in the global and regional cycling of carbon, it is necessary to know the masses of emissions and their spatial and temporal patterns. We have tried to summarize this information here. To understand the trends and the driving forces behind the growth in fossil-fuel emissions, and the opportunities for controlling emissions, it is necessary to look in detail at how the fuels are used. This is the goal of the next four chapters of this report.

Before looking at the details of how energy is used and where CO_2 emissions occur in the economies of North America, however, there are two indices of CO_2 emissions at the national level that provide perspective on the scale and distribution of emissions. These two indices are emis-

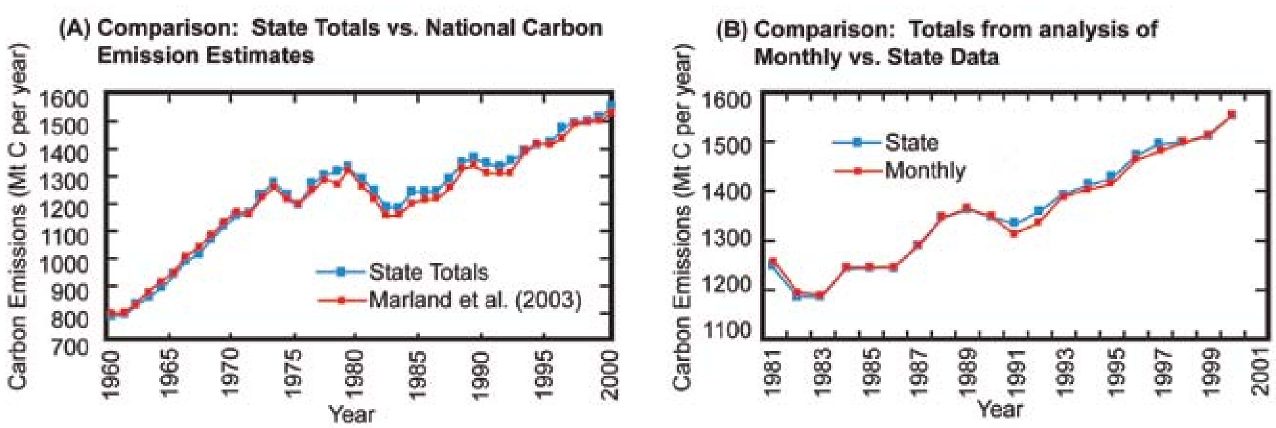


Figure. II.6 A comparison of three different estimates of national annual emissions of CO_2 from fossil-fuel consumption in the United States. (A) Estimates from U.S. Department of Energy data on fuel consumption by state (blue squares) vs. estimates based on UN Statistics Office data on apparent fuel consumption for the full United States (red squares). (B) Estimates based on DOE data on fuel consumption in the 50 U.S. states (blue squares) vs. estimates based on national fuel consumption for each of the 12 months (red squares). The state and monthly data include estimates of oxidation of non-fuel hydrocarbon products; the UN-based estimates do not. *Source*: Blasing *et al.*, (2005b).

Table II.3 Emissions of CO_2 from fossil-fuel consumption (cement manufacture and gas flaring are not included) per unit of GDP for the United States, Canada, Mexico and for the global total.

Country	CO_2 emissions per unit of GDP[a]		
	Year		
	1990	1998	2002
United States	0.19	0.17	0.15
Canada	0.18	0.18	0.16
Mexico	0.13	0.12	0.11
Global Total	0.17	0.15	0.14

[a] Carbon dioxide is measured in kg carbon and GDP is reported in 2000 US$ purchasing power parity.
Source: IEA (2005).

sions *per capita* and emissions per unit of economic activity, the latter generally represented by CO_2 per unit of gross domestic product (GDP). Figure II.8 shows the 1950–2002 record of CO_2 emissions *per capita* for the three countries of North America and for perspective includes the same data for the Earth as a whole. Similarly, Table II.3 shows CO_2 emissions per unit of GDP for the three countries of North America and for the world total. These are, of course, very complex indices and though they provide some insight they say nothing about the details and the distributions within the means. The data on CO_2 *per capita* for the 50 United States' states (Figure II.9) show that values range over a full order of magnitude, differing in complex ways with the structure of the economies and probably with factors like climate, population density, and access to resources (Blasing *et al.*, 2005b; Neumayer, 2004).

Chapters 6 through 9 of this report discuss the patterns and trends of CO_2 emissions by sector and the driving forces behind the trends that are observed. Estimating emissions by sector brings special challenges in defining sectors and assembling the requisite data. Readers will find that there is consistency and coherence within each of the following chapters but will encounter difficulty in aggregating or summing numbers across chapters. Different experts use different sector boundaries, different data sources, different conversion factors, *etc.* Different analysts and literature sources will find data for different base years and may treat electricity and biomass fuels differently. The national reports of the United States, Canada, and Mexico do not cover the same time periods, nor do they present data in the same way. In a discussion of the possibilities for reducing CO_2 emissions in the building sector it is not obvious, for example, whether to include the relevant electricity within the building sector, to leave electric power generation as a separate sector, or to accept some overlap in the discussion. The authors of Chapters 6, 7, 8, and 9 have chosen the system boundaries and data they find most useful for the individual sectors, even though it makes it more difficult to aggregate across sectors.

Despite these differences in accounting procedures, the four chapters that follow accurately characterize the patterns of emissions and the opportunities for controlling the growth in emissions. They reveal that there are major differences between the countries of North America where, for example, the United States derives 51% of its electricity from coal, Mexico gets 68% from petroleum and natural gas, and Canada gets 58% from hydroelectric stations. Partially as a reflection of this difference, 40% of United States' CO_2 emissions are from enterprises whose primary business is to generate electricity and heat, while this number is only 31% in

Forty percent of the United States' CO_2 emissions are from enterprises whose primary business is to generate electricity and heat, while this number is only 31% in Mexico and 23% in Canada.

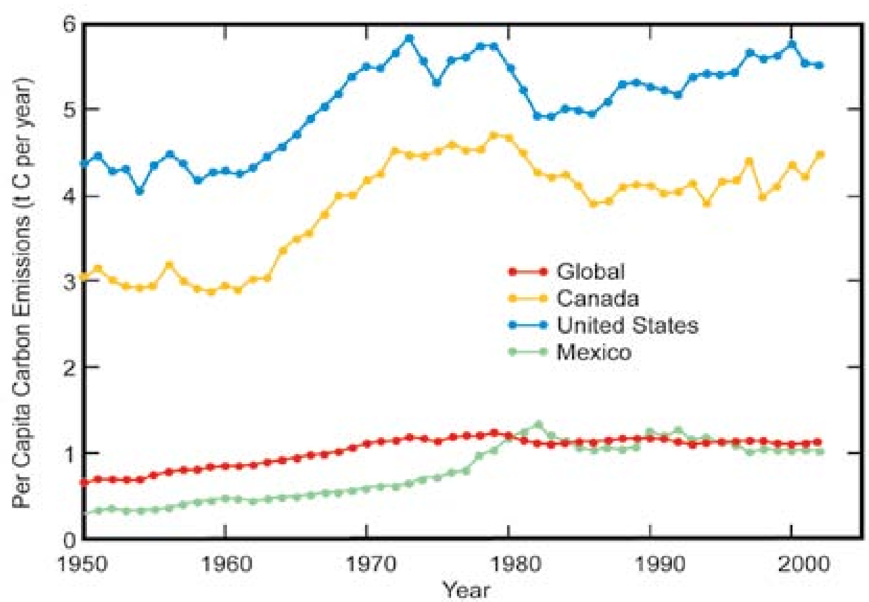


Figure II.8 *Per capita* emissions of CO_2 from fossil-fuel consumption and cement manufacture in the United States, Canada, and Mexico and for the global total of emissions. *Source:* Marland *et al.*, (2005).

Mexico and 23% in Canada (for 2003; from IEA, 2005). Chapter 8 reveals that the sectors are not independent as, for example, a change from fuel burning to electricity in an industrial process will decrease emissions from the industrial sector but increase emissions in the electric power sector. The database of the IEA allows us to summarize CO_2 emissions for the three countries according to sectors that closely correspond to the sectoral division of chapters 6 through 9 (Table II.4).

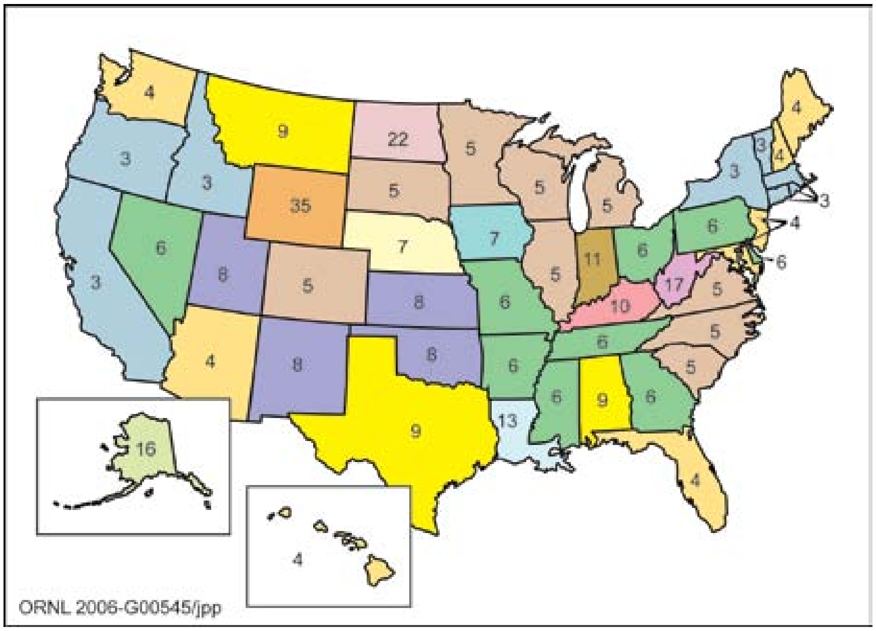


Figure II.9 *Per capita* emissions of CO_2 from fossil-fuel consumption for the 50 United States in 2000. To demonstrate the range, values have been rounded to whole numbers of metric tons carbon *per capita*. A large portion of the range for extreme values is related to the occurrence of coal resources and inter-state transfers of electricity. *Source*: Blasing *et al.* (2005b).

II.2 CONCLUSION

There are a variety of reasons that we want to know the emissions of CO_2 from fossil fuels, there are a variety of ways of coming up with the desired estimates, and there are a variety of ways of using the estimates. By the nature of the process of fossil-fuel combustion, and because of its economic importance, there are reasonably good data over long time intervals that we can use to make reasonably accurate estimates of CO_2 emissions to the atmosphere. In fact, it is the economic importance of fossil-fuel burning that has assured us of both good data on emissions and great challenges in altering the rate of emissions.

Table II.4 Percentage of CO_2 emissions by sector for 2003.

Sector	United States	Canada	Mexico	North America
Energy extraction and conversion[a]	46.2	36.2	47.7	45.4
Transportation[b]	31.3	27.7	30.3	31.0
Industry[c]	11.2	16.8	13.6	11.8
Buildings[d]	11.3	19.3	8.4	11.8

[a] The sum of three IEA categories, "public electricity and heat production," "unallocated autoproducers," and "other energy industries."
[b] IEA category "transport."
[c] IEA category "manufacturing industries and construction."
[d] IEA category "other sectors."
Source: IEA (2005).

Energy Extraction and Conversion

Lead Author: Thomas J. Wilbanks, ORNL

Contributing Authors: Marilyn Brown, Ga. Inst. Tech.; Ken Caldeira, Carnegie Inst.; William Fulkerson, Univ. Tenn.; Erik Haites, Margaree Consultants, Inc; Stephen Pacala, Princeton Univ.; David M. Fairman, Consensus Building Inst., Inc.

KEY FINDINGS

- In recent years, the extraction of primary energy sources and their conversion into energy commodities in North America released on the order of 760 million tons of carbon (2800 million tons of carbon dioxide) per year to the atmosphere, approximately 40% of total North American emissions in 2003 and 10% of total global emissions. Electricity generation is responsible for a very large share of North America's energy extraction and conversion emissions.
- Carbon dioxide emissions from energy supply systems in North America are currently rising.
- Principal drivers behind carbon emissions from energy supply systems are (1) the growing appetite for energy services, closely related to economic and social progress, and (2) the market competitiveness of fossil energy compared with alternatives.
- Emissions from energy supply systems in North America are projected to increase in the future. Projections vary among the countries, but increases approaching 50% or more in coming decades appear likely. Projections for the United States, for example, indicate that carbon dioxide emissions from electricity generation alone will rise to above 900 million tons of carbon (3300 million tons of carbon dioxide) by 2030, an increase of about 45% over emissions in 2004, with three-quarters of the increase associated with greater coal use in electric power plants.
- Prospects for major reductions in carbon dioxide emissions from energy supply systems in North America appear dependent upon (a) the extent, direction, and pace of technological innovation and (b) whether policy conditions favoring carbon emissions reduction that do not now exist will emerge (Figure 6.1). In these regards, the prospects are brighter in the long term (*e.g.*, more than several decades in the future) than in the near term.
- Research and development priorities for managing carbon emissions from energy supply systems include, on the technology side, clarifying and realizing potentials for carbon capture and storage, and on the policy side, understanding the public acceptability of policy incentives for reducing dependence on carbon-intensive energy sources.

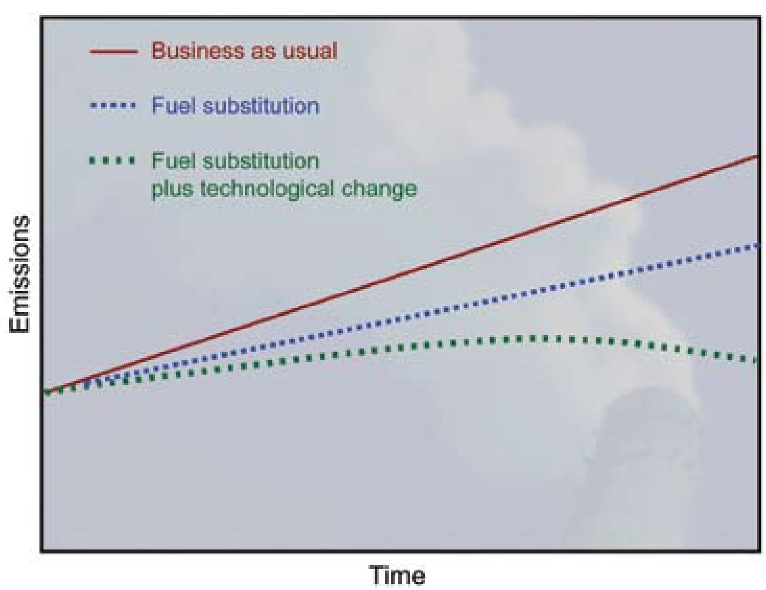


Figure 6.1 Prospects for carbon emissions from energy extraction and conversion in North America, assuming substantial improvement in energy efficiency.

6.1 INTRODUCTION

The energy supply system in North America is a significant part of the North American carbon cycle, because so many of its primary energy resources are fossil fuels associated with extraction and conversion activities that emit greenhouse gases. This chapter summarizes the knowledge bases related to emissions from energy extraction, energy conversion, and other energy supply activities such as energy movement and energy storage, along with options and measures for managing emissions.

Clearly, this topic overlaps the subject matter of other chapters. For instance, the dividing line between energy conversion and other types of industry is sometimes indistinct. One prominent case is emissions associated with electricity and process heat supply for petroleum refining, and other fossil-fuel processing (a large share of their total emissions) included in industrial sector emission totals; another example is industrial co-generation as an energy-efficiency strategy. In addition, biomass energy extraction/conversion is directly related to agriculture and forestry. Moreover, emission-related policy alternatives for energy supply systems are often directed at both supply and demand responses, involving not only emission reductions, but also potential payoffs from efficiency improvements in buildings, industry, and transportation, especially where they reduce the consumption of fossil fuels.

Canada is the world's fifth-largest energy producing country, a significant exporter of both natural gas and electricity to the United States.

6.2 CARBON EMISSIONS INVENTORY

6.2.1 Carbon Emissions From Energy Extraction and Conversion

Carbon emissions from energy resource extraction, conversion into energy commodities, and transmission are one of the "big three" sectors accounting for most of the total emissions from human systems in North America, along with industry and transportation. The largest share of total emissions from energy supply (not including energy end use) is from coal and other fossil-fuel use in producing electricity; fossil-fuel conversion activities such as oil refining and natural gas transmission and distribution also contribute to this total, but in much smaller amounts. Other emission sources are less well defined, but generally small, such as emissions from oil production and methane from reservoirs established partly to support hydropower production (Tremblay *et al.*, 2004), or from materials production (*e.g.*, metals production) associated with other renewable or nuclear energy technologies. Generally, data on emissions have a relatively low level of uncertainty, although the source materials do not include quantitative estimates of uncertainty.

Data on emissions from energy supply systems are unevenly available for the countries of North America, and none are associated with sufficient information to support an assessment of uncertainty. Most emission data sets are organized by fuel consumed rather than by consuming sector, and countries differ in sectors identified and the units of measurement. As a result, inventories are reported in this chapter by country in whatever forms are available rather than constructing a North American inventory that could not be consistent across all three major countries. It is worth noting that Canada and Mexico export energy supplies to the United States, therefore, some emissions from energy supply systems in these countries are associated with energy uses in the United States.

6.2.1.1 CANADA

Canada is the world's fifth-largest energy producing country, a significant exporter of both natural gas and electricity to the United States. In Alberta, which produces nearly two-thirds of Canada's energy, energy accounts for about one-quarter of the province's economic activity; its oil sands are estimated to have more potential energy value than the remaining oil reserves of Saudi Arabia (U.S. Department of Energy, 2004). Although Canada has steadily reduced its energy and carbon intensities since the early 1970s, its overall energy intensity remains high—in part due to its prominence as an energy producer—and total greenhouse gas emissions have grown by 9% since 1990. As of 2003, greenhouse gas emissions were 36.5 million metric tons of carbon (Mt C) equivalents (134 million tons of carbon dioxide [Mt CO_2] equivalents) for electricity and heat generation and 19 Mt C (71 Mt CO_2) for petroleum refining and upgrading and other fossil-fuel production (Environment Canada, 2003). Although the mix of

BOX 6.1: CCSP SAP 2.2 Uncertainty Conventions

*****	=	95% certain that the actual value is within 10% of the estimate reported,
****	=	95% certain that the estimate is within 25%,
***	=	95% certain that the estimate is within 50%,
**	=	95% certain that the estimate is within 100%, and
*	=	uncertainty greater than 100%.
†	=	The magnitude and/or range of uncertainty for the given numerical value(s) is not provided in the references cited.

carbon dioxide (CO_2) and methane (CH_4) in these figures is unclear, the carbon emission equivalent is probably within the range of 60-80 Mt C.

6.2.1.2 Mexico

Mexico is one of the largest sources of energy-related greenhouse gas emissions in Latin America, although its *per capita* emissions are well below the *per capita* average of industrialized countries. The first large oil-producing nation to ratify the Kyoto Protocol, it has promoted shifts to natural gas use to reduce greenhouse gas emissions. The most recent emission figures are from the country's Second National Communication to the United Nations Framework Convention on Climate Change (UNFCCC) in 2001, which included relatively comprehensive data from 1996 and some data from 1998. In 1998, total emissions from "energy industries" were 13 Mt C (47.3 Mt CO_2); from electricity generation they totaled 27.6 Mt C (101.3 Mt CO_2); and "fugitive" emissions from oil and gas production and distribution were between 1.4 and 2.0 Mt C (1.9 and 2.6 Mt of CH_4), depending on the estimated "emission factor" (Government of Mexico, 2001).

6.2.1.3 United States

The United States is the largest national emitter of greenhouse gases in the world, and CO_2 emissions associated with electricity generation in 2004 account for 627 Mt C (2299 Mt CO_2), or 39% of a national total of 1600 Mt C (5890 Mt CO_2) (EIA, 2006a). Greenhouse gases are also emitted from oil refining, natural gas transmission, and other fossil energy supply activities, but apart from energy consumption figures included in industry sector calculations, these emissions are relatively small compared with electric power plant emissions. For instance, emissions from petroleum consumed in refining processes in the United States are about 40 Mt C per year (EIA, 2004), while fugitive emissions from gas transmission and distribution pipelines in the United States are about 2.2 Mt C per year[1]**(see Box 6.1 for uncertainty conventions). On the other hand, a study of greenhouse gas emissions from a six-county area in southwestern Kansas found that compressor stations for natural gas pipeline systems are a significant source of emissions at that local scale (AAG, 2003).

6.2.2 Carbon Sinks Associated With Energy Extraction and Conversion

Generally, energy supply in North America is based heavily on mining hydrocarbons from carbon sinks accumulated over millions of years; but current carbon sequestration occurs in plant growth, including the cultivation of feedstocks for bioenergy production. Limited strictly to energy sector applications, the total contribution of these sinks to the North American carbon cycle is relatively small, while other aspects of bioenergy development are associated with carbon emissions; but the substitution of biomass-derived fuels (approximately emisson-neutral, as stored carbon is released with fuel use) for fossil fuels represents a potentially significant net savings in emissions.

The substitution of biomass-derived fuels for fossil fuels represents a potentially significant net savings in emissions.

6.3 TRENDS AND DRIVERS

Three principal drivers are behind carbon emissions from energy extraction and conversion:

1. The growing global and national appetite for energy services such as comfort, convenience, mobility, and labor productivity, so closely related to progress with economic and social development and the quality of life (Wilbanks, 1992). Globally, the challenge is to increase total energy services (not necessarily supplies) over the next half-century by a factor of at least three or four—more rapidly than overall economic growth—while reducing environmental impacts from the associated supply systems (NAS, 1999). Mexico shares this need, while increases in Canada and the United States are likely to be more or less proportional to rates of economic growth.
2. The market competitiveness of fossil energy sources compared with supply- and demand-side alternatives. Production costs of electricity from coal, oil, or natural gas at relatively large scales are currently lower than other sources, except large-scale hydropower, and production costs of liquid and gas fuels are currently far lower than other sources, though rising. This is mainly because the energy density and portability of fossil fuels is as yet unmatched by other energy sources, and in some cases policy conditions reinforce fossil-fuel use. These

1 This numerical value represents the authors' estimate.

conditions appear likely to continue for some years. In many cases, the most cost-competitive alternative to fossil-fuel production and use is not alternative supply sources, but efficiency improvement.

3. Enhanced future markets for alternative energy supply sources. In the longer run, however, emissions from energy supply systems may—and in fact, are likely to—begin to decline as alternative technology options are developed and/or improved.

Other possible driving forces for attention to alternatives to fossil fuels, at least in the mid to longer term, include the possibility of shrinking oil and/or gas reserves and changes in attitudes toward energy policy interventions.

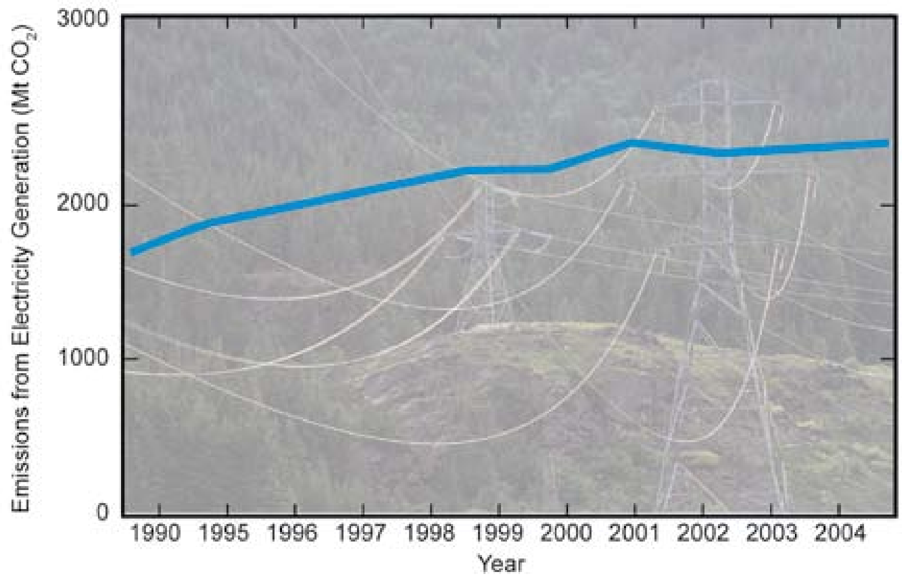


Figure 6.2 U.S. carbon dioxide emissions from electricity generation, 1990-2004. *Source:* EIA, 2004, and the authors' extensions for year 2004.

Total carbon emissions from energy extraction and conversion in North America are currently rising.

Given the power of the first two of these drivers, total carbon emissions from energy extraction and conversion in North America are currently rising (*e.g.*, Figure 6.2). National trends and drivers are as follows. As is always the case, projections of the future involve higher levels of uncertainty than measurements of the present, but source materials do not include quantitative estimates of uncertainties associated with projections of future emissions.

6.3.1 Canada

Canada has ratified the Kyoto Protocol, and it is seeking to meet the Kyoto target of CO_2 emission reduction to 6% below 1990 levels. Of these reductions, 25% are to be through domestic actions and 75% through market mechanisms such as purchases of carbon credits (Government of Canada, 2005). Domestic actions will include a significant reduction in coal consumption. Available projections, however, indicate a total national increase of emissions in CO_2 equivalent of 36.1% by 2020 from 1990 levels (Environment Canada, 2005). Emissions from electricity generation could increase 2000-2020 by as much as two-thirds, while emissions from fossil-fuel production would remain relatively stable (although substantial expansion of oil sands production could be a factor).

It has been estimated that total Mexican CO_2 emissions will grow 69% by 2010, although mitigation measures could reduce this rate of growth by nearly half.

6.3.2 Mexico

It has been estimated that total Mexican CO_2 emissions will grow 69% by 2010, although mitigation measures could reduce this rate of growth by nearly half (Pew Center, 2002). Generally, energy sector emissions in Mexico vary in proportion to economic growth (*e.g.*, declining somewhat with a recession in 2001). However, factors, such as a pressing need for additional electricity supplies (calling for more than doubling production capacity between 1999 and 2008) could increase net emissions, while a national strategy to promote greater use of natural gas (along with other policies related in part to concerns about emissions associated with urban air pollution) could reduce emissions compared with a reference case (EIA, 2005).

6.3.3 United States

The Energy Information Administration (EIA, 2006b) projects that emissions from electricity generation in the United States between 2004 and 2030 will rise from about 627 Mt C (2299 Mt CO_2) to more than 900 Mt C (3300 Mt CO_2) (an increase of about 45%) with three-quarters of the increase associated with greater coal use in electric power plants. EIA projects that technology advances could lower emissions by as much as 9%. Projections of other emissions from energy supply systems appear to be unavailable, but emissions could be expected to rise at a rate just below the rate of change in product consumption in the United States' economy.

6.4 OPTIONS FOR REDUCING EMISSIONS FROM ENERGY EXTRACTION AND CONVERSION

Few aspects of the carbon cycle have received more attention in the past several decades than emissions from fossil energy extraction and conversion. As a result, there is a wide array of technology and policy options, many of which have been examined in considerable detail, although there is not a strong consensus on courses of action.

6.4.1 Technology Options

Technology options for reducing energy-supply-related emissions (other than reduced requirements due to end-use efficiency improvements) consist of:

- reducing emissions from fossil energy extraction, production, and movement (*e.g.*, for electricity generation by improving the efficiency of existing power plants or moving toward the use of lower-emission technologies such as coal gasification-combined cycle generation facilities) and
- shifting from fossil energy sources to other energy sources (*e.g.*, energy from the sun [renewable energy] or from the atom [nuclear energy]).

The most comprehensive description of emission-reducing and fuel switching technologies and their potentials is the U.S. Climate Change Technology Program (CCTP) draft Strategic Plan (U.S. Climate Change Technology Program, 2005), especially Chapters 5 (energy supply) and 6 (capturing and sequestering CO_2)—see also National Laboratory Directors (1997). The CCTP report focuses on five energy supply technology areas: low-emission fossil-based fuels and power, hydrogen as an energy carrier, renewable energy and fuels, nuclear fission, and fusion energy.

There is a widespread consensus that no one of these options, nor one family of options, is a good prospect to stabilize greenhouse gas emissions from energy supply systems, nationally or globally, because each faces daunting constraints (Hoffert *et al.*, 2002). An example is possible physical and/or technological limits to effective global "decarbonization" (*i.e.*, reducing the use of carbon-based energy sources as a proportion of total energy supplies), including renewable or other non-fossil sources of energy use at scales that would dramatically change the global carbon balance between now and 2050. One conclusion is that "the disparity between what is needed and what can be done without great compromise may become more acute."

If many contributions can be combined, the total effect could approach requirements for even relatively ambitious carbon stabilization goals.

Instead, progress with technologies likely to be available in the coming decades may depend on adding together smaller "wedges" of contributions by a variety of resource/technology combinations (Pacala and Socolow, 2004), each of which may be feasible if the demands upon it are moderate. If many such contributions can be combined, the total effect could approach requirements for even relatively ambitious carbon stabilization goals, at least in the first half of the century, although each contribution would need to be economically competitive with current types of fossil energy sources.

A fundamental question is whether prospects for significant decarbonization depend on the emergence of new technologies, in many cases requiring advances in science. For instance, efforts are being made to develop economically affordable and socially acceptable options for large-scale capture of carbon from fossil-fuel streams—with the remaining hydrogen offering a clean energy source—and sequestration of the carbon in the ground or the oceans. This approach is known to be technologically feasible and is being practiced commercially in the North Sea. Recent assessments suggest that it may have considerable promise (*e.g.*, IPCC, 2006). If so, there is at least some chance that fossil energy sources may be used to provide energy services in North America and the world in large quantities in the mid to longer terms without contributing to a carbon cycle imbalance.

What can be expected from technology options over the next quarter to half a century is a matter of debate, partly because the pace of technology development and use depends heavily on policy conditions. Chapter 3 in the CCTP draft Strategic Plan (2005) shows three advanced technology scenarios drawn from work by the Pacific Northwest National Laboratory, varying according to carbon constraints. Potential cumulative contributions to global emission reduction by energy supply technology initiatives between

2000 and 2100 range from about 25 billion tons of carbon (Gt C) equivalent to nearly 350 Gt, which illustrates uncertainties related to both science and policy issues. Carbon capture and storage, along with terrestrial sequestration, could add reductions between about 100 and 325 Gt C. It has been suggested, however, that significantly decarbonizing energy systems by 2050 could require massive efforts on a par with the Manhattan Project or the Apollo Space Program (Hoffert *et al.*, 2002).

Estimated costs of potential technology alternatives for reducing greenhouse gas emissions from energy supply systems are summarized after the following discussion of policy options, because cost estimates are generally based on assumptions about policy interventions.

6.4.2 Policy Options

Policy options for carbon emission reduction from energy supply systems revolve around either incentives or regulatory requirements for such reductions. Generally, interventions may be aimed at (a) shaping technology choice and use or (b) shaping technology development and supply. Many of the policy options are aimed at encouraging end-use efficiency improvement as well as supply-side emission reduction.

Options for intervening to change the relative attractiveness of available energy supply technology alternatives include appealing to voluntary action (*e.g.*, improved consumer information, "green power"), a variety of regulatory actions (*e.g.*, mandated purchase policies such as energy portfolio standards), carbon emission rights trading (where emission reduction would have market value), technology/product standards, production tax credits for non-fossil energy production, tax credits for alternative energy use, and carbon emission taxation or ceilings. Options for changing the relative attractiveness of investing in carbon-emission-reducing technology development and dissemination include tax credits for certain kinds of energy research and development, public-private sector research and devleopment cost sharing, and electric utility restructuring. For a more comprehensive listing and discussion, see Chapter 6 in IPCC (2001).

In some cases, perceptions that policies and market conditions of the future will be more favorable to emission reduction than at present are motivating private industry to consider investments in technologies whose market competitiveness would grow in such a future. Examples include the CO_2 Capture Project and industry-supported projects at MIT, Princeton, and Stanford (*e.g.*, see http://www.co2captureproject.org/index.htm).

Most estimates of the impacts of energy policy options on greenhouse gas emissions do not differentiate the contributions from energy supply systems from the rest of the energy economy (*e.g.*, IWG, 1997; IWG, 2000; IPCC, 2001; National Commission on Energy Policy, 2004; also see OTA, 1991 and NAS, 1992). For instance the IWG (1997) considered effects of $25 and $50 per ton carbon emission permits on both energy supply and use, while Interlaboratory Working Group (IWG) considered fifty policy/technology options (IWG, 2000; also see IPCC, 2001), most of which would affect both energy supply and energy use decisions.

6.4.3 Estimated Costs of Implementation

Estimating the costs of emission reduction associated with the implementation of various technology and policy options for energy supply and conversion systems is complicated by several realities. First, many estimates are aggregated for the United States or the world as a whole, without separate estimates for the energy extraction and conversion sector. Second, estimates differ in the scenarios considered, the modeling approaches adopted, and the units of measure that are used.

More specifically, estimates of costs of emission reduction vary widely according to assumptions about such issues as how welfare is measured, ancillary benefits, and effects in stimulating technological innovation; and therefore any particular set of cost estimate includes considerable uncertainty. According to IWG (2000), benefits of emission reduction would be comparable to costs, and the National Commission on Energy Policy (2004) estimates that their recommended policy initiatives would be, overall, revenue-neutral with respect to the federal budget. Other participants in energy policymaking, however, are convinced that truly significant carbon emission reductions would have substantial economic impacts (GAO, 2004).

Globally, IPCC (2001) projected that total CO_2 emissions from energy supply and conversion could be reduced in 2020 by 350 to 700 Mt C equivalents per year, based on options that could be adopted using generally accepted policies, at a positive direct cost of less than U.S. $100 per ton of carbon (t C) equivalents. Based on DOE/EIA analyses in 2000, this study includes estimates of the cost of a range of specific emission-reducing technologies for power generation, compared with coal-fired power, although the degree of uncertainty is not clear. Within the United States, the report estimated that the cost of emission reduction per metric ton of carbon emissions reduced would range from -$170 to +$880, depending on the technology used. Marginal abatement costs for the total United States' economy (in 1990 U.S. dollars per metric ton carbon) were estimated by a variety of models compared by the Energy Modeling Forum at $76 to $410 with no emission trading, $14 to $224 with Annex I trading, and $5 to $123 with global trading.

Similarly, the National Commission on Energy Policy (2004) considered costs associated with a tradable emission permit system that would reduce United States' national greenhouse gas emission growth from 44% to 33% from 2002 to 2025, a reduction of 207 Mt C (760 Mt CO_2) in 2025 compared with a reference case. The cost would be a roughly 5% increase in total end-use expenditures compared with the reference case. Electricity prices would rise by 5.4% for residential users, 6.2% for commercial users, and 7.6% for industrial users.

The IWG (2000) estimated that a domestic carbon trading system with a $25/t C permit price would reduce emissions by 13%, or 63 Mt C (230 Mt CO_2), compared with a reference case, while a $50 price would reduce emissions by 17 to 19%, or 83 to 91 Mt C (306 to 332 Mt CO_2). Both cases assume a doubling of United States' government appropriations for cost-shared clean energy research, design, and development.

For carbon capture and sequestration, IPCC (2006) concluded that this option could contribute 15 to 55% to global mitigation between now and 2100 if technologies develop as projected in relatively optimistic scenarios and very large-scale geological carbon sequestration is publicly acceptable. Under these assumptions, the cost is projected to be $110 to $260/t C ($30 to $70/t CO_2). With less optimistic assumptions, the cost could rise above $730/t C ($200/t CO_2).

Net costs to the consumer, however, are balanced in some analyses by benefits from advanced technologies, which are developed and deployed on an accelerated schedule due to policy interventions and changing public preferences. The U.S. Climate Change Technology Program (2005: pp. 3-19) illustrates how costs of achieving different stabilization levels can conceivably be reduced substantially by the use of advanced technologies, and IWG (2000) estimates that net end-user costs of energy can actually be reduced by a domestic carbon trading system if it accelerates the market penetration of more energy-efficient technologies.

Costs of achieving different stabilization levels can conceivably be reduced substantially by the use of advanced technologies.

In many cases, however, discussions of the promise of technology options are not associated with cost estimates. Economic costs of energy are not one of the drivers of the IPCC Special Report on Emissions Scenarios (SRES) scenarios, and such references as Hoffert *et al.* (2002) and Pacala and Socolow (2004) are concerned with technological potentials and constraints as a limiting condition on market behavior rather than with comparative costs and benefits of particular technology options at the margin.

6.4.4 Summary

In terms of prospects for major emission reductions from energy extraction and conversion in North America, the key issues appear to be the extent, direction, and pace of technological innovation and the likelihood that policy conditions favoring carbon emissions reduction that do not now exist will emerge if concerns about carbon cycle imbalances grow. In these regards, the prospects are brighter in the long term (*e.g.*, more than several decades in the future) than in the near term. History suggests that technology solutions are usually easier to implement than policy solutions, but observed impacts of carbon cycle imbalances might change the political calculus for policy interventions in the future.

6.5 RESEARCH AND DEVELOPMENT NEEDS

If it is possible that truly effective management of carbon emissions from energy supply and conversion systems cannot be realized with the current portfolio of technology alternatives under current policy conditions, then research and development needs and opportunities deserve expanded attention and support (*e.g.*, National Commission on Energy Policy, 2004). If so, the priorities include the following:

Technology. Several objectives seem to be especially relevant to carbon management potentials:

- clarifying and realizing potentials for carbon capture and sequestration;
- clarifying and realizing potentials of affordable renewable energy systems at a relatively large scale;
- addressing social concerns about the nuclear energy fuel cycle, especially in an era of concern about terrorism;
- improving estimates of economic costs and emission reduction benefits of a range of energy technologies

across a range of economic, technological, and policy scenarios; and
- "Blue Sky" research to develop new technology options and families, such as innovative approaches for energy from the sun and from biomass, including possible applications of nanoscience (Caldeira *et al.*, 2005; Lewis, 2005).

Policy. Research and development could also be applied to policy options in order to enlarge their knowledge bases and explore their implications. For instance, research priorities might include learning more about:
- public acceptability of policy incentives for reducing dependence on energy sources associated with carbon emissions;
- possible effects of incentives for the energy industry to increase its support for pathways not limited to fossil fuels;
- approaches toward a more distributed electric power supply enterprise in which certain renewable (and hydrogen) energy options might be more attractive;
- transitions from one energy system/infrastructure to another; and
- interactions and linkage effects among driving forces and responses, along with possible effects of exogenous processes and policy interventions.

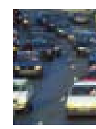
In these ways, technology and policy advances might be combined with multiple technologies to transform the capacity to manage carbon emissions from energy supply systems, if that is a high priority for North America.

CHAPTER 7

Transportation

Lead Author: David L. Greene, ORNL

KEY FINDINGS

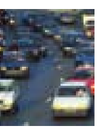


- The transportation sector of North America released 587 million tons of carbon into the atmosphere in 2003, nearly all in the form of carbon dioxide from combustion of fossil fuels. This comprises 37% of the total carbon dioxide emissions from worldwide transportation activity, which in turn, accounts for about 22% of total global carbon dioxide emissions.
- Transportation energy use in North America and the associated carbon emissions have grown substantially and relatively steadily over the past 40 years. Growth has been most rapid in Mexico, the country most dependent upon road transport.
- Carbon emissions by transport are determined by the levels of passenger and freight activity, the shares of transport modes, the energy intensity of passenger and freight movements, and the carbon intensity of transportation fuels. The growth of passenger and freight activity is driven by population, *per capita* income, and economic output.
- Chiefly as a result of economic growth, energy use by North American transportation is expected to increase by 46% from 2003 to 2025. If the mix of fuels were assumed to remain the same, carbon dioxide emissions would increase from 587 million tons of carbon in 2003 to 859 million tons of carbon in 2025. Canada, the only one of the three countries in North America to have committed to specific greenhouse gas reduction goals, is expected to show the lowest rate of growth in carbon emissions.
- The most widely proposed options for reducing the carbon emissions of the North American transportation sector are increased vehicle fuel economy, increased prices for carbon-based fuels, liquid fuels derived from vegetation (biomass), and in the longer term, hydrogen produced from renewable energy sources (such as hydropower), nuclear energy, or from fossil fuels with carbon capture and storage. Biomass fuels appear to be a promising near- and long-term option, while hydrogen could become an important energy carrier after 2025.
- After the development of advanced energy efficient vehicle technologies and low-carbon fuels, the most pressing research need in the transportation sector is for comprehensive, consistent, and rigorous assessments of carbon emissions mitigation potentials and costs for North America.

7.1 BACKGROUND

Transportation is the largest source of carbon emissions among North American energy end uses (electricity generation is considered energy conversion rather than end use). This fact reflects the vast scale of passenger and freight movements in a region that comprises one-fourth of the global economy, as well as the dominance of relatively energy-intensive road transport and the near total dependence of North American transportation systems on petroleum as a source of energy. If present trends continue, carbon emissions from North American transportation are expected to increase by more than one-half by 2050. Options for mitigating carbon emissions from the transportation sector, like increased vehicle fuel economy and biofuels, could offset the expected growth in transportation activity. However, at present only Canada has committed to achieving a specific reduction in future greenhouse gas (GHG) emissions: 6% below 1990 levels by 2012 (Environment Canada, 2005b).

Transportation is the largest source of carbon emissions among North American energy end uses (electricity generation is considered energy conversion rather than end use).



7.2 INVENTORY OF CARBON EMISSIONS

Worldwide, transportation produced about 22% (1.5 billion tons of carbon [Gt C]) of total global carbon dioxide (CO_2) emissions from the combustion of fossil fuels (6.6 Gt C) in 2000 (page 3-1 in U.S. EPA, 2005; Marland, Boden, and Andres, 2005). Home to 6.7% of the world's 6.45 billion people and source of 24.8% of the world's $55.5 trillion gross world product (CIA, 2005), North America produces 37% of the total carbon emissions from worldwide transportation activity (Fulton and Eads, 2004).

Transportation activity is driven chiefly by population, economic wealth, and geography. Of the approximately 435 million residents of North America, 68.0% reside in the United States, 24.5% in Mexico, and 7.5% in Canada (CIA, 2005) (these population estimates are judged by the author to have 95% certainty that the actual value is within 10% of the estimate reported, and the gross

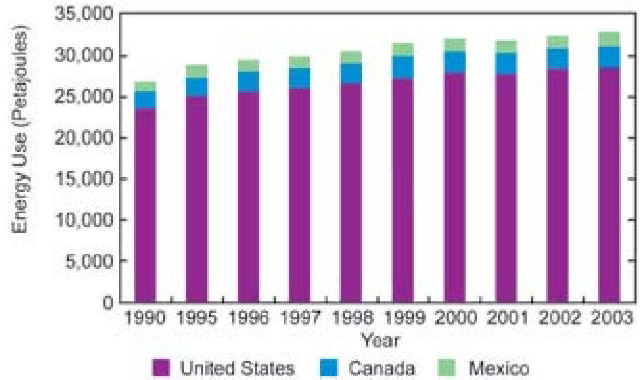


Figure 7.1 Transportation energy use in North America, 1990-2003. *Sources:* NATS (2005), Table 4-1; U.S. DOE/EIA (2005a), Table 2.1e.

domestic product (GDP) estimates are judged to have 95% certainty that the actual value is within 25% of the estimate reported, chiefly because they are not based on triple bottom line accounting). The differences in the sizes of the three countries' economies are far greater. The United States is the world's largest economy, with an estimated GDP of $11.75 trillion in 2004.

Although Mexico has approximately three times the population of Canada, its GDP is roughly the same, $1.006 trillion compared to $1.023 trillion (measured in 2004 purchasing power parity dollars). With the largest population and largest economy, the United States has by far the largest transportation system. The United States accounted for 87% of the energy used for transportation in North America in 2003, Canada for 8%, and Mexico 5% (Figure 7.1) (see Table 4.1 in

Table 7.1 Carbon emissions from transportation in North America in 2003.

North American Carbon Emissions by Country and Mode, 2003/2001 (Mt C)				
	United States 2003	Canada 2003	Mexico 2001	North America 2003/2001
Road	399.4	36.7	26.0	462.0
Domestic Air	46.7	1.9	1.8	50.4
Rail	11.7	1.4	0.4	13.5
Domestic Water	15.7	1.6	0.9	18.1
Pipeline	9.5	2.4		11.9
International Bunker	23.0	3.0	0.5	26.4
Off-Road		4.6		4.6
Total	505.9	51.7	29.4	587.0

Sources: U.S. EPA (2005); Environment Canada (2005a); INE (2003)

Note: Data for Mexico is 2001, United States and Canada are 2003.

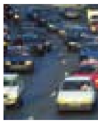
Carbon dioxide emissions estimates are considered by the Canadian and Mexican sources to have 95% certainty that the actual value is within 10% of the estimate reported. The United States did not provide quantitative uncertainty estimates for 2003, but these estimates are considered to be equally accurate by the author.

NATS, 2005). These differences in energy use are directly reflected in carbon emissions from the three countries' transportation sectors (Table 7.1)[1].

Transportation is defined as private and public vehicles that move people and commodities (U.S. EPA, 2005, p. 296). This includes automobiles, trucks, buses, motorcycles, railroads and railways (including streetcars and subways), aircraft, ships, barges, and natural gas pipelines. This definition excludes petroleum, coal slurry, and water pipelines, as well as the transmission of electricity, although many countries consider all pipelines part of the transport sector. It also generally excludes mobile sources not engaged in transporting people or goods, such as construction equipment and on-farm agricultural equipment. In addition, carbon emissions from international bunker fuel-use in aviation and waterborne transport, though considered part of transport emissions, are generally accounted for separately from a nation's domestic GHG inventory. In this chapter, however, they are included, as are carbon emissions from military transport operations, because they are real inputs to the carbon cycle. Upstream, or well-to-tank, carbon emissions are not included with transportation end-use, nor are end-of-life emissions produced in the disposal or recycling of materials used in transportation vehicles or infrastructure because these carbon flows are in the domain of other chapters. These two categories of emissions typically comprise 20-30% of total life cycle emissions for transport vehicles (see Table 5.4 in Weiss *et al*., 2000). In the future, it is likely that upstream carbon emissions will be of greater importance in determining the total emissions due to transportation activities.

In addition to CO_2, the combustion of fossil fuels by transportation produces other GHGs including methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), nitrogen oxides (NO_x), and non-CH_4 volatile organic compounds (VOCs). Those containing carbon are generally oxidized in the atmosphere to ultimately produce CO_2. However, the quantities of non-CO_2 gases produced by transportation vehicles are very minor sources of carbon in comparison to the volume of CO_2 emissions. For example, North American emissions of CH_4 by transportation accounted for only 0.03% of total transportation carbon emissions in 2003. This chapter will therefore address primarily the CO_2 emissions from transportation activities (CH_4 emissions are included in the totals presented in Table 7.1, but they are not included in any other estimates presented in this chapter). Estimates of non-CO_2 emissions are also subject to much greater uncertainty. INE (2003) generally put the accuracy of the Mexican 2001 non-CO_2 GHG emissions at 95% certainty that the actual value is within 50% of the estimate reported. However, Environment Canada's 2003 inventory (Environment Canada, 2005a) rates the uncertainty of CH_4 emissions from mobile sources as 95% certain that the actual value is within 10% of the estimate reported.

Four main sources of information on carbon emissions are used in this chapter. The estimates shown in Table 7.1 were obtained from the GHG inventory reports of the three countries, estimated by environmental agencies in accordance with Intergovernmental Panel on Climate Change (IPCC) guidelines. As Annex 1 countries, Canada and the United States are obliged to compile annual inventories under IPCC guidelines. As a non-Annex 1 country, Mexico is not. These inventories are the most authoritative sources for estimates of carbon emissions. The inventory reports, however, do not generally provide estimates of associated energy use and the most recent inventory data available for Mexico are for 2001. Estimates of energy use and carbon emissions produced by the countries' energy agencies are also used in this chapter to illustrate the relationship between energy use and carbon emissions and its historical trends. There are some minor differences between the carbon emissions estimates from the two sources. Finally, future projections of carbon emissions for North America to 2025 were taken from the U.S. Energy Information's Annual Energy Outlook 2005, and projections to 2050 were taken from the World Business Council on Sustainable Development's Sustainable Mobility Project (WBCSD, 2004).



7.2.1 Fuels Used in Transportation

Virtually all of the energy used by the transport sector in North America is derived from petroleum, and most of the remainder comes from natural gas (Table 7.2). In the United States, 96.3% of total transportation energy is obtained by combustion of petroleum fuels (U.S. DOE/EIA, 2005a). Most of the non-petroleum energy is natural gas used to power natural gas pipelines (2.5%, 744 petajoules). During the past two decades, ethanol use (as a blending component for gasoline) has increased from a negligible amount to 1.1% of transportation energy use (312 petajoules). Electricity, mostly for passenger rail transport, comprises only 0.1% of United States transport energy use. This pattern of energy use has persisted for more than half a century.

Virtually all of the energy used by the transport sector in North America is derived from petroleum, and most of the remainder comes from natural gas.

The pattern of energy sources is only a little different in Mexico where 96.2% of transportation energy use is gasoline, diesel, or jet fuel, 3.4% is liquefied petroleum gas, and less than 0.2% is electricity (Rodríguez, 2005). In Canada, natural gas use for natural gas pipelines accounts for 7.5%

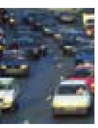
[1] Uncertainties in these estimates are discussed later in this chapter (see Section 7.5).

Table 7.2 Summary of North American transport energy use and CO_2 emissions in 2003 by energy source or fuel type.

North America energy source	Energy input (Petajoules)	Carbon input (Mt C)
Gasoline	20,923	358.3
Diesel/distillate	7,344	129.5
Jet fuel/kerosene	2,298	68.5
Residual	681	14.5
Other fuels	124	1.3
Natural gas	926	9.7
Electricity	36	0.0
Unallocated/error	466	-
Total	32,798	581.8
United States		
Gasoline	18,520	312.5
Diesel/distillate	6,193	107.1
Jet fuel/kerosene	1,986	62.3
Residual	612	13.1
Other fuels	50	0.2
Natural gas	748	9.7
Electricity	20	0.0
Unallocated/error	466.2	-
Total	28,595.2	504.9
Sources: U.S. EPA (2005), Tables 3-7 and 2-17; Davis and Diegel (2004), Tables 2.6 and 2.7.		
Canada		
Gasoline	1,355	26.2
Diesel/distillate	698	13.9
Jet fuel/kerosene	223	4.3
Residual	67	1.3
Other fuels	17	0.2
Natural gas	2	0.0
Electricity	3	0.0
Unallocated/error	0	
Total	2,363	45.9
NRCan (2006), Tables 1 and 8.		
Mexico		
Gasoline	1,066	19.5
Diesel/distillate	447	8.5
Jet fuel/kerosene	106	1.9
Residual	4	0.1
Other fuels	57	0.9
Natural gas	1	0.0
Electricity	4	0.0
Unallocated/error		
Total	1,685	31.0
Sources: Transportation energy use by fuel and mode from Rodríguez (2005).		

The accuracy of the data in the above table is judged by the author to be 95% certain that the actual value is within 10% of the estimate reported.

Data sources differ somewhat by country with respect to modal, fuel, and greenhouse gas definitions so that the numbers are not precisely comparable. Canadian carbon emissions data include all GHGs produced by transportation in CO_2 equivalents, while the United States' data are CO_2 emissions only. Carbon dioxide emissions for Mexico were estimated by applying U.S. EPA emissions factors to the Mexican energy use data. For Mexico, it is asumed that no transportation carbon emissions result from electricity use.



of transport energy use, 91.8% is petroleum, 0.5% is propane, and only 0.1% is electricity (see Table 1 in NRCan, 2006).

7.2.2 Mode of Transportation

Mode of transportation refers to how people and freight are moved about, whether by road, rail, or air, or in light or heavy vehicles. Carbon dioxide emissions from the North American transportation sector are summarized by mode in Table 7.3, and the distribution of emissions by mode for North America in 2003 is illustrated in Figure 7.2.

7.2.2.1 Freight Transport

Movement of freight is a major component of the transportation sector in North America. Total freight activity in the United States, measured in metric ton-km, is 20 times that in Mexico and more than 10 times the levels observed in Canada (Figures 7.3A, 7.3B, and 7.3C).

In Mexico, trucking is the mode of choice for freight movements. Four-fifths of Mexican metric ton-km is produced by trucks. Moreover, trucking's modal share has been increasing over time.

In Canada, rail transport accounts for the majority of freight movement (65%). Rail transport is well suited to the approximately linear distribution of Canada's population in close proximity to the United States border, the long-distances from east to west, and the large volumes of raw material flows typical of Canadian freight traffic (see Table 5.2 in NATS, 2005).

Table 7.3 Summary of North American transport energy use and carbon dioxide emissions in 2003 by mode of transportation.

North America transport mode	Energy use (Petajoules)	Carbon emissions (Mt C)
Road	25,830	463.5
Air	2,667	53.0
Rail	751	13.7
Waterborne	1,386	18.4
Pipeline	990	12.3
Internatl./Bunker	0	23.0
Total	31,624	583.9
United States		
Road		
Light vehicles	17,083	303.8
Heavy vehicles	5,505	95.5
Air	2,335	46.7
Rail	655	11.7
Waterborne	1,250	15.7
Pipeline/other	986	9.5
Internatl./Bunker		23.0
Total	27,814	505.8
Source: U.S. EPA (2005), Tables 3-7 and 2-17; Davis and Diegel (2004), Tables 2-6 and 2-7.		
Canada		
Road		
Light vehicles	1,233	23.8
Heavy vehicles	491	12.4
Air	226	4.3
Rail	74	1.6
Waterborne	103	2.1
Pipeline/other		1.8
Total	2,126	46.1
Source: NRCan (2006); Tables 1 and 8.		
Mexico		
Road	1,518	27.9
Light vehicles		
Heavy vehicles		
Air	107	2.0
Rail	22	0.5
Waterborne	33	0.6
Electric	4	-
Total	1,684	32.0
Source: Rodríguez (2005).		

The accuracy of the data in the above table is judged by the author to be 95% certain that the actual value is within 10% of the estimate reported for the larger modes of transportation, and 95% certain that the value is within 25% for the smaller modes.

Data sources differ somewhat by country with respect to modal, fuel, and GHG defintions so that the numbers are not precisely comparable. Canadian carbon emissions data include all GHGs produced by transportation in CO_2 equivalents, while United States data are CO_2 emissions only. Carbon dioxide emissions for Mexico were estimated by applying U.S. EPA emissions factors to the Mexican energy use data. Electricity is assumed to produce no carbon emssions in end use.

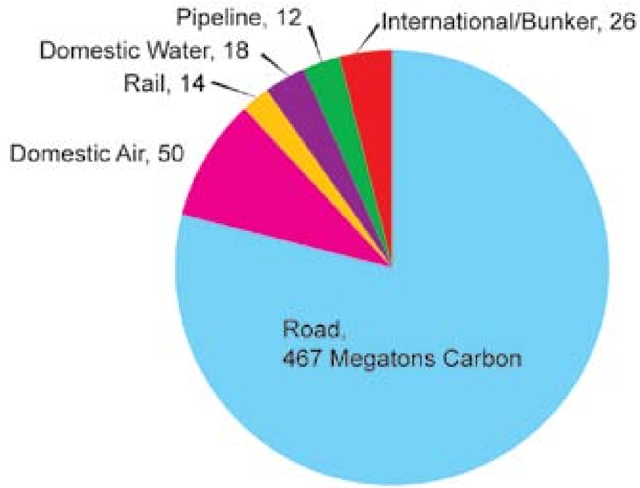
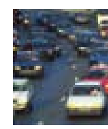


Figure 7.2 North American carbon emissions from transportation by mode; United States and Canada 2003, Mexico 2001. *Sources:* U.S. EPA (2005); Environment Canada (2005a); INE (2003).

In the United States, road freight plays a greater role than in Canada, and rail is less dominant, although rail still carries the largest share of metric ton-km (40%). In none of the countries does air freight account for a significant share of metric ton-km.



7.2.2.2 Passenger Transport

In all three countries, passenger transport is predominantly by road, followed in distant second by air travel. The rate of growth in air travel in North America is more than double that of road transport, so air transport's share of carbon emissions will increase in the future. Nearly complete data are available for passenger-kilometers-traveled (pkt) by mode in the United States and Canada in 2001. Of the more than 8 trillion pkt accounted for by the United States, 86% was by light-duty personal vehicles, most by passenger car but a growing share by light trucks (Figure 7.4A) (motorcycle pkt, about 0.2% of the total, is included with passenger car). Air travel claims 10%; other modes are minor.

In all three countries, passenger transport is predominantly by road, followed in distant second by air travel.

Canadian passenger travel exhibits a very similar modal structure, but with a smaller role played by light trucks and air and a larger share for buses (Figure 7.4B) (transit numbers for Canada were not available at the time these figures were compiled).

7.3 TRENDS AND DRIVERS

Driven by economic and population growth, transportation energy use has increased substantially in all three countries since 1990. Figures 7.5A and 7.5B illustrate the evolution of transport energy use by mode for Mexico and the United

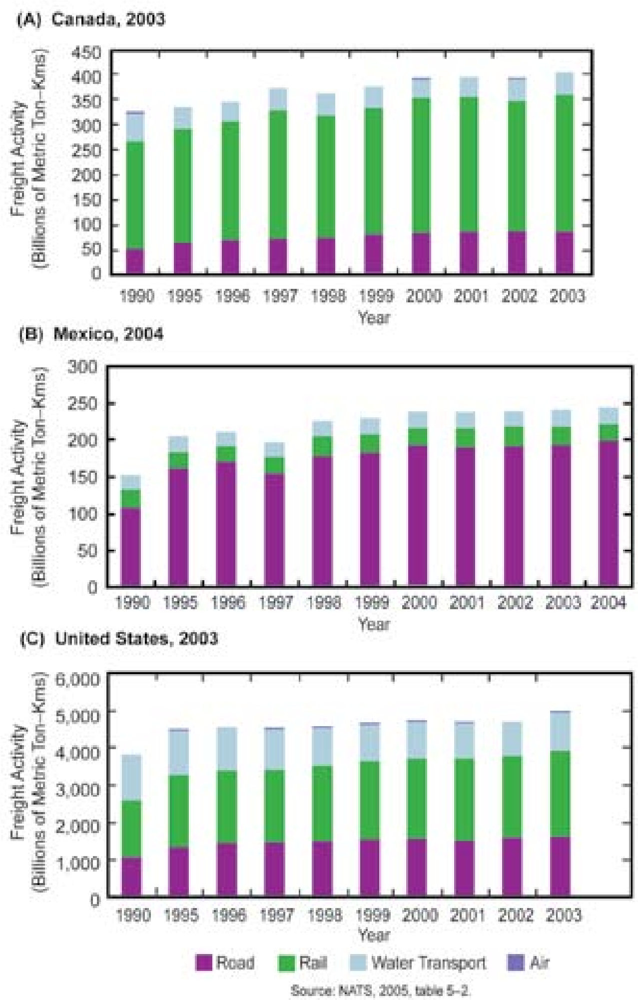
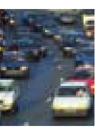


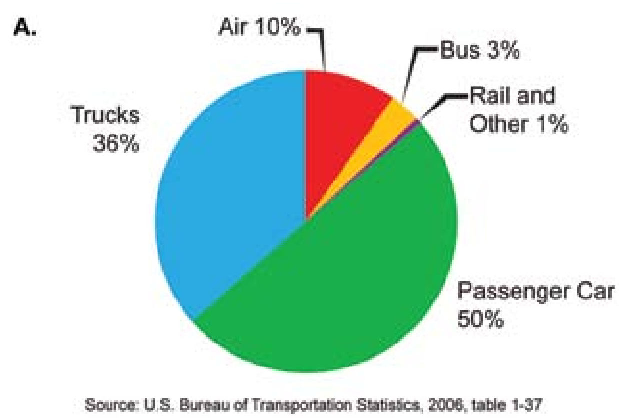
Figure 7.3A Freight activity by mode in Canada.
Figure 7.3B Freight activity by mode in Mexico.
Figure 7.3C Freight activity by mode in the United States.



States. Energy use has grown most rapidly in Mexico, the country most dependent on road transport. In the United States, the steady growth of transportation oil use was interrupted by oil price shocks in 1973-74, 1979-80, and to a much lesser degree in 1991. The impact of the attack on the World Trade Center in 2001 and subsequent changes in air travel procedures had a visible effect on energy use for air travel.

The evolution of transport carbon emissions has closely followed the evolution of energy use. Carbon dioxide emissions by mode are shown for the United States and Canada for the period 1990-2003 in Figures 7.6A and 7.6B. The Canadian data include light-duty commercial vehicles in road freight transport, while all light trucks are included in the light-duty vehicle category in the United States data. These data illustrate the relatively faster growth of freight-transport energy use. Fuel economy standards in both countries restrained the growth of passenger car and light-truck energy use (NAS, 2002). From 1990 to 2003 passenger kilometers traveled by road in Canada increased by 23%, while energy use increased by only 15%. In 2003, freight activity accounted for more than 40% of Canada's transport energy use. In addition, while passenger transport energy use increased by 15% from 1990 to 2003, freight energy use increased by 40%. The Canadian transport energy statistics do not include natural gas pipelines as a transport mode.

Carbon emissions by transport are determined by the levels of passenger and freight activity, the shares of transport modes, the energy intensity of passenger and freight movements, and the carbon intensity of transportation fuels. In North America, petroleum fuels supply over 95% of transportation's energy requirements and account for 98% of the sector's GHG emissions. Among modes, road vehicles are predominant, producing almost 80% of sectoral GHG emissions. Consequently, the driving forces for transportation GHG emissions have been changes in activity and energy intensity. The principal driving forces of the growth of passenger transportation are population and *per capita* income (WBCSD, 2004). Increased vehicle ownership follows rising *per capita* income, as do vehicle use, fuel consumption, and emissions. In general, energy forecasters expect the greatest growth in vehicle ownership and fossil-fuel use in transpor-



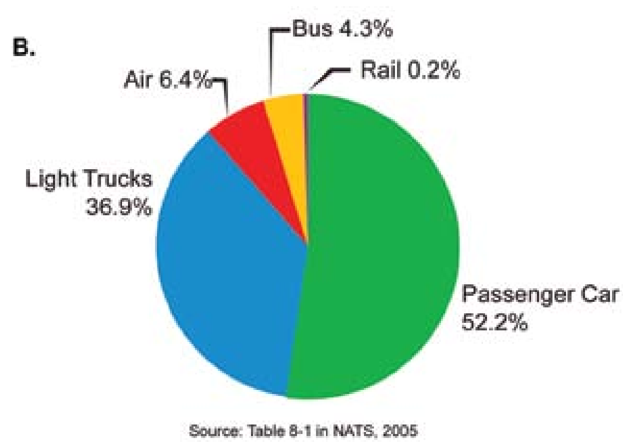


Figure 7.4A Distribution of passenger travel in the United States by mode.
Figure 7.4B Distribution of passenger travel by mode in Canada.

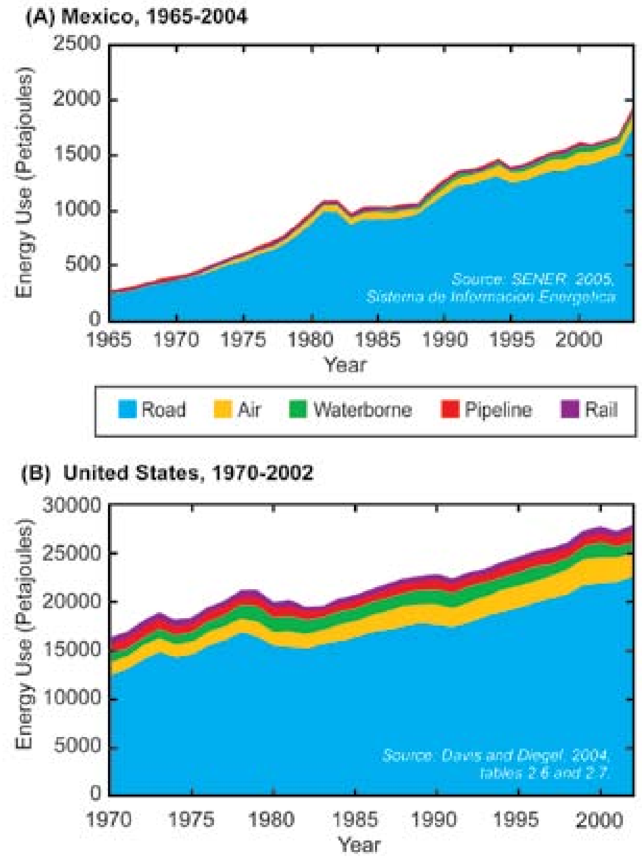


Figure 7.5A Evolution of transport energy use in Mexico.
Figure 7.5B Evolution of transport energy use in the United States.

tation over the next 25-50 years to occur in the developing economies (U.S. DOE/EIA, 2005b; IEA, 2004; WBCSD, 2004; Nakićenović, Grűbler, and McDonald, 1998). The chief driving forces for freight activity are economic growth and the integration of economic activities at both regional and global scales (WBCSD, 2004).

Projections of North American transportation energy use and carbon emissions to 2030 have been published by the U.S. Energy Information Administration (U.S. DOE/EIA, 2005b) and the International Energy Agency (IEA, 2005a). Historical population growth rates are similar in the three countries, 0.92% per year in the United States, 1.17% per year in Mexico, and 0.90% per year in Canada. Recent annual GDP growth rates are 4.4% for the United States, 4.1% for Mexico, and 2.4% for Canada (CIA, 2005). The U.S. Energy Information Administration's Reference Case projection assumes annual GDP growth rates of 3.1% for the United States, 2.4% for Canada, and 3.9% for Mexico (see Table A3 in U.S. DOE/EIA, 2005b). Assumed population growth rates are United States: 0.9%; Canada: 0.6%; Mexico: 1.0% (see Table A14 in U.S. DOE/EIA, 2005b). Chiefly because of economic growth, energy use by North American transportation is expected to increase by 46% from 2003 to 2025 (U.S. DOE/EIA, 2005b). If the mix of fuels is assumed to remain the same, as it nearly does in the IEO 2005 Reference Case projection, CO_2 emissions would increase from 587 million metric tons of carbon (Mt C) in 2003 to 859 Mt C in 2025 (Figure 7.7). Canada, the only one of the three countries to have committed to specific GHG reduction goals, is expected to show the lowest rate of growth in CO_2 emissions.

The World Business Council for Sustainable Development (WBCSD), in collaboration with the International Energy Agency developed a model for projecting world transport energy use and GHG emissions to 2050 (Table 7.4). The WBCSD's reference case projection foresees the most rapid growth in carbon emissions from transportation occurring in Asia and Latin America (Figure 7.8). Still, in 2050, North America accounts for 26.4% of global CO_2 emissions from transport vehicles (down from a 37.2% share in 2000).

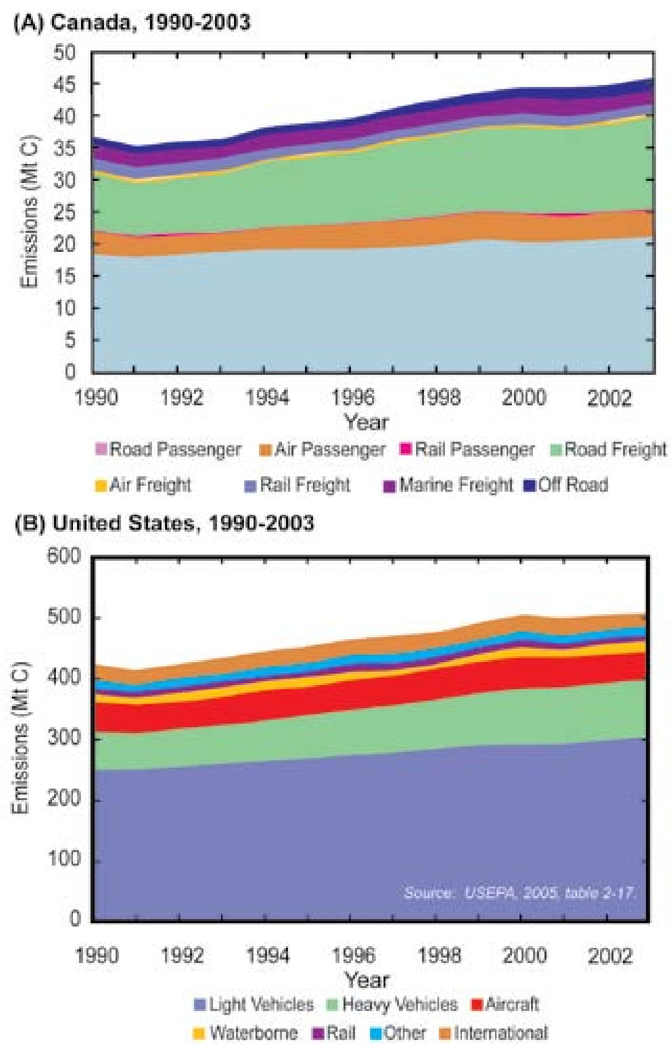
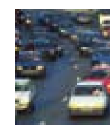


Figure 7.6A Evolution of transport energy use in Mexico. *Source:* SENER (2005).
Figure 7.6B Transport CO_2 emissions in the United States.



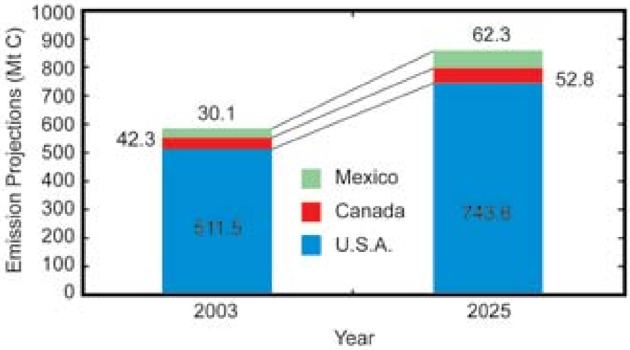


Figure 7.7 Projected CO_2 emissions from the North American transport sector in 2025, based on EIA IEO (2005) reference case. *Source:* NRCan (2006).

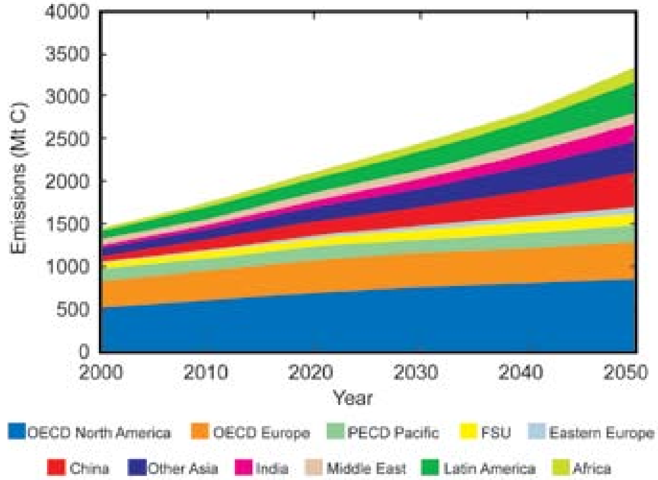
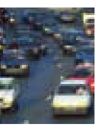


Figure 7.8 World Business Council for Sustainable Development (WBCSD) projections of world transportation vehicle CO_2 emissions to 2050. *Source:* U.S. EPA (2005), Table 2-17.

7.4 OPTIONS FOR MANAGEMENT



Dozens of policies and measures for reducing petroleum consumption and mitigating carbon emissions from transportation in North America have been identified and assessed (*e.g.*, U.S. DOT, 1998; IEA, 2001; Greene and Schafer, 2003; Greene *et al.*, 2005; CBO, 2003; Harrington and McConnell, 2003; NRTEE, 2005). However, there is no consensus about how much transportation GHG emissions can be reduced and at what cost. In general, top-down models estimating the mitigation impacts of economy-wide carbon taxes or cap-and-trade systems find the cost of mitigation high and the potential modest. On the other hand, bottom-up studies evaluating a wide array of policy options tend to reach the opposite conclusion. Part of the explanation of this paradox may lie in the predominant roles that governments play in constructing, maintaining, and operating the majority of transportation infrastructure and in the strong interrelationship between land-use planning and transportation demand. In addition, top down models typically assume that all markets are efficient, whereas there is evidence of real-world transportation energy market failures, especially with respect to the determination of light-duty vehicle fuel economy (*e.g.*, Turrentine and Kurani, 2004; Chapter 5 in NAS, 2002). Estimates of the costs and benefits of mitigation policies also vary widely and depend critically on premises concerning (1) the efficiency of transportation energy markets, (2) the values consumers attach to vehicle attributes such as acceleration performance and vehicle weight, and (3) the current and future status of carbon-related technology.

A U.S. Energy Information Administration evaluation of a GHG cap and trade system, expected to result in carbon permit prices of \$79/t C in 2010 and \$221/t C in 2025, was estimated to reduce 2025 transportation energy use by 4.3 Petajoules (PJ) and to cut transportation's carbon emissions by 10% from 225 Mt C in the reference case to 203 Mt C under this policy (U.S. DOE/EIA, 2003). The average fuel economy of new light-duty vehicles was estimated to increase from 26.4 miles per gallon (mpg, or 8.9 L per 100 km) to 29.0 mpg (8.1 L per 100 km) in the policy case, an improvement of only 10%. A 2002 study by the U.S. National Academy of Sciences (NAS, 2002) estimated that "cost-efficient" fuel economy improvements for United States' light-duty vehicles using proven technologies ranged from 12% for subcompact cars to 27% for large cars, and from 25% for small

Table 7.4 Global carbon emissions from transportation vehicles to 2050 by regions, WBCSD reference case projection (Mt C).

	2000	2010	2020	2030	2040	2050
OECD North America	544	623	708	768	824	882
OECD Europe	313	359	392	412	420	428
OECD Pacific	133	142	153	161	169	179
FSU	48	64	88	109	132	153
Eastern Europe	23	28	36	42	52	66
China	69	108	163	225	308	417
Other Asia	98	131	174	220	283	368
India	38	54	80	108	146	203
Middle East	59	71	88	106	122	138
Latin America	95	127	172	216	275	352
Africa	43	58	80	103	127	158
TOTAL - All Regions	1463	1766	2134	2470	2858	3343

Source: Fulton and Eads (2004).

sport utility vehicles (SUVs) to 42% for large SUVs. The NAS study did not include the potential impacts of diesel or hybrid vehicle technologies and assumed that vehicle size and horsepower would remain constant.

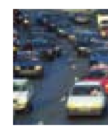
The U.S. Congressional Budget Office (CBO, 2003) estimated that achieving a 10% reduction in United States gasoline use would create total economic costs of approximately $3.6 billion per year if accomplished by means of Corporate Average Fuel Economy (CAFE) standards, $3.0 billion if the same standards allowed trading of fuel economy credits among manufacturers, and $2.9 billion if accomplished via a tax on gasoline. This partial equilibrium analysis assumed that it would take about 14 years for the policies to have their full impact. If one assumes that the United States would consume 22,600 PJ of gasoline in 2017, resulting in 387 Mt of CO_2 emissions, then a 10% reduction amounts to 39 Mt C. At a total cost of $3 billion per year, and attributing the full cost to carbon reduction (vs. other objectives such as reducing petroleum dependence), produces an upper-bound mitigation cost estimate of $77/t C.

The bipartisan National Commission on Energy Policy (NCEP, 2004) surveyed recent assessments of the potential to increase light-duty vehicle fuel economy in the United States. Taking into consideration uncertainties about the costs and technical potential of fuel economy technologies, as well as the future price of fuel, the Commission concluded that future increases in fuel economy of from 40% to 80% could be achieved at a cost that would be fully offset by the value of fuel saved over the life of a vehicle. They estimated that the essentially costless carbon emissions reductions would amount to between 250 and 400 million metric tons per year by 2030.

Systems of progressive vehicle taxes on purchases of less efficient new vehicles and subsidies for more efficient new vehicles ("feebates") are yet another alternative for increasing vehicle fuel economy. A study of the United States market (Greene *et al*., 2005) examined a variety of feebate structures under two alternative assumptions: (1) consumers consider only the first three years of fuel savings when making new vehicle purchase decisions, and (2) consumers consider the full discounted present value of lifetime fuel savings. The study found that if consumers consider only the first three years of fuel savings, then a feebate of $1000 per 0.01 gal/mile (3.5 L per 100 km), designed to produce no net revenue to the government, would produce net benefits to society in terms of fuel savings and would reduce carbon emissions by 139 Mt C in 2030. If consumers fully valued lifetime fuel savings, the same feebate system would cause a $3 billion loss in consumers' surplus (a technical measure of the change in economic well-being closely approximating income loss) and reduce carbon emissions by only 67 Mt C, or an implied cost of $44/Mt CO_2.

The most widely proposed options for reducing the carbon content of transportation fuels are liquid fuels derived from biomass and hydrogen produced from renewables, nuclear energy, or from fossil fuels with carbon sequestration. Biomass fuels, such as ethanol from cellulosic feedstocks or liquid hydrocarbon fuels produced via biomass gasification and synthesis, appear to be a promising mid- to long-term option, while hydrogen could become an important energy carrier, but not before 2025 (WBCSD, 2004). The carbon emission reduction potential of biomass fuels for transportation is strongly dependent on the feedstock and conversion processes. Advanced methods of producing ethanol from grain, the predominant feedstock in the United States can reduce carbon emissions by 10% to 30% (Wang, 2005; p. 16 in IEA, 2004). Production of ethanol from sugar cane, as is the current practice in Brazil, or by not-yet-commercialized methods of cellulosic conversion can achieve up to a 90% net reduction over the fuel cycle. Conversion of biomass to liquid hydrocarbon fuels via gasification and synthesis may have a similar potential (Williams, 2005). The technical potential for liquid fuels production from biomass is very large and very uncertain; recent estimates of the global potential range from 10 to 400 exajoules per year (see Table 6.8 in IEA, 2004). The U.S. Departments of Energy and Agriculture have estimated that 30% of United States' petroleum use could be replaced by biofuels by 2030 (Perlack *et al*., 2005). The economic potential will depend on competition for land with other uses, the development of a global market for biofuels, and advances in conversion technologies.

The most widely proposed options for reducing the carbon content of transportation fuels are liquid fuels derived from biomass and hydrogen produced from renewables, nuclear energy, or from fossil fuels with carbon sequestration.



Hydrogen must be considered a long-term option because of the present high cost of fuel cells, technical challenges in hydrogen storage, and the need to construct a new infrastructure for hydrogen production and distribution (NAS, 2004; U.S. DOE, 2005; IEA, 2005b). Hydrogen's potential to mitigate carbon emissions from transport will depend most strongly on how hydrogen is produced. If produced from coal gasification without sequestration of CO_2 emissions in production, it is conceivable that carbon emissions could increase. If produced from fossil fuels with sequestration, or from renewable or nuclear energy, carbon emissions from road and rail vehicles could be virtually eliminated (General Motors *et al*., 2001).

In a comprehensive assessment of opportunities to reduce GHG emissions from the United States transportation sector, a study published by the Pew Center on Global Climate Change (Greene and Schafer, 2003) estimated that sector-wide reductions in the vicinity of 20% could be achieved by 2015 and 50% by 2030 (Table 7.5). The study's premises assumed no change in the year 2000 distribution of energy use by mode. A wide range of strategies was considered, including research and development, efficiency standards, use of biofuels and hydrogen, pricing policies to encourage efficiency and reduce travel demand, land-use transportation planning options, and public education (Table 7.5). Other key premises of the analysis were that (1) for efficiency improvements the value of fuel saved to the consumer must be greater than or equal to the cost of the improvement, (2) there is no change in vehicle size or performance, (3) pricing

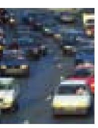


Table 7.5 Potential impacts of transportation GHG reduction policies in the United States by 2015 and 2030[a] based on the 2000 distribution of emissions by mode and fuel (Greene and Shafer, 2003).

		Reduction potential per mode/fuel (%)		Transportation sector reduction potential (%)	
Management option	**Carbon emission (Mt C) 2000**	**2015**	**2030**	**2015**	**2030**
Research, development, and demonstration					
Light-duty vehicles (LDVs)	289	11[b]	38[b]	7[b]	23[b]
Heavy trucks	80	11[b]	24[b]	2[b]	4[b]
Commercial aircraft	53	11[b]	27[b]	1[b]	3[b]
Efficiency standards					
Light-duty vehicles	289	9	31	6	18
Heavy trucks	80	9	20	2	3
Commercial aircraft	53	9	22	1	2
Replacement and alternative fuels					
Low-carbon replacement fuels (~10% of LDV fuel)	27	30	100	2	7
Hydrogen fuel (All LDV fuel)	289	1	6	1	4
Pricing policies					
Low-carbon replacement fuels (~10% of LDV fuel)	27	30	100	2	6
Carbon pricing (All transportation fuel)	489	3	6	3	6
Variabilization (All highway vehicle fuel)	370	8	12	6	9
Behavioral					
Land use and infrastructure (2/3 of highway fuel)	246	5	10	3	5
System efficiency (25% LDV fuel)	72	2	5	0	1
Climate change education (All transportation fuel)	489	1	2	1	2
Fuel economy information (All LDV fuel)	289	1	2	1	1
Total	**489**			**22**	**48**

Notes:

[a] Carbon emissions for the year 2000 are used to weight percent reductions for the respective emissions source and example policy category in calculating total percent reduction potential. The elasticity of vehicle travel with respect to fuel price is –0.15 for all modes. Price elasticity of energy efficiency with respect to fuel price is –0.4.

[b] R&D efficiency improvements have no direct effect on total. Their influence is seen through efficiency standards impacts.

Policies affecting the same target emissions, such as passenger car efficiency, low carbon fuels, and land-use policies are multiplicative, to avoid double counting (e.g. [1–0.1]*[1.0–0.2] = 1–0.28, a 28% rather than a 30% reduction.)

policies shift the incidence but do not increase the overall cost of transportation, and (4) there is a carbon cap and trade system in effect equivalent to a charge of approximately $50/t C. Similar premises underlie the 2030 estimates, except that technological progress is assumed to have expanded the potential for efficiency improvement and lowered the cost of biofuels.

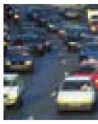
The Pew Center study notes that if transportation demand continues to grow as the IEO 2005 and WBCSD projections anticipate, the potential reductions shown in Table 7.4 would be just large enough to hold United States transportation CO_2 emissions in 2030 to 2000 levels.

A study for the U.S. Department of Energy (ILWG, 2000) produced estimates of carbon mitigation potential for the entire United States economy using a variety of policies generally consistent with carbon taxes of $25-$50/t C. In the study's business as usual case, transportation CO_2 emissions increased from 478 Mt C in 1997 to 700 Mt C in 2020. A combination of technological advances, greater use of biofuel, fuel economy standards, paying for a portion of automobile insurance as a surcharge on gasoline, and others, were estimated to reduce 2020 transportation CO_2 emissions by 155 Mt C to 545 Mt CO_2. The study did not produce cost estimates and did not consider impacts on global energy markets.

A joint study of the U.S. Department of Energy and Natural Resources Canada (Patterson *et al.*, 2003) considered alternative scenarios of highway energy use in the two countries to 2050. The study did not produce estimates of cost-effectiveness for GHG reduction strategies but rather focused on the potential impacts of differing social, economic, and technological trends. Two of the scenarios describe paths that lead to essentially constant GHG emissions from highway vehicles through 2050 through greatly increased efficiency and biofuel and hydrogen use and, in one scenario, reduced demand for vehicle travel.

7.5 INCONSISTENCIES AND UNCERTAINTIES

There are some inconsistencies in the way the three North American countries report transportation carbon emissions. The principal source for Mexican emissions data breaks out transportation into four modes (road, air, rail, and waterborne), it does not report emissions for pipelines but does report emissions from use of international bunker fuels. The United States and Canada report transport emissions in much greater modal detail, by vehicle type and fuel type within modes. The United States and Mexico report emissions from international bunker fuels in their national inventory reports, while Canada does not. Estimates of international bunker fuel emissions for Canada presented in this chapter were derived by subtracting Air and Waterborne emissions reported by Environment Canada (2005a) which exclude international bunker fuels from total air and waterborne emissions as reported by Natural Resources Canada (2006) which include them. Environment Canada reports off-road emissions from mobile sources separately; in the tables and figures in this chapter, Canadian off-road emissions have been added to road emissions. Both Canada and the United States include emissions from military transport operations in their inventories. It is not clear whether these are included in the estimates for Mexico.



All three countries' GHG inventories discuss uncertainties in estimated emissions. In general, the uncertainties were estimated in accordance with IPCC guidelines. The U.S. EPA provides only an estimate of a 95% confidence

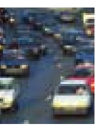
Table 7.6 Uncertainty in estimates of carbon dioxide emissions from energy use in transport: Canada (2003).

Mode	% Below (2.5th Percentile)	% Above (97.5th Percentile)
Total Mobile Sources excluding pipeline	-4	0
Road Transportation	-8	-3
On-Road Gasoline Vehicles	-7	-3
On-Road Diesel Vehicles	-13	-1
Railways	-5	3
Navigation	-3	3
Off-Road Mobile Sources	4	45
Pipeline	-3	3

Source: Environment Canada (2005a), table A7-9.

interval for all CO_2 emissions from the combustion of fossil fuels (-1% to 6%) which can be inferred to apply to transportation. Mexico's INE estimates a total uncertainty for transportation GHG emissions of about ± 10%. For CO_2 emissions from road transport, the uncertainty is put at ± 9% (INE, 2003, Appendix B). The Canadian Greenhouse Gas Inventory provides by far the most extensive and detailed estimates of uncertainty. Given the similarity in methods, the Canadian uncertainty estimates are probably also approximately correct for the United States, and therefore may be considered indicative of the uncertainty of North American carbon emission estimates (Table 7.6). Most significant is the apparent overestimation of carbon emissions from on-road vehicles, offset to a degree by the underestimation of off-road mobile source emissions. Still, total mobile source carbon emissions are estimated to have a 95% confidence interval of (-4% to 0%).

7.6 RESEARCH AND DEVELOPMENT NEEDS



Research needs with respect to the transport sector as a part of the carbon cycle fall into three categories: (1) improved data, (2) comprehensive assessments of mitigation potential, and (3) advances in key mitigation technologies and policies for transportation. The available data are adequate to describe carbon inputs by fuel type and carbon emissions by very broad modal breakdowns by country. Environment Canada (2005a) and the U.S. Environmental Protection Agency (2005) annually publish estimates of transportation's carbon emissions that closely follow IPCC guidelines with respect to methods, data sources, and quantification of uncertainties (GAO, 2003). The Mexican Instituto Nacional de Ecología has published estimates for 2001 that are also based on IPCC methods. However, that report also notes deficiencies in the data available for Mexico's transport sector and recommends establishing an information system for estimating Mexico's transportation GHG emissions on a continuing basis (INE, 2003, p. 21). Knowledge of the magnitude of GHG emissions by type of activity and fuel, and of trends is essential if policies are to be focused on the most important GHG sources.

The most pressing research need is for comprehensive, consistent, and rigorous assessments of the carbon emissions mitigation potential for North American transportation.

The most pressing research need is for comprehensive, consistent, and rigorous assessments of the carbon emissions mitigation potential for North American transportation. The lack of such studies for North America parallels a similar dearth of consistent and comprehensive global analyses noted by the IPCC (Moomaw and Moreira, 2001). Existing studies focus almost exclusively on a single country, with premises and assumptions varying widely from country to country. Even the best single country studies omit the impacts of carbon reduction policies on global energy markets. Knowledge of how much contribution the transport sector can make to GHG mitigation, at what cost, and what options are capable of achieving those potentials is crucial to the global GHG policy discussion.

Continued research and development of vehicle technologies and fuels that can cost-effectively increase energy efficiency and displace carbon-based fuels is essential to achieving major reductions in transportation carbon emissions. Highly promising technologies for reducing transportation GHG emissions include hybrid vehicles, which are available today, and in the future, plug-in hybrid vehicles capable of accepting electrical energy from the grid, and eventually fuel cell vehicles powered by hydrogen. While hybrids are already in the market and fuel cell vehicles are still years away, all three technologies would benefit from cost reduction. Hydrogen fuel cell vehicles also face significant technological challenges with respect to hydrogen storage and fuel cell durability. Energy-efficient technologies could also greatly reduce GHG emissions from other transport modes. For example, blended wing-body aircraft designs are under development that could reduce fuel burn rates by one-third. Biofuels in the near term and hydrogen in the longer term appear to be the most promising low-carbon fuel options. To achieve the greatest GHG reduction benefits, biofuels must be made from plants' ligno-cellulosic components either by conversion to alcohol or by gasification and synthesis of liquid hydrocarbon fuels. Cost reductions in both feedstock production and fuel conversion are needed.

CHAPTER 8

Industry and Waste Management

Lead Author: John Nyboer, Simon Fraser Univ.

Contributing Authors: Mark Jaccard, Simon Fraser Univ.; Ernst Worrell, LBNL

KEY FINDINGS

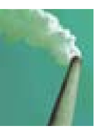
- In 2002, North America's industry (not including fossil-fuel mining and processing or electricity generation) contributed 225 million metric tons of carbon (826 million tons of carbon dioxide), 16% of the world's carbon dioxide emissions to the atmosphere from industry. Waste treatment plants and landfill sites in North America accounted for 13.4 million tons of methane (282 million tons of carbon dioxide equivalent; 10 million tons of carbon), roughly 20% of global totals.
- Industrial carbon dioxide emissions from North America decreased nearly 11% between 1990 and 2002, while energy consumption in the United States and Canada increased 8% to 10% during that period. In both countries, a shift in production activity toward less energy-intensive industries and dissemination of more energy efficient equipment kept the rate of energy demand growth lower than industrial gross domestic product growth.
- Changes in industrial carbon dioxide emissions are a consequence of changes in industrial energy demand and changes in the mix of fossil fuels used by industry to supply that demand. Changes in industrial energy demand are themselves a consequence of changes in total industrial output, shifts in the relative shares of industrial sectors, and increases in energy efficiency. Shifts from coal and refined petroleum products to natural gas and electricity contributed to a decline in total industrial carbon dioxide emissions since 1997 in both Canada and the United States.
- An increase in carbon dioxide emissions from North American industry is likely to accompany the forecasted increase in industrial activity (2.3% per year until 2025 for the United States).
- Emissions per unit of industrial activity will likely decline as non-energy intensive industries grow faster than energy intensive industries and with increased penetration of energy efficient equipment. However, continuation of the trend toward less carbon-intensive fuels is uncertain given the rise in natural gas prices relative to coal in recent years.
- Options for reducing carbon dioxide emissions from North American industry can be broadly classified as methods to: (1) reduce process/fugitive emissions or convert currently released emissions; (2) increase energy efficiency, including combined heat and power management; (3) change industrial processes (materials efficiency, recycling, substitution between materials or between materials and energy, and nanotechnology); (4) substitute less carbon intense fuels; and (5) capture and store carbon dioxide.
- Further work on materials substitution holds promise for industrial emissions reduction, such as the replacement of petrochemical feedstocks by feedstocks derived from vegetative matter (biomass), of steel by aluminum in the transport sector, and of concrete by wood in the buildings sector. The prospects for greater usage of energy efficiency technologies are equally substantial.

8.1 INTRODUCTION

This chapter assesses carbon flows through industry (manufacturing and construction including industry process emissions, but excluding fossil-fuel mining and processing)[1] and municipal waste disposal.

In 2002, industry was responsible for 21% of human-caused (anthropogenic) emissions to the atmosphere.

In 2002, industry was responsible for 1423.8 million metric tons of carbon (Mt C) (5220.6 million tons of carbon dioxide [Mt CO_2]), which is 21% of human-caused (anthropogenic) emissions to the atmosphere (244.8 Mt C [4322.9 Mt CO_2] from fuel combustion and 1179.0 Mt C [897.7 Mt CO_2] from industrial processes). North America's industry contributed 206.9 Mt C (758.7 Mt CO_2) of combustion-sourced emissions and 18.2 Mt C (66.8 Mt CO_2) of process emissions for a total of 225 Mt C (826 Mt CO_2) or 16% of global totals (WRI, 2005; see Figure 8.1A)[2]†. The manufacturing industry contributed 12% of total North American greenhouse gas (GHG) emissions, lower than in many other parts of the world. However, with North America's population at 6.8% of the world's total, industry contributed a proportionally larger share of total industrial emissions *per capita* than the rest of the world[3].



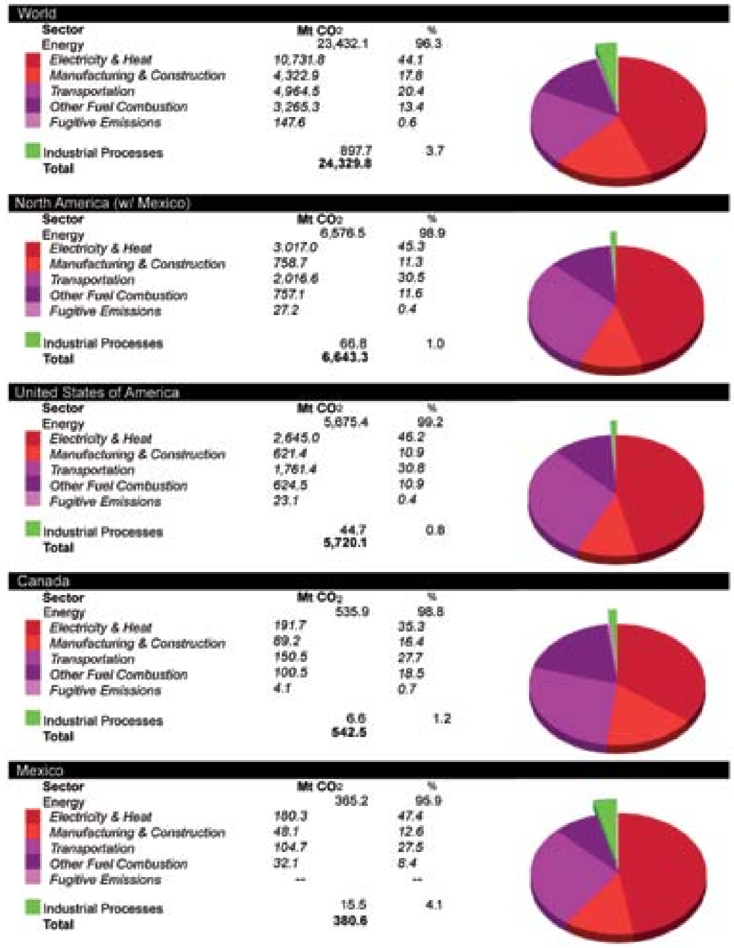


Figure 8.1A Carbon dioxide emissions by sector in 2002. *Source:* WRI (World Resources Institute)(2005). The magnitude and/or range of uncertainty for the given numerical values is not provided in the reference. To convert from Mt CO_2 to MtC, multiply the Mt CO_2 value by 12/44.

Industrial CO_2 emissions decreased nearly 11% between 1990 and 2002 while energy consumption in the United States and Canada increased 8% to 10% (EIA, 2005; CIEEDAC, 2005). In both countries, a shift in production activity toward less energy-intensive industries and dissemination of more energy efficient equipment kept the rate of growth in energy demand lower than industrial gross domestic product (GDP) growth (IEA, 2004)[4]. This slower demand growth, in concert with a shift toward less carbon-intensive fuels, explains the decrease in industrial CO_2 emissions.

The municipal waste stream excludes agricultural and forestry wastes but includes wastewater. Carbon dioxide, generated from aerobic metabolism in waste removal and storage processes, arises from biological material and is considered GHG neutral. Methane (CH_4) released from anaerobic activity at waste treatment plants and landfill sites, forms a substantial portion of carbon emissions to the atmosphere. Given its high global warming potential (GWP) (*i.e.*, the GWP for CH_4 is 21 times that of CO_2), CH_4 plays an important role in the evaluation of possible climate change impacts (WRI, 2005; see Figure 8.1B)[5]†. Globally, CH_4 emissions from waste amount to 66 Mt, or 378 Mt C equivalent (1386 Mt CO_2 equivalent). North American activity accounts for 13.4 Mt of CH_4 (77 Mt C equivalent [282 Mt CO_2 equivalent]) or roughly 20% of global totals.

Substantial sequestration of carbon occurs in landfills[6]. Data on carbon buried there are poor. The Environmental Protection Agency (EPA), using data from Barlaz and Ham (1990) and Barlaz (1994), estimated that 30% of carbon in food waste and up to 80% of carbon in newsprint, leaves, and

[1] This includes direct flows only. Indirect carbon flows (*e.g.*, due to electricity generation) are associated with power generation.

[2] † A dagger symbol indicates that the magnitude and/or range of uncertainty for the given numerical value(s) is not provided in the references cited.

[3] North America, including Mexico, was responsible for about 27% of global CO_2 emissions in 2002.

[4] Decomposition analyses can assess changes in energy consumption due to, for example, increases in industry activity, changes in relative productivity to or from more intense industry subsectors, or changes in material or energy efficiency in processes.

[5] While not carbon-based, N_2O from sewage treatment is included in Figure 8.4, below, to show its relative GHG importance.

[6] IPCC guidelines currently do not address landfill sequestration. Such guidelines will be in the 2006 publication.

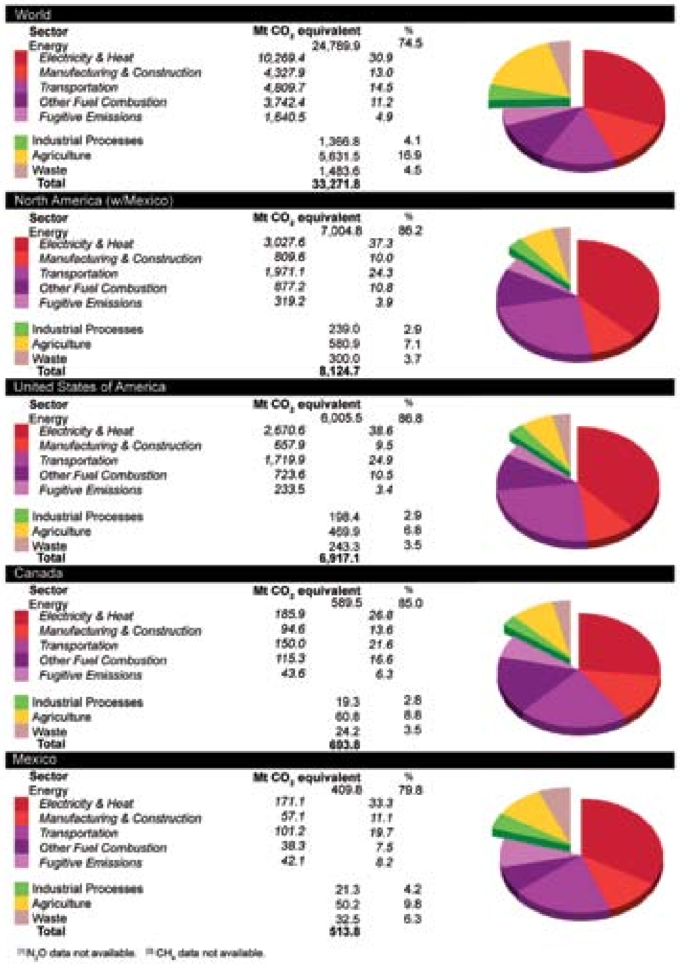


Figure 8.1B Greenhouse gas emissions by sector in 2000, CO_2, CH_4, N_2O, PFCs, HFCs, and SF_6. *Source:* WRI (World Resources Institute)(2005). The magnitude and or range of uncertainty for the given numerical values is not provided in the reference. To convert from $MtCO_2$ equivalent to MtC equivalent, multiply the Mt CO_2 value by 12/44.

branches remain in the landfill†. Plastics show no deterioration. In all, 80% of the carbon entering a landfill site may be sequestered, depending on moisture, aeration, and site conditions. Bogner and Spokas (1993) estimate that "more than 75% of the carbon deposited in landfills remains in sedimentary storage."

8.2 INDUSTRY CARBON CYCLE

Carbon may enter industry as a fuel or as a feedstock where the carbon becomes entrained in the industry's final product. Carbon in the waste stream can be distinguished as atmospheric and non-atmospheric, the former being comprised of process and combustion-related emissions. Process CO_2 emissions, a non-combustive source, are the result of the transformation of the material inputs to the production process. For example, cement production involves the calcination of lime, which chemically alters limestone to form calcium oxide and releases CO_2. Of course, combustion-related CO_2 emissions occur when carbon-based fuels provide thermal energy to drive industrial processes.

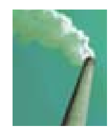
8.2.1 Overview of Carbon Inputs and Outputs

Industry generates about one-third as much emitted carbon as the production of electricity and other fuel supply in North America and only about 55% as much as is generated by the transportation sector.

8.2.1.1 Carbon In

Carbon-based raw materials typically enter industrial sites as biomass (primarily wood), limestone, soda ash, oil products, coal/coke, natural gas, and natural gas liquids. These inputs are converted to dimension lumber and other wood products, paper and paperboard, cement and lime, glass, and a host of chemical products, plastics, and fertilizers.

While the bulk of the input carbon leaves the industrial site as a product, some leaves as process CO_2 and some is converted to combustible fuel. Waste wood (or hog fuel) and black liquor, generated in the production of chemical pulps, are burned to provide process heat or steam for digesting wood chips or for drying paper or wood products, in some cases providing electricity through cogeneration. Chemical processes utilizing natural gas often generate off-gases that, mixed with conventional fuels, provide process heat. Finally, some of the carbon that enters as a feedstock leaves as solid or liquid waste.



In some industries, carbon is used to remove oxygen from other input materials through "reduction." In most of the literature, such carbon is considered an input to the process and is released as "process" CO_2, even though it acts as a fuel (*i.e.*, it unites with oxygen to form CO_2 and releases heat). For example, in metal smelting and refining processes, a carbon-based reductant separates oxygen from the metal atoms. Coke, from the destructive distillation of coal, enters a blast furnace with iron ore to strip off the oxygen associated with the iron. Carbon anodes in electric arc furnaces in steel mills and specialized electrolytic "Hall-Heroult" cells oxidize to CO_2 as they melt recycled steel or reduce alumina to aluminum.

8.2.1.2 Carbon Out

Carbon leaves industry as part of the intended commodity or product, as a waste product or as a gas, usually CO_2.

Process emissions are CO_2 emissions that occur as a result of the process itself—the calcining of limestone releases about 0.5 tons CO_2 per ton of clinker (unground cement) or about 0.8 tons per ton of lime[7,8]. The oxidation of carbon anodes generates about 1.5 tons CO_2 to produce a ton of aluminum. Stripping hydrogen from CH_4 to make ammonia releases about 1.6 tons CO_2 per ton of ammonia.

Biomass fuels are considered carbon neutral because return of the biomass carbon to the atmosphere completes a cycle that began with carbon uptake from the atmosphere by vegetation.

Combustion of carbon-based fuels results in the emission of CO_2. In many cases, the combustion process is not complete and other carbon-based compounds may be released (carbon monoxide, CH_4, volatile organic compounds). These often decompose into CO_2, but their life spans in the atmosphere vary.

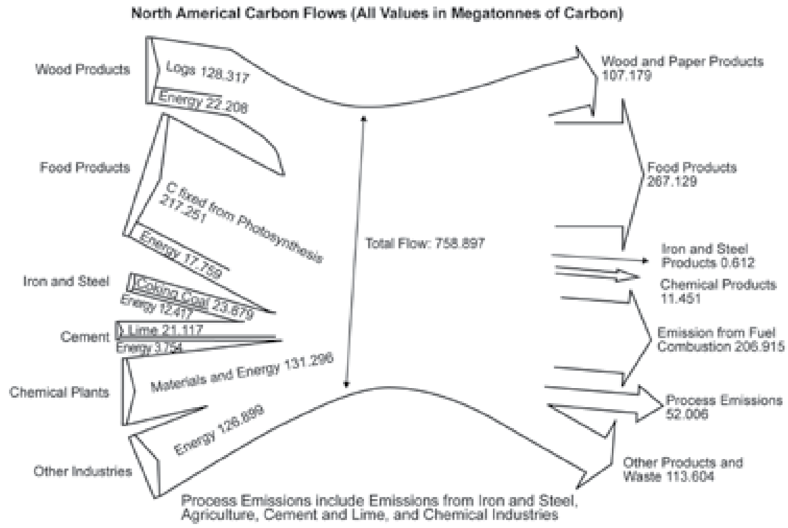


Figure 8.2 Carbon flows for Canada, the United States, and Mexico combined. Values in megatons carbon can be converted to megatons CO_2 equivalents by multiplying by 44/12; the ratio of CO_2 mass to carbon mass. Comparable diagrams for the individual countries are in Appendix C. *Source:* Energy data from Statistics Canada Industrial Consumption of Energy survey, Conversion coefficients, IEA Oil Information (2004), IEA Coal Information (2005), IEA Natural Gas Information (2004). Process emissions from Environment Canada, Canada GHG Inventory (2002), EPA, U.S. Emissions Inventory. Production data from Statistics Canada, CANSIM Table 002-0010, Tables 303-0010, -0014 to -0021, -0024, -0060, Pub. Cat. Nos.: 21-020, 26-002, 45-002, Canadian Pulp and Paper Association on forestry products. Production of forestry products: USDA Database; FO-2471000, -2472010, -2482000, -2483040, -6342000, -6342040, U.S. Timber Production, Trade, Consumption, and Price Statistics 1965-2005. Production of organic products (e.g., food): USDA PS&D Official Statistical Results. Steel: International Iron and Steel Institute, World steel in figures (2003). Minerals production: USGS mineral publications.

8.2.1.3 Carbon Flow

Figure 8.2 illustrates the flows of carbon in and out of industries in North America. Comparable diagrams for individual countries are presented in Appendix C. On the left side of Figure 8.2, all carbon-based material by industry sector is accounted for, whether in fuel or in feedstock. On the right, the exiting arrows portray how much of the carbon leaves as part of the final products from that industry. The carbon in the fossil fuel and feedstock materials leave in the waste stream as emissions from fuel combustion (including biomass), as process emissions, or as other products and waste. Carbon capture and storage potentials are assessed in the industry subsections below.

8.2.2 Sectoral Trends in the Industrial Carbon Cycle

Figure 8.2 shows that energy-intensive industries differ significantly in their carbon cycle dynamics.

8.2.2.1 Pulp and Paper

While pulp and paper products are quite energy-intensive, much of the energy is obtained from biomass. By using hog fuel and black liquor, some types of pulp mills are energy self-sufficient. Biomass fuels are considered carbon neutral because return of the biomass carbon to the atmosphere completes a cycle that began with carbon uptake from the atmosphere by vegetation[9]. Fuel handling difficulties and air quality concerns can arise from the use of biomass as a fuel.

8.2.2.2 Cement, Lime, and Other Nonmetallic Minerals

Cement and lime production require the calcination of limestone, which releases CO_2; about 0.78 tons of CO_2 per ton of lime calcined.

$CaCO_3$	$\rightarrow$	CaO	+	CO_2
calcium carbonate		calcium oxide		carbon dioxide

[7] In these industries, more CO_2 is generated from processing limestone than from the fossils fuels combusted.
[8] The calcination of limestone also takes place in steel, pulp and paper, glass, and sugar industries.

[9] This is also reflected in the United Nations Framework Convention on Climate Change (UNFCCC) IPCC guidelines to estimate CO_2 emissions.

Outside of the combustion of fossil fuels, lime calcining is the single largest human-caused source of CO_2 emissions. Annual growth in cement production is forecast at 2.4% in the United States for at least the next decade. This industry could potentially utilize sequestration technologies to capture and store CO_2 generated.

The production of soda ash (sodium carbonate) from sodium bicarbonate in the Solvay process releases CO_2, as in glass production, in its utilization. Soda ash is used to produce pulp and paper, detergents, and soft water.

$$\underset{\text{sodium bicarbonate}}{2NaHCO_3} \rightarrow \underset{\text{sodium carbonate}}{Na_2CO_3} + \underset{\text{carbon dioxide}}{CO_2} + \underset{\text{water}}{H_2O}$$

8.2.2.3 Nonferrous Metal Smelting and Iron and Steel Smelting

Often metal smelting requires the reduction of metal oxides to obtain pure metal through use of a "reductant", usually coke. Because reduction processes generate relatively pure streams of CO_2, the potential for capture and storage is good.

In electric arc furnaces, carbon anodes decompose to CO_2 as they melt the scrap iron and steel feed in "mini-mills". In Hall-Heroult cells, a carbon anode oxidizes when an electric current forces oxygen from aluminum oxide (alumina) in the production of aluminum[10].

8.2.2.4 Metal and Nonmetal Mining

Mining involves the extraction of ore and its transformation into a concentrated form. This involves transportation from mine site, milling, and separating mineral-bearing material from the ore. Some transportation depends on truck activity, but the grinding process is driven by electric motors (*i.e.*, indirect release of CO_2). Some processes, like the sintering or agglomeration of iron ore and the liquid extraction of potash, use a considerable amount of fossil fuels directly.

8.2.2.5 Chemical Products

This diverse group of industries includes energy-intensive electrolytic processes as well as the consumption of large quantities of natural gas as a feedstock to produce commodities like ammonia, methanol, and hydrogen. Ethylene and propylene monomers from natural gas liquids are used in plastics production. Some chemical processes generate fairly pure streams of CO_2 suitable for capture and storage.

[10] Ceramic anodes may soon be available to aluminum producers and significantly reduce process CO_2 emissions.

8.2.2.6 Forest Products

This industry uses biomass waste to dry commercial products such as lumber, plywood, and other products. The industry also includes silviculture, the practice of replanting and managing forests.

8.2.2.7 Other Manufacturing

Most of the remaining industries, while economically important, individually play a relatively minor role in the carbon cycle because they are not energy intensive and use little biomass[11]. In aggregate, however, these various industries contribute significantly to total industrial CO_2 emissions. Industries in this group include the automotive industry, electronic products, leather and allied products, fabricated metals, furniture and related products, and plastics and rubber products.

8.2.3 Changing Role of Industry in the Carbon Cycle

Energy consumption per unit GDP has declined in Canada and the United States by more than 30% since the mid-1970s. In manufacturing, the decline was even greater—more than 50% in the United States since 1974.

The National Energy Modeling System operated by the United States' Energy Information Administration applies growth forecasts from` the Global Insight macroeconomic model. While the United States economy is forecast to grow at an aver age rate of 3.1% per year to 2025, industrial growth is forecast at 2.3% per year—an amalgam of manufactur-

The shift from coal and refined petroleum products to natural gas and electricity contributed to a decline in total industrial CO_2 emissions since 1997 in both Canada and the United States.

[11] Except, of course, the food, beverage, and some textile industries.

ing growth of 2.6% per year and non-manufacturing of 1.5% per year. Manufacturing is further disaggregated into energy-intensive industries, growing at 1.5% per year, and non-energy intensive industries at 2.9% per year. The slower growth in the energy-intensive industries is reflected in the expected decline in industrial energy intensity of 1.6% per year over the EIA (2005) forecast.

Table 8.1 Energy reductions in recycling.

Recycled material	Energy saved	Recycled material	Energy saved
Aluminum	95%	Glass	31%
Tissue paper	54%	Newsprint	45%
Printing/writing paper	35%	Corrugated cardboard	26%
Plastics	57%–75%	Steel	61%

Source: Hershkowitz (1997)

The International Energy Agency reviewed energy consumption and emissions during the last 30 years to identify and project underlying trends in carbon intensity[12]. The review's decomposition analysis (Figure 8.3) attributes changes in industrial energy demand to changes in total industrial output (activity), shifts in the relative shares of industrial sectors (structure), and increases in energy efficiency (intensity).

Changes in carbon emissions result from these three factors, but also from changes in fuel shares—substitution away from or toward more carbon-intensive fuels. The shift from coal and refined petroleum products to natural gas and electricity[13] contributed to a decline in total industrial CO_2 emissions since 1997 in both Canada and the United States. The continuation of this trend is uncertain given the rise in natural gas prices relative to coal in recent years.

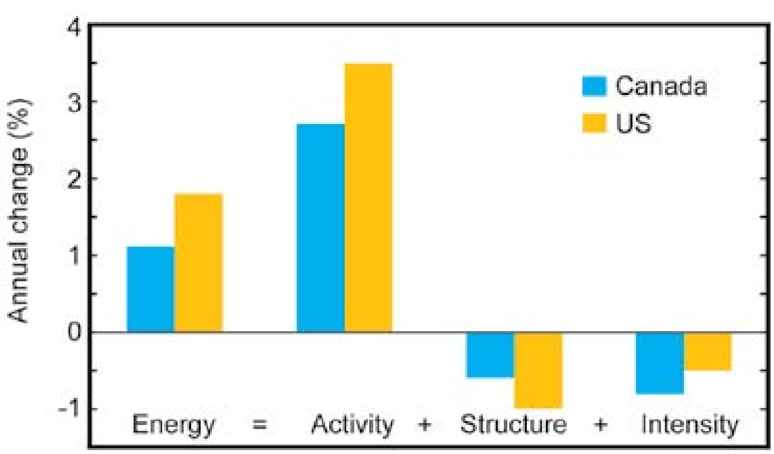


Figure 8.3 Decomposition of energy use, manufacturing section, 1990-1998. *Source:* IEA (2004).

8.2.4 Actions and Policies for Carbon Management in Industry

Industry managers can reduce carbon flows through industry by altering the material or energy intensity and character of production (IPCC, 2001). Greater materials efficiency typically reduces energy demands in processing because of reduced materials handling. For example, recycling materials often reduces energy consumption per unit of output by 26 to 95% (Table 8.1). Further work on materials substitution also holds promise for reduced energy consumption and emissions reduction[14].

The prospects for greater energy efficiency are equally substantial. Martin *et al.* (2001) characterized more than 50 key emerging energy efficient technologies, including efficient Hall-Heroult cell retrofits, black liquor gasification in pulp production, and shape casting in steel industries. Worrell *et al.* (2004) covers many of the same technologies and notes that significant potential exists in utilizing efficient motor systems and advanced cogeneration technologies.

At the same time, energy is a valuable production input that, along with capital, can substitute for labor as a means of increasing productivity. Thus overall productivity gains in industry can be both energy-saving and energy-augmenting, and the net impact depends on the nature of technological innovation and the expected long-run cost of energy relative to other inputs. This suggests that, if policies to manage carbon emissions from industry were to be effective, they would need to provide a significant signal to technology innovators and adopters to reflect the negative value that society places on carbon emissions. This in turn suggests the application of regulations or financial instruments, examples being energy efficiency regulations, carbon management regulations, and fees on carbon emissions.

8.3 WASTE MANAGEMENT CARBON CYCLE

The carbon cycle associated with human wastes includes industrial, commercial,

[12] Most of the information in this section is obtained from IEA (2004).

[13] As noted earlier, emissions associated with electricity are allocated to the electricity supply sector. Thus a shift to electricity reduces the GHG intensity of the industry using it. If electricity is made in coal-fired plants, however, total CO_2 emissions may actually increase.

[14] For example, substitute petrochemical feedstocks by biomass or concrete by wood in home foundations.

construction, demolition, and residential waste. Municipal solid waste contains significant amounts of carbon. Paper, plastics, yard trimmings, food scraps, wood, rubber, and textiles made up more than 80% of the 236 Mt of municipal solid waste generated in the United States in 2003 (EPA, 2005) and the 25 Mt generated in Canada (Statistics Canada, 2004), as shown in Table 8.2. In Mexico, as much as 20% of wastes are not systematically collected; no disaggregated data are available (EPA, 2005).

Table 8.2 Waste materials flows by region in North America, 2003.

	United States	Canada	Mexico
Total waste (Mt per year)	236.0	24.8	29.2
Recycled	72.0	6.6	–
Carbon-based waste	197.1	19.6	–
Carbon-based waste recycled	47.3[a]	4.3	–
Carbon sequestered (CO_2 equivalents)	10.1	–	–
Methane (kt per year)			
Generated	12,486	1,452	–
Captured, oxidized	6,239	336	–
Emitted	6,247	1,117	–
Emitted (CO_2 equivalents)	131,187	23,453	–

[a] Calculated estimate

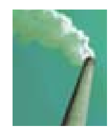
Source: EPA (2003b, 2005), Statistics Canada (2004), Mohareb (2004) for Canada methane data, California Evironmental Protection Agency (2003) for Mexico data point.

A portion of municipal solid waste is recycled: 31% in the United States (EPA, 2003b)† and 27% in Canada (Statistics Canada, 2004).† Up to 14% of the remaining waste is incinerated in the United States, slightly less in Canada. Incineration can reduce the waste stream by up to 80%, but this ensures that more of the carbon reaches the atmosphere as opposed to being sequestered (or subsequently released as CH_4) in a landfill. Incineration, however, can be used to cogenerate electricity and useful heat, which may reduce carbon emissions from stand-alone facilities.

Once in a landfill, carbon in wastes may be acted upon biologically, releasing roughly equal amounts of CO_2 and CH_4 by volume[15] depending on ambient conditions, as well as a trace amount of carbon monoxide and volatile organic compounds. While no direct data on the quantity of CO_2 released from landfills exists, one can estimate the CO_2 released by using this ratio; the estimated amount of CO_2 released from landfills in Canada and the United States (no data from Mexico) would be approximately 38 Mt[16], a relatively small amount compared to the total of other subsectors in this chapter. Also, recall that these emissions are from biomass and, in the context of IPCC assessment guidelines, are considered GHG-neutral.

Depending on the degree to which aerobic or anaerobic metabolism takes place, a considerable amount of carbon remains unaltered and more or less permanently stored in the landfill (75%-80%; see Barlaz and Ham, 1990; Barlaz, 1994; and Bogner and Spokas, 1993). Because data on the proportions of carboniferous material entering landfills can be estimated, approximate carbon contents of these materials can be determined and the degree to which these materials can decompose, it would be possible to estimate the amount of carbon sequestered in a landfill site (see EPIC, 2002; Mohareb *et al.*, 2004; EPA, 2003b; EPA, 2005). While EPA (2005) provides an estimate of carbon sequestered in US landfills (see Table 8.2), no data are available for other regions.

Municipal solid waste contains significant amounts of carbon.

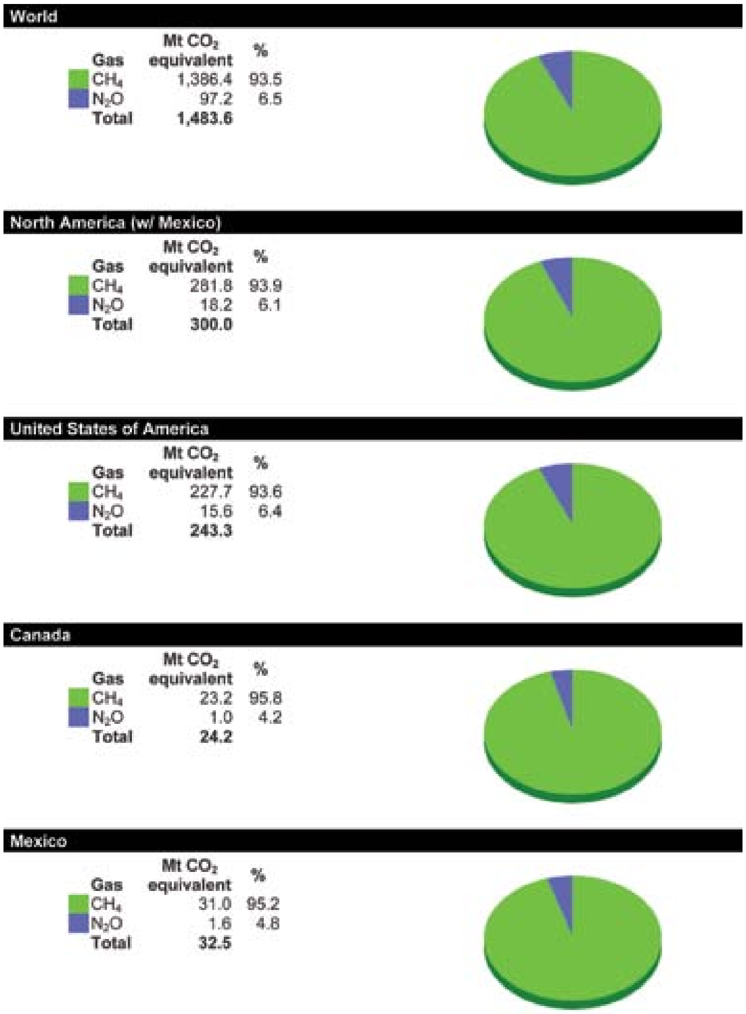


Anaerobic digestion generates CH_4 gases that can be captured and used in cogenerators. Many of the 1800 municipal solid waste sites in 2003 in the United States captured and combusted landfill-generated CH_4; about half of all the CH_4 produced was combusted or oxidized in some way (EPA, 2005). In Canada, about 23% of the CH_4 emissions were captured and utilized to make energy in 2002 (Mohareb *et al.*, 2004). The resultant CO_2 released from such combustion is considered biological in origin. Thus only CH_4 emissions, at 21 times the CO_2 warming potential, are included as part of GHG inventories. Their combustion greatly alleviates the net contribution to GHG emissions and, if used in cogeneration, may offset the combustion of fossil fuels elsewhere. Figure 8.4 provides an estimate of CH_4 (and nitrous oxide [N_2O] as the other GHG for comparison) released from landfills and waste treatment facilities.

8.4 COSTS RELATED TO CONTROLLING HUMAN-CAUSED IMPACTS ON THE CARBON CYCLE

Defining costs associated with reducing human-caused (anthropogenic) impacts on the carbon cycle is a highly contentious issue. Different approaches to cost assessments (top-down, bottom-up, applicable discount rates, social

[15] Based on gas volumes, this means that roughly equivalent amounts of carbon are released as CO_2 as CH_4.
[16] 14 Mt of CH_4 (see Table 8.3) are equivalent, volume wise at standard temperature and pressure, to 38 Mt of CO_2. This derived estimate is highly uncertain and not of the same caliber as other emissions data provided here.



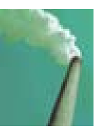


Figure 8.4 Greenhouse gas emissions by gas from waste in 2000. *Source*: WRI (World Resources Institute) (2005). The magnitude and/or range of uncertainty for the given numerical values is not provided in the reference. To convert from Mt CO_2 equivalent to Mt C equivalent, multiply the Mt CO_2 value by 12/44.

costing, cost effectiveness, no regrets), different understandings of what costs include (risk, welfare, intangibles, capital investment cycles), different values associated with energy demand in different countries (accessibility, availability, infrastructure, resource type and size), actions and technologies included in the analysis, and the perspective on technology development all have an impact on evaluating costs. Should analysts consider only historical responses to energy prices, production and demand elasticities, or income changes? Does one consider only technology options and their strict financial costs or see historic technology investments as sunk costs? Should one include producers' or consumers' welfare? Are there local, national, international issues?

Cost variation within industries is significant. Costs associated with various methods to reduce emissions also vary. Reduction methods can be classified as:

- reducing or altering process/fugitive emissions,
- energy efficiency, including combined heat and power,
- process changes,
- fuel substitution,
- carbon capture and storage.

One can attribute potential reductions over a set time under a range of costs. We suggest the cost-range categories ("A" through "D") shown in Table 8.3. The table contains estimates of the percentage reduction by industry under these cost categories. Costs are not drawn from a single source but are the authors' estimates based on a long history of costs reported in various documents[17]. Some studies focus on technical potential and do not provide the cost of achieving the reductions. As such, achievable reductions are likely overestimated. Others describe optimization models that provide normative costs and likely overestimate potentials and underestimate costs. Still others use top-down approaches where historic data sets are used to determine relationships between emissions and factors of production; costs are often high and emissions reductions underestimated.

When looking at cost numbers like this, one should remember that, for each \$10 cost increment per t CO_2 (or about \$37 per t C), gasoline prices would increase about 2.4¢/L (9¢/U.S. gallon). Diesel fuel cost would be nearly 2.7¢/L (10¢/U.S. gallon). Costs per Gigajoule (GJ)[18] vary by fuel: coal rises about 90¢/GJ, depending on type, heavy fuel oil (HFO) by 73¢, and natural gas by 50¢. At 35% efficiency, coal-fired electricity generation would be about 0.8¢/kWh higher, about 0.65¢/kWh for HFO, and about 0.45¢/kWh for natural gas.

Of course, as the cost of carbon increases, one moves up the carbon supply curve for industrial sectors. However, reductions become marginal or insignificant and so are not included in Table 8.3. If a cell in Table 8.3 shows two cost categories (*e.g.*, A/B) and two reduction levels (%Q_{red} is 15/20), the value associated with the second portrays the additional reduction at that increased expenditure level. Thus spending up to \$50/t CO_2 to improving efficiency in metal smelting implies a potential reduction of 35% (see Table 8.3). Reductions in each category are not additive for an industry type because categories are not independent.

[17] Studies vary widely in how they define system boundaries, baseline, and time periods, which sectors or subsectors are included, economic assumptions, and many other factors. See `*Some Explanatory Notes*` in Section 8.4.1 for a list.
[18] A Gigajoule (GJ), or one billion joules, is slightly smaller than 1 MMBtu (1 GJ = 0.948 MMBtu).

Table 8.3 Approximate costs and reductions potential.

Sector	Reduction of fugitives		Energy efficiency		Process change		Fuel substitution		Carbon Capture and Storage	
	Cost category	$\%Q_{red}$	Cost category[a]	$\%Q_{red}$[a]	Cost category	$\%Q_{red}$	Cost category	$\%Q_{red}$	Cost category[a]	$\%Q_{red}$[a]
All industry	B	3	A/B	12/8	B	20	A	10	C	30
P&P	B	5	A/B	10/5	B	40	A	40	D	?
Nonmetal min			A	10	A	40	A	40	C	80
Metal smelt			A/B	15/20	B	10	A	15	C	40
Mining			A	5						
Chemicals	B	10	A/B	10/5	B	25	A	5	C/D	40/20
Forest products	B	5	A	5						
Other man			A	15	A	20	A	5	D	?
Waste	A	90							D	30

[a] If two letters appear, two percent quantities reduced are shown. Each shows the quantity reduced at that cost. That is, if all lesser and higher costs were made, emissions reduction would be the sum of the two values.

Note: The reductions across categories are NOT additive. For example, if "Carbon Capture and Storage" is employed, then fuel switching would have little bearing on the emissions reduction possible. Also, it is difficult to isolate process switching and efficiency improvements.

The "Cost Categories" are as follows:

CO_2-Based: A: \$0–\$25/t CO_2; B: \$25–\$50/t CO_2; C: \$50–\$100/t CO_2; D: >\$100/t CO_2

Carbon-Based: A: \$0–\$92/t C; B: \$92–\$180/t C; C: \$180–\$367/t C; D: >\$367/t C

Because not all reduction methods are applicable to all industries, as one aggregates to an "all industry" level (top line, Table 8.3), the total overall emissions reduction level may be less than any of the individual industries sited.

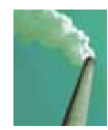
8.4.1 Some Explanatory Notes

Data come from a variety of sources and do not delineate costs as per the categories described here. Data sources can be notionally categorized into the following groups (with some references listed twice)[19]:

- *General overviews*: Grubb *et al.* (1993), Weyant *et al.* (1999)[20], Grubb *et al.* (2002), Löschel (2002).
- *Top-down analyses*: McKitrick (1996), Herzog (1999), Sands (2002), McFarland *et al.* (2004), Schäfer and Jacoby (2005), Matysek *et al.* (2006).
- *Bottom up analyses*: Martin *et al.* (2001), Humphreys and Mahasenan (2002), Worrell *et al.* (2004), Kim and Worrell (2002), Morris *et al.* (2002), Jaccard *et al.* (2003a), DOE (2006), IEA (2006).
- *Hybrid model analyses*: Böhringer (1998), Jacobsen (1998), Edmonds *et al.* (2000), Koopmans and te Velde (2001), Jaccard (2002), Frei *et al.* (2003), Jaccard *et al.* (2003a), Jaccard *et al.* (2003b), Edenhofer *et al.* (2006).
- *Others*: Newell *et al.* (1999), Sutherland (2000), Jaffe *et al.* (2002).

8.4.1.1 Process and Fugitives

Process and fugitive reductions are only available in certain industries. For example, because wood-products industries burn biomass, fugitives are higher than in other industries and reduction potentials exist.



In the waste sector, the reductions potentials are very large; we have simply estimated possible reductions if we were to trap and burn all landfill CH_4. The costs for this are quite low. EPA (2003a) estimates of between 40% and 60% of CH_4 available for capture may generate net economic benefits.

8.4.1.2 Energy Efficiency

The potential for emissions reductions from efficiency improvements is strongly linked with both process change and fuel switching. For example, moving to Cermet-based processes in electric arc furnaces in steel and aluminum smelting industries can significantly improve efficiencies and lower both combustion and process GHG emissions.

A "bottom up" technical analyses tends to show higher potentials and lower costs than when one uses a hybrid or a "top-down" approach to assess reduction potentials due to efficiency improvements; Table 8.3 portrays the outcome of the more conservative hybrid (mix of top-down and bottom-up) approach and provides what some may consider conservative estimates of reduction potential (see particularly Martin *et al.*, 2001; Jaccard *et al.*, 2002; Jaccard *et al.*, 2003a; Jaccard *et al.*, 2003b; and Worrell *et al.*, 2004).

[19] Two authors are currently involved with IPCC's upcoming fourth assessment report where estimated costs of reduction are provided. Preliminary reviews of the cost data presented there do not differ substantially from those in table 8.3.

[20] John Weyant of Stanford University is currently editing another analysis similar to this listed publication to be released in the near future.

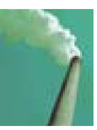
8.4.1.3 Process Change

Reductions from process change requires not only an understanding of the industry and its potential for change but also an understanding of the market demand for industry products that may change over time. In pulp production, for example, one could move from higher quality kraft pulp to mechanical pulp and increase production ratios (the kraft process only converts one-half the input wood into pulp), but will market acceptability for the end product be unaffected? Numerous substitution possibilities exist in the rather diverse *Other Manufacturing* industries (carpet recycling, alternative uses for plastics, *etc*.).

8.4.1.4 Fuel Substitution

It is difficult to isolate fuel substitution and efficiency improvement because fuels display inherent qualities that affect efficiency. Fuel substitution can reduce carbon flow but efficiency may become worse. In wood products industries, shifts to biomass reduces emissions but increases energy use. In terms of higher heating values, shifts from coal or oil to natural gas may worsen efficiencies while reducing emissions[21].

8.4.1.5 Carbon Capture and Storage (CC&S)



In one sense, all industries and landfills could reduce emissions through CC&S but the range of appropriate technologies has not been fully defined and/or the costs are very high. For example, one could combust fuels in a pure oxygen environment such that the exhaust steam is CO_2-rich and suitable for capture and storage. Even so, some industries, like cement production, are reasonable candidates for capture, but cost of transport of the CO_2 to storage may prohibit implementation (see particularly Herzog, 1999; DOE, 2006).

8.5 RESEARCH AND DEVELOPMENT NEEDS

If we assume that carbon management will play a significant role in the future and that fossil fuels are likely to remain an economical energy supply for industries, research and development (R&D) will focus on the control of carbon emissions related to the extraction of this energy. Typical combustion technologies extract and transform fossil fuels' chemical energy relatively efficiently but, outside of further improvements in efficiency, they generally do little to manage the emissions generated. More recently, advanced technologies remove particularly onerous airborne emissions, such as compounds of sulphur and nitrogen, particulates, volatile organic compounds, and other criteria air contaminants. However, emissions of CO_2 remain relatively unaltered. In the light of changing views on the impacts of CO_2 released to the atmosphere, R&D will likely focus on the extraction of the energy while preventing CO_2 release. Fossil fuels might well remain economically competitive and socially desirable as a source of energy in some circumstances, even when one includes the extra cost of capturing the CO_2 and preventing its atmospheric release when converting these fuels into non-carbon secondary forms of energy like electricity, hydrogen, or heat.

Some carbon capture and storage processes currently exist; indeed, oil companies have long "sequestered" CO_2 to enhance oil recovery from underground wells simply by injecting it into the oil reservoir. Many newer processes to accomplish CO_2 capture are being investigated, primarily in two categories: pre-combustion and post-combustion processes. Pre-combustion alternatives include gasification processes where, for example, coal's energy is entrapped in hydrogen and the CO_2 stream is subsequently sequestered. Post-combustion alternatives include carbon combustion in pure oxygen atmospheres and then trapping the resultant CO_2 for sequestration, and flue stack devices designed to extract the CO_2 from the flue gases for delivery to sequestration systems. Research has also been conducted on devices that can extract CO_2 directly from the atmosphere (Keith *et al*., 2003).

[21] As the ratio of hydrogen to carbon rises in a fossil fuel, more of the total heat released upon combustion is caught up in the latent heat of vaporization of water and is typically lost to process. This loss is equivalent to the difference between a fuel's higher heating value and its lower heating value.

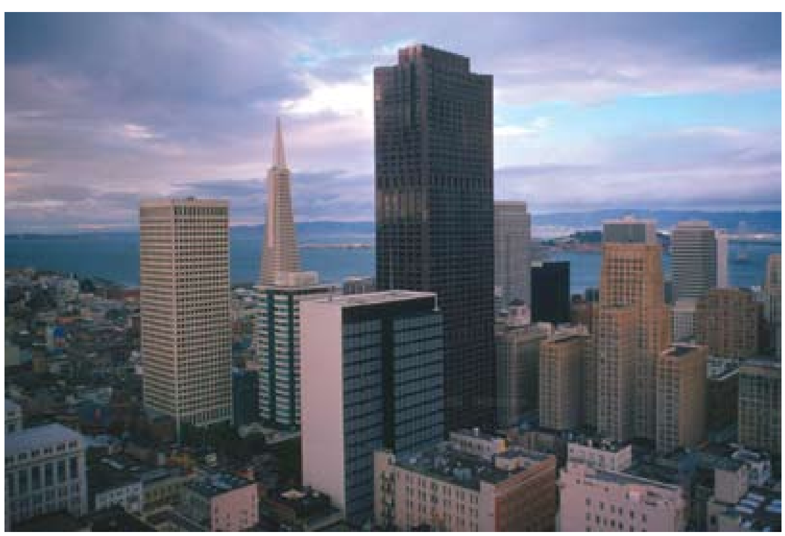
Buildings

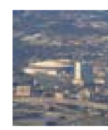
Lead Author: James E. McMahon, LBNL

Contributing Authors: Michael A. McNeil, LBNL, Itha Sánchez Ramos, Instituto de Investigaciones Eléctricas, Mexico

KEY FINDINGS

- The buildings sector of North America was responsible for annual carbon dioxide emissions of 671 million tons of carbon in 2003, which is 37% of total North American carbon dioxide emissions and 10% of global emissions. United States buildings alone are responsible for more carbon dioxide emissions than total carbon dioxide emissions of any other country in the world, except China.
- Carbon dioxide emissions from energy use in buildings in the United States and Canada increased by 30% from 1990 to 2003, an annual growth rate of 2.1% per year.
- Carbon dioxide emissions from buildings have grown with energy consumption, which in turn is increasing with population and income. Rising incomes have led to larger residential buildings and increased household appliance ownership.
- These trends are likely to continue in the future, with increased energy efficiency of building materials and equipment and slowing population growth, especially in Mexico, only partially offsetting the general growth in population and income.
- Options for reducing the carbon dioxide emissions of new and existing buildings include increasing the efficiency of equipment and implementing insulation and passive design measures to provide thermal comfort and lighting with reduced energy. Current best practices can reduce emissions from buildings by at least 60% for offices and 70% for homes. Technology options could be supported by a portfolio of policy options that take advantage of cooperative activities, avoid unduly burdening certain sectors, and are cost effective.
- Because reducing carbon dioxide emissions from buildings is currently secondary to reducing building costs, continued improvement of energy efficiency in buildings and reduced carbon dioxide emissions from the building sector will require a better understanding of the total societal cost of carbon dioxide emissions as an externality of building costs, including the costs of mitigation compared to the costs of continued emissions.

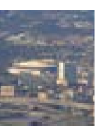




9.1 BACKGROUND

In 2003, buildings were responsible for 615 million metric tons of carbon (Mt C)[1] emitted in the United States (DOE/EIA, 2005), 40 Mt C in Canada (Natural Resources Canada, 2005a), and 17 Mt C in Mexico (SENER México, 2005), for a total of 671 Mt C in North America[2 †]. According to the International Energy Agency, total energy-related emissions in North America in this year were 1815 Mt C (IEA, 2005). Therefore, buildings were responsible for 37% of energy-related emissions in North America. North American buildings accounted for 10% of global energy emissions, which totaled 6814 Mt C. United States' buildings alone are responsible for more carbon dioxide (CO_2) emissions than total CO_2 emissions of any other country in the world, except China (Kinzey *et al*., 2002). Significant carbon emissions are due to energy consumption during the operation of the buildings; other emissions, not well quantified, may occur from water use in and around the buildings and from land-use impacts related to buildings. Buildings are responsible for 72% of United States electricity consumption and 54% of natural gas consumption (DOE/EERE, 2005)[3]. The discussions in this chapter include an accounting of CO_2 emissions from electricity consumed in the buildings sector; however, this represents a potential double counting of the CO_2 emissions from fossil fuels that are used to generate that electricity (Chapter 6, this report). This chapter provides a description of how energy, including electrical energy, is used within the buildings sector. Following the discussion of such end uses of energy, this chapter then describes the opportunities and potential for reducing energy consumption within the sector.

North American buildings accounted for 10% of global energy emissions, 2003.



Many options are available for reducing the carbon impacts of new and existing buildings, including increasing equipment efficiency and implementing alternative design, construction, and operational measures to provide thermal comfort and lighting with reduced energy. Current best practices can reduce carbon emissions for buildings by at least 60% for offices[4] and up to 70% for homes[5]. Residential and commercial buildings in the United States and Canada occupy 27 billion m^2 (2.7 million hectares)[†] of floor space, providing a large area available for siting non-carbon-emitting on-site energy supplies (*e.g.*, photovoltaic panels on roofs)[6]. With the most cutting-edge technology, at the least, emissions can be dramatically reduced, and at best, buildings can produce electricity without carbon emissions by means of on-site renewable electricity generation.

Current best practices can reduce carbon emissions for buildings by at least 60% for offices and up to 70% for homes.

9.2 CARBON FLUXES

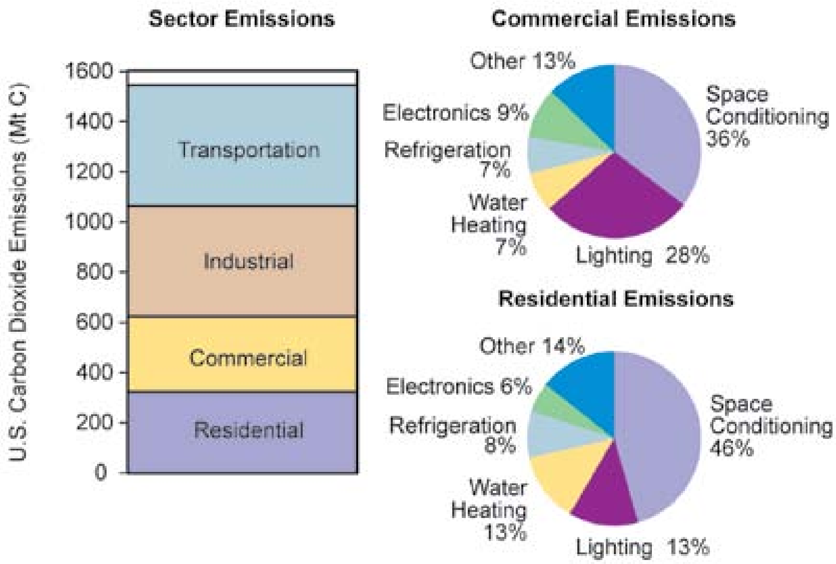
Carbon fluxes from energy emissions in buildings are well understood, since primary energy inputs from the source of production are tracked, their emissions rates are known, and the total end user consumption data are gathered and reported by energy utilities, typically monthly. The quantity of energy consumed by each particular end use is slightly less well known because attribution requires detailed data on use patterns in a wide variety of contexts. The governments of North America have invested in detailed energy consumption surveys, which allow researchers to identify opportunities for reducing energy use.

The largest contribution to carbon emissions from buildings is through the operation of energy-using equipment. The energy consumed in the average home accounts for 2.9 metric tons[7] of carbon per year in the United States, 1.7 metric tons[8] per year in Canada, and 0.6 metric tons[9] in Mexico (DOE/EIA, 2005; Natural Resources Canada, 2005b; SENER México, 2004)[†]. Energy consumption in a 500 m^2 commercial, government, or public-use building in the United States produces 1.9 metric tons of carbon (DOE/EIA, 2005)[10 †]. Energy consumption includes electricity as

[1] Carbon dioxide emissions only.
[2†] A dagger symbol indicates that the magnitude and/or range of uncertainty for the given numerical value(s) is not provided in the references cited.
[3] See Tables 1.1.6 and 1.1.7 in DOE/EERE (2005).
[4] Leadership in Energy and Environment Design (LEED) Gold Certification (USGBC, 2005).
[5] U.S. DOE Building America Program (DOE/EERE, 2006).

[6] A recent study estimates a potential of 711 GW generation capacity from rooftop installation of photovoltaic systems (Chaudhari *et al*., 2004).
[7] United States' residential sector emissions of 334 Mt C divided by 114 million households in 2004; the numerical value given for "tons of carbon" is for carbon dioxide emissions only.
[8] Canada residential sector emissions of 20.6 Mt C divided by 12.2 million households in 2003.
[9] Mexico residential sector emissions of 13.2 Mt C divided by 23.8 million households in 2004.
[10] United States' commercial sector emissions per m^2 in 2003 times 500 m^2.

well as the direct combustion of fossil fuels (natural gas, bottled gas, and petroleum distillates) and the burning of wood. Because most electricity in North America is produced from fossil fuels, each kilowatt-hour consumed in a building contributed about 180 g of carbon to the atmosphere in 2003 (DOE/EIA, 2005)[11]. The equivalent amount of energy from natural gas or other fuels contributed about 52 g of carbon (DOE/EIA, 2005)[12]. Renewable energy accounted for 9% of electricity production in 2003, down from 12% in 1990. Renewable site energy use in buildings also decreased in that time, from 4% to 2%, mostly due to decreasing use of wood as a household fuel (DOE/EERE, 2005)[13].



Source: DOE EERE Buildings Energy Data Book 2005

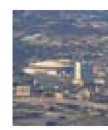
Figure 9.1 United States' carbon emissions by sector and (for commercial and residential buildings) by end use.

Buildings-sector CO_2 emissions and the relative contribution of each end use are shown in Figure 9.1. In the United States, five end uses account for 87% of primary energy consumption in buildings: space conditioning (including space heating, cooling, and ventilation), 40.9%; lighting, 19.8%; water heating, 10.5%; refrigeration, 7.9%; and electronics (including televisions, computers, and office equipment), 7.7% (DOE/EERE, 2005)[14 †]. Space heating and cooling are the largest single uses for residences, commercial, and public-sector buildings, accounting for 46% and 35% of primary energy, respectively, in the United States (DOE/EERE, 2005)[15]. Water heating is the second-highest energy consumer in the United States and Canada in terms of site energy, while lighting is the second-highest source of CO_2 emissions, due to the higher emissions per unit of electricity compared to natural gas.

Heating and cooling loads are highly climate dependent; colder regions use heating during much of the year (primarily with natural gas), while warm regions seldom use heating. The majority of United States households own an air conditioner; and although air-conditioner ownership has been historically low in Mexico[16], sales of this equipment are now growing significantly, 14% per year over the past 10 years[17]. Space-conditioning energy end use depends significantly on building construction (*e.g.*, insulation, air infiltration) and operation (thermostat settings). Water heating is a major consumer of energy in the United States and Canada, where storage-tank systems are common.

Aside from heating and cooling, lighting, and water heating, energy is consumed by a variety of appliances, mostly electrical. Most homes in the United States and Canada own all of the major appliances, including refrigerators, freezers, clothes washers, clothes dryers, dishwashers, and at least one color television. The remainder of household energy consumption comes from small appliances (blenders and microwaves, for example) and increasingly from electronic devices such as entertainment equipment and personal computers. In Mexico, 96.6% of households used electricity in 2005, and recent years have shown a marked growth in appliance ownership: ownership rates in 2000 were 85.9% for televisions, 68.5% for refrigerators, 52% for washing machines, and only 9.3% for computers. By the end of 2005 ownership rates had grown to 91% for televisions, 79% for refrigerators, 62.7% for washing machines, and 19.6% for computers (INEGI, 2005).

Many end uses—such as water heating and space heating, cooling, and ventilation—occur in most commercial sector buildings. Factors such as climate and building construction influence the carbon emissions by these buildings. In addition, commercial buildings contain specialized equipment, such as large-scale refrigeration units in supermarkets, cooking equipment in food preparation businesses, and computers, printers, and copiers in office buildings. Office equipment is the largest component of electricity use



11 United States' emissions from electricity divided by delivered energy.
12 United States'emissions from natural gas and other fuels divided by delivered energy.
13 See Table 1.1.2 and Summary Table 2 in DOE/EERE (2005).
14 Does not include the adjustment EIA uses to relieve differences between data sources.
15 Table 1.2.3 and Table 1.3.3 in DOE/EERE (2005); available at http://buildingsdatabook.eere.energy.gov (2003 data).
16 Air conditioners have typically been used only in the northern and coastal areas of Mexico.
17 Air conditioner sales 1995–2004 from Asociacion Nacional de Fabricantes de Aparatos Domesticos, A.C. (ANFAD).

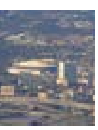
aside from cooling and lighting. Due to heat from internal loads, many commercial buildings use air-conditioning year round in most climates in North America.

Table 9.1 Carbon dioxide emissions from energy consumed in buildings.

2003 Carbon Dioxide Emissions (Mt C)				
	Electricity	Natural Gas	Other Fuels	All Fuels
United States	**445.8**	**122.1**	**46.5**	**614.5**
Residential	229.2	75.6	29.3	334.1
Commercial	216.6	46.5	17.2	280.4
Canada	**17.7**	**15.8**	**6.1**	**39.5**
Residential	9.4	8.7	2.5	20.6
Commercial	8.2	7.1	3.5	18.9
Mexico	**10.7**	**0.5**	**5.6**	**16.9**
Residential	7.3	0.4	5.5	13.2
Commercial [a]	3.5	0.1	0.1	3.7

[a] Mexican commercial building emissions include electricity statistics provided by the National Energy Balance (SENER, 2004). Recent investigations suggest that these may be significantly underestimated, since the methodology used categorizes most large commercial and public sector buildings in the category "medium industry" (Odón de Buen Rodríguez, President, Energía Technología y Educación SC, Puente de Xoco, Mexico, personal communication to James McMahon, Lawrence Berkeley National Laboratory, Berkeley, California, November 23, 2006).

Residential and commercial buildings in the United States are responsible for 37% of CO_2 emissions from energy nationally and 34% of emissions from energy in North America as a whole. Total emissions from buildings in the United States are ten times as high as in the other two countries combined, due to a large population compared to Canada, and high *per capita* consumption compared to Mexico. On a *per capita* basis, building energy consumption in the United States (65 Gigajoules [GJ] per person per year) is comparable with that of Canada (75 GJ per person per year).[†] This is about seven to eight times higher than in Mexico, where 9 GJ is consumed per person per year[18 †].



In general, contributions from the residential sector are roughly equal to that of the commercial sector, except in Mexico, where the commercial sector contributes less. Electricity contributes more emissions than all other fuels combined in the United States and Mexico (2.6 and 1.8 times as much, respectively). In Canada, natural gas is on par with electricity (0.85 times as many emissions) due to high heating loads resulting from the cold climate. Fuel oil represents most of Canada's "other fuels" for the commercial sector. Firewood (*leña*) remains an important fuel for many Mexican households for heating, water heating, and cooking. Table 9.1 summarizes CO_2 emissions by country, sector, and fuel type.

Emissions from energy use in buildings in the United States and Canada increased 30% from 1990 to 2003.

The energy consumed during building operation is the most important input to the carbon cycle from buildings; but it is not the only one. The construction, renovation, and demolition of buildings also generate a significant flux of wood and other materials. Construction of a typical 204 m² (2200 ft²) house requires about 20 metric tons of wood and creates 2 to 7 metric tons of construction waste (DOE/EERE, 2005)[19 †]. Building lifetimes are many decades and, especially for commercial buildings, may include several cycles of remodeling and renovation. In the United States as a whole, water supplied to residential and commercial customers accounts for about 6% of total national fresh water consumption. This water consumption also impacts the carbon cycle because water supply, treatment, and waste disposal require energy.

9.3 TRENDS AND DRIVERS

Several factors influence trends in carbon emissions in the buildings sector. Some driver variables tend to increase emissions, while others decrease emissions. Emissions from energy use in buildings in the United States and Canada increased 30% from 1990 to 2003 (DOE/EERE, 2005; Natural Resources Canada, 2005a)[20], corresponding to an annual growth rate of 2.1%.

Carbon emissions from buildings have grown with energy consumption, which in turn is increasing with population and income. Demographic shifts therefore have a direct influence on residential energy consumption. Rising incomes have led to larger residential buildings and the amount of living area *per capita* is increasing in all three countries in North America. On one hand, total population growth is slowing, especially in Mexico, as families are having fewer children than in the past. Annual population growth during the 1990s was 1.1% in the United States, 1.0% in Canada,

[18] Total building energy in 1999 (Source: IEA) divided by population (Source: UN Department of Economic and Social Affairs) United States, 18296 million GJ divided 282 million; Canada 2280 million GJ divided by 30.5 million; Mexico 855 million GJ divided by 97.4 million.

[19] Construction data from Table 2.1.7 in DOE/EERE (2005); wood content estimated from lumber content. Construction waste from Table 3.4.1 in DOE/EERE (2005).

[20] Data from Table 3.1.1 in DOE/EERE (2005).

Table 9.2 Principal drivers of buildings emissions trends.

Driver	United States		Canada		Mexico	
	Total 2000	Growth Rate 1990-2000	Total 2000	Growth Rate 1990-2000	Total 2000	Growth Rate 1990-2000
Population (millions)	288	1.1%	31.0	1.0%	100	1.7%
Household Size (persons per household)	2.5	-0.6%	2.6	-0.9%	5.3	-0.1%
Per capita GDP (thousand $US 1995)	31.7	2.0%	23.0	1.8%	3.8	1.8%
Residential Floor space (billion m^2)	15.7	2.4%	1.5	2.4%	0.85	N/A
Commercial Floor space (million m^2)	6.4	0.6%	0.5	1.6%	N/A	N/A
Building Energy Emissions per GDP (g C/$US)	70	-0.5%	59	-0.9%	N/A	N/A

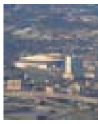
Source: Population - United Nations Department of Economic and Social Affairs (UNDESA); Household Size - United Nations Development Programme (UNDP); gross domestic product (GDP) - World Bank
Source: Floor space - EIA-EERE (2005), U.S. residential floor space estimated from 2001 Residential Energy Consumption Survey (DOE-EIA), Natural Resources Canada (2005a). Mexican residential floor space estimated from Table 1.8 in CONAFOVI (2001)
Source: Emissions - EIA-EERE (2005), Natural Resources Canada (2005b)

and 1.7% in Mexico. In the period from 1970 to 1990, it was 1.0%, 1.2%, and 2.5%, respectively[21 †]. By 2005, annual population growth in Mexico declined to 1% (INEGI, 2005). On the other hand, a shift from large, extended-family households to nuclear-family and single-occupant households means an increase in the number of households per unit population[22], each with its own heating and cooling systems and appliances.

The consumption of energy on a *per capita* basis or per unit economic activity (gross domestic product [GDP]) is also not constant but depends on several underlying factors. Economic development is a primary driver of overall *per capita* energy consumption and influences the mix of fuels used[23]. *Per capita* energy consumption generally grows with economic development, since wealthier people live in larger dwellings and use more energy[24]. Recently, computers, printers, and other office equipment have become commonplace in nearly all businesses and in most homes. These end uses now constitute 7% of primary household energy consumption. Because of these growing electricity uses, the ratio of electricity to total household primary energy has increased. This is significant to emissions because of the large emissions associated with the combustion of fossil fuels in power plants. Electricity can be generated from renewable sources such as solar or wind, but their full potential has yet to be realized.

In the United States, the major drivers of energy consumption growth are growth in commercial floor space and an increase in the size of the average home. The size of an average United States single-family home has grown from 160 m^2 (1720 ft^2) for a house built in 1980 to 216 m^2 (2330 ft^2) in 2003[†]. In the same time, commercial floor space *per capita* has increased from 20 to 22.6 m^2 (215 to 240 ft^2) (DOE/EERE, 2005)[25 †]. Certain end uses once considered luxuries have now become commonplace. Only 56% of United States' homes in 1978 used mechanical space-cooling equipment (DOE/EIA, 2005). By 2001, ownership grew to 83% driven by near total saturation in warmer climates and a demographic shift in new construction to these regions. Table 9.2 shows emissions trends as well as the underlying drivers.

In the United States, the major drivers of energy consumption growth are growth in commercial floor space and an increase in the size of the average home.

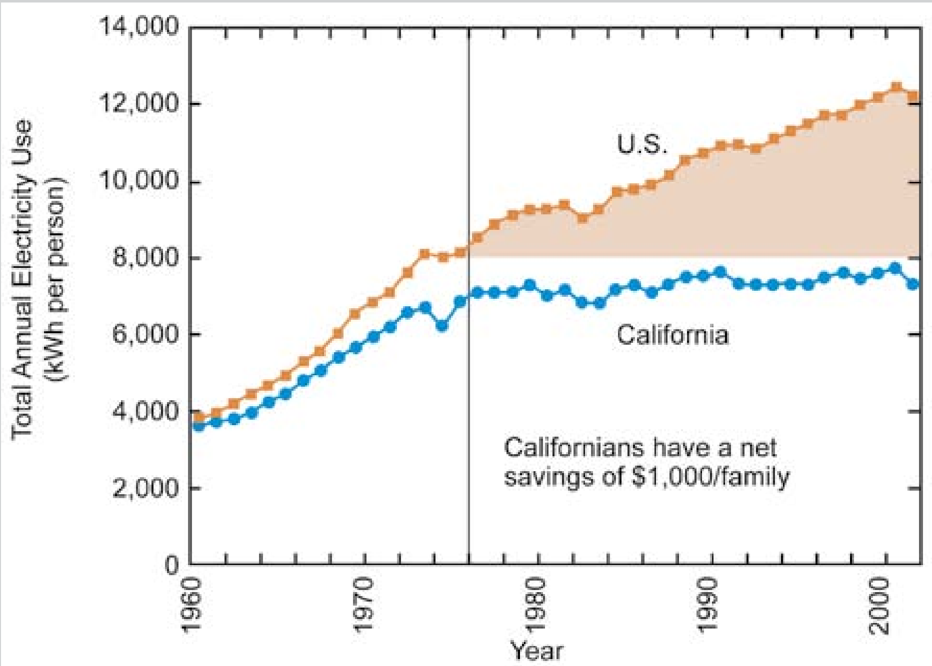


Although the general trend has been toward growth in *per capita* emissions, emissions per unit of GDP have decreased in past decades due to improvements in efficiency. Efficiency performance of most types of equipment has generally increased, as has the thermal insulation of buildings, due to influences such as technology improvements and voluntary and mandatory efficiency standards and building codes. The energy crisis of the 1970s was followed by

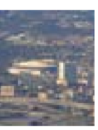
[21] *Source:* U.N. Department of Economic and Social Affairs.
[22] See household size statistics in Table 9.2.
[23] For example, whether biomass, natural gas, or electricity is used for space heating and cooking.
[24] See Table 4.2.6 in DOE/EERE (2005).
[25] See Tables 2.1.6 and 2.2.1 in DOE/EERE (2005). Residential data are from 1981.

BOX 9.1: Electricity Consumption in the United States and in California

Since the mid-1970s, the state of California has pursued an aggressive set of efficiency regulations and utility programs. As a result, *per capita* electricity consumption has stabilized in that state, while it continues to grow in the United States as a whole.



Source: California Energy Commission— Available at http://www.energy.ca.gov/2005publications/CEC-999-2005-007/CEC-999-2005-007.PDF, Slide 5



a sharp decline in economic energy intensity. Increases in efficiency were driven both by market-related technology improvements and incentives and by the establishment of federal and state/provincial government policies designed to encourage or require energy efficiency.

9.4 OPTIONS FOR MANAGEMENT

A variety of alternatives exists for reducing emissions from the buildings sector. Technology- and market-driven improvements in efficiency are expected to continue for most equipment, but this will probably not be sufficient to curtail emissions growth adequately without government intervention. The government has many different ways in which it can manage emissions that have been proven effective in influencing the flow of products from manufacturers to users (Interlaboratory Working Group, 2000). That flow may involve six steps: advancing technologies; product development and manufacturing; supply, distribution, and wholesale purchasing; retail purchasing; system design and installation; and operation and maintenance (Wiel and McMahon, 2005). Options for specific products or packages include government investment in research and development, information and education programs, energy pricing and metering, incentives and financing, establishment of voluntary guidelines, procurement programs, energy audits and retrofits, and mandatory regulation. The most effective approaches will likely include more than one of these options in a policy portfolio that takes advantage of synergies, avoids unduly burdening certain sectors, and is cost effective. Major participants include not only federal agencies, but also state and local governments, energy and water utilities, private research and development firms, equipment manufacturers and importers, energy services companies (ESCOs), nonprofit organizations, and building owners and occupants. An ESCO is a company that offers to reduce a client's utility costs, often with the cost savings being split with the client through an energy performance contract or a shared savings agreement.

- **Technology adoption supported by research and development:** Government has the opportunity to encourage development and adoption of energy-efficient technologies through investment in research and development, which can advance technologies and bring down prices, therefore enabling a larger market. Successful programs have contributed to the development of high-efficiency lighting, heating, cooling, and refrigeration. Research and development has also had an impact on the improvement of insulation, ducting, and windows. Finally, government support of research and development has been critical in the reduction of costs associated with development of renewable energy.
- **Voluntary Programs:** By now, there are a wide range of efficiency technologies and best practices available and if the most cost-effective among them were widely utilized, carbon emissions would be reduced. Voluntary measures can be effective in overcoming some market barriers. Government has been active with programs to educate consumers with endorsement labels or ratings (such as the U.S. Environmental Protection Agency's [EPA's] and U.S. Department of Energy's [DOE's] En-

ergy Star Appliances and Homes) and public-private partnerships (such as DOE's "Building America Program"). Government is not the only player, however. Energy utilities can offer rebates for efficient appliances and ESCOs can facilitate best practices at the firm level. Finally, nongovernmental organizations and professional societies (such as the U.S. Green Building Council and the American Institute of Architects) can play a role in establishing benchmarks and ratings.

- **Regulations:** Governments can dramatically impact energy consumption through well-considered regulations that address market failures with cost-effective measures. Regulations facilitate best practices in two ways: they eliminate the lowest-performing equipment from the market, and they boost the market share of high-efficiency technologies. Widely used examples are mandatory energy efficiency standards for appliances, equipment, and lighting, mandatory labeling programs, and building codes. Most equipment standards are instituted at a national level, whereas most states have their own set of prescriptive building codes (and sometimes energy performance standards for equipment) to guarantee a minimum standard for energy-saving design in homes and businesses.

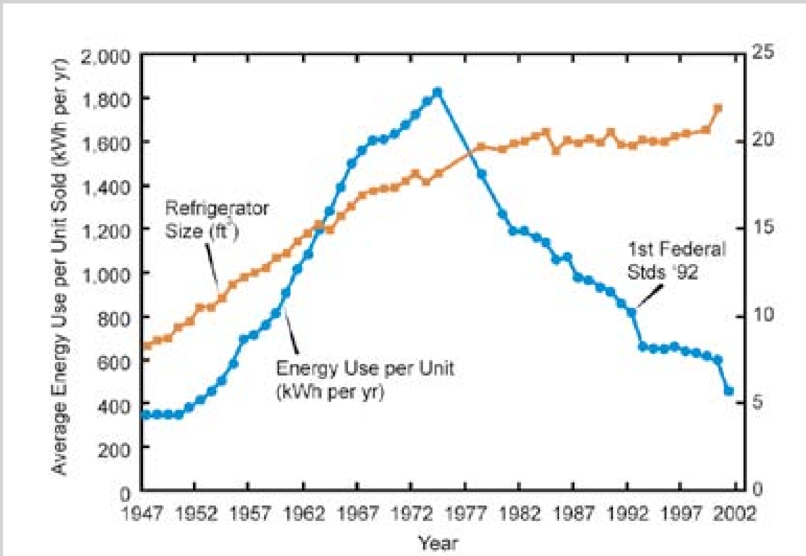
Although large strides in efficiency improvement have been made over the past three decades, significant improvements are still possible. They will involve continued improvement in equipment technology and will increasingly take a whole-building approach that integrates the design of the building and the energy consumption of the equipment inside it. The improvements may also involve alternative ways to provide energy services, such as cogeneration of heat and electricity and thermal energy storage units (Public Technology Inc. and U.S. Green Building Council, 1996).

Whole-building certification standards evaluate a package of efficiency and design options. An example is the Leadership in Energy and Environmental Design (LEED) certification system developed by the U.S. Green Building Council, a non-profit organization. In existence for five years, the LEED program has certified 36 million m^2 (390 million ft^2) of commercial and public-sector buildings and has recently implemented a certification system for homes. The LEED program includes a graduated rating system (Certified, Silver, Gold, or Platinum) for environmentally friendly design, of which energy efficiency is a key component (USGBC, 2005).

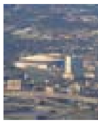
On the government side, the EPA's Energy Star Homes program awards certification to new homes that are independently verified to be at least 30% more energy-efficient than homes built to the 1993 national Model Energy Code, or 15% more efficient than state energy code, whichever is more rigorous. Likewise, the DOE's Building America program partners with homebuilders, providing research and development toward goals to decrease primary energy consumption by 30% for participating projects by 2007, and by 50% by 2015.

BOX 9.2: Impact of Efficiency Improvements

Between 1974 and 2001, the energy consumption of the average refrigerator sold in the United States dropped by 74%, a change driven by market forces and regulations. From 1987 to 2005, the U.S. Congress and DOE promulgated labels or minimum efficiency standards for over 40 residential and commercial product types. Canada and Mexico also have many product labels and efficiency standards, and a program is under way to harmonize standards throughout North America in connection with the North American Free Trade Agreement (NAFTA).

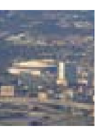


Source: California Energy Commission—Available at http://www.energy.ca.gov/2005publications/CEC-999-2005-007/CEC-999-2005-007.PDF, Slide 7



9.5 RESEARCH AND DEVELOPMENT NEEDS

Research, development, demonstration, and deployment of technologies and programs to improve energy efficiency in buildings and to produce energy with fewer carbon emissions have involved significant effort over the last 30 years. These efforts have contributed options toward carbon management. Technologies and markets continue to evolve, representing new crops of "low-hanging fruit" available for harvesting. However, in most buildings-related decisions in North America, reducing carbon emissions remains a secondary objective to other goals, such as reducing first costs (DeCanio, 1993 and 1994). The questions for which answers could significantly change the discussion about options for carbon management include the following:



- What is the total societal cost of environmental externalities[26], including carbon emissions? Energy resources in North America have been abundant and affordable, but external costs have not been completely accounted for. Most economic decisions are weighted toward the short term and do not consider the complete costs. Total societal costs of carbon emissions are unknown and because it is a global issue, difficult to allocate. Practical difficulties notwithstanding, this is a key issue, answers to which could influence priorities for research and development as well as policies such as energy pricing, carbon taxes, or credits.
- What cost-effective reduced-carbon-emitting equipment and building systems—including energy demand (efficient equipment) and supply (renewable energy)—are available in the short, medium, and long term? Policymakers must have sufficient information to be confident that particular new technology types or programs will be effective and affordable. For consumers to consider a set of options seriously, the technologies must be manifested as products that are widely available and competitive in the marketplace. Therefore, economic and market analyses are necessary before attractive options for managing carbon can be proposed.
- How do the costs of mitigation compare to the costs of continued emissions? The answers to the previous two questions can be compared in order to develop a supply curve of conserved carbon comprising a series of least-cost options, whether changes to energy demand or to supply, for managing carbon emissions. The supply curve of conserved carbon will need to be updated at regular intervals to account for changes in technologies, production practices, and market acceptance of competing solutions.

[26] External costs are the costs borne by society beyond those included in the market prices of goods. For example, carbon emissions may cause environmental damage not reflected in the market transactions associated with the buying and selling of energy (Rabl and Spadaro, 2007).