PART II OVERVIEW

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

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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 (C), and when the fuels are burned the hydrogen and carbon oxidize to water and 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 (Fig. 1).

Figure 1. Cumulative global emissions of CO_2 from fossil-fuel combustion and cement manufacture from 1751 to 2002 (data from Marland *et al.*, 2006).

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 anthropogenic source of CO_2 (after fossil-fuel use and the clearing and oxidation of forests and soils; see Part III of this report). The CO_2 emissions from cement manufacture are often included with the accounting of anthropogenic CO_2 emissions from fossil fuels.

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 distribution of emissions and some 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.

Estimating CO_2 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 is 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.

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 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 ± 2.33% per 10^9 joules (also shown in Fig. 2). Similar correlations exist for all fuels and Table 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 1 and those in Fig. 1 are small, but they begin to explain how different data compilations can end up with different estimates of CO_2 emissions.

Figure 2. The carbon content of coal varies with the heat content, shown here as the net heating value.

Table 1. A sample of the coefficients used for estimating CO_2 emissions from the amount of fuel burned (from IPCC, 1997).

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].

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

[1] Net heating value (NHV) is the heat release measured when fuel is burned at constant pressure so that the 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 H content of the fuel.

[2] The C 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).

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 US 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.

The Magnitude of National and Regional CO_2 Emissions

Figure 3 shows that from the beginning of the fossil-fuel era (1751 in these graphs) to the end of 2002, there were 93.5 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*., 2006). Figure 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.

Figure 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 (from Marland *et al*., 2006).

Figure 4. Annual emissions of CO_2 from fossil-fuel use by fuel type.

The long time series of emissions estimates in Figs. 1, 3, and 4 are from the CDIAC (Marland *et al*., 2006). These estimates are derived from the "apparent consumption" of fuels and are based on data from the UN 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 countries 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].

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 2. All of the estimates in Table 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 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 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 3 years 1990-1992, and these kinds of analyses result in re-examination of some of the fundamental data.

[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.

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

Table 2. Different estimates (in Mt C) of CO_2 emissions from fossil-fuel consumption for the United States, Canada, and Mexico.

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.

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 5 shows the variation in U.S. 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.

Figure 5. Emissions of CO_2 from fossil-fuel consumption in the United States, by month.

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 U.S. states. Figure 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 U.S. energy data as aggregated by the UN Statistics Office and calculate the annual total of CO_2 emissions directly. Again, the state and monthly emissions data are based on estimates of fuel consumption while the national emissions estimates calculated using UN 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.

Figure 6. A comparison of three different estimates of national annual emissions of CO_2 from fossil-fuel consumption in the United States.

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 7 is based on sales data for most fossil fuel commodities and the CDIAC estimates of total national emissions, and shows how the CO_2 emissions from North America vary at a monthly time scale.

Figure 7. CO_2 emissions from fossil-fuel consumption in North America, by month.

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 emissions per capita and emissions per unit of economic activity, the latter generally represented by CO_2 per unit of gross domestic product (GDP). Figure 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 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 U.S. states (Fig. 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).

Figure 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 (from Marland *et al.*, 2005).

Table 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, and Mexico and for the global total.

Figure 9. Per capita emissions of CO_2 from fossil-fuel consumption for the 50 U.S. states in 2000.

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 will find data for different base years and may treat electricity and biomass fuels differently. Despite these differences in accounting procedures, the four chapters 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 U.S. 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 (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 4).

Table 4. Percent of CO_2 emissions by sector for 2003.

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.

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Table 1. A sample of the coefficients used for estimating CO_2 emissions from the amount of fuel burned (from IPCC, 1997)

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

Table 2. Different estimates (in Mt C) of CO_2 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.

Values are from CDIAC (Marland *et al.*, 2005), IEA (2005), USEPA (2005), Canada (Environment Canada, 2005), and Mexico (2001).

All data except CDIAC include oxidation of non-fuel hydrocarbons.

All data except IEA include flaring of gas at oil and gas processing facilities.

Table 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, and Mexico 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]CO_2 is measured in kg carbon and GDP is reported in 2000 US$ purchasing power parity (from IEA, 2005).

Table 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.” (IEA, 2005).
[b]IEA category “transport.” (IEA, 2005).
[c]IEA category “manufacturing industries and construction.” (IEA, 2005).
[d]IEA category “other sectors.” (IEA, 2005).

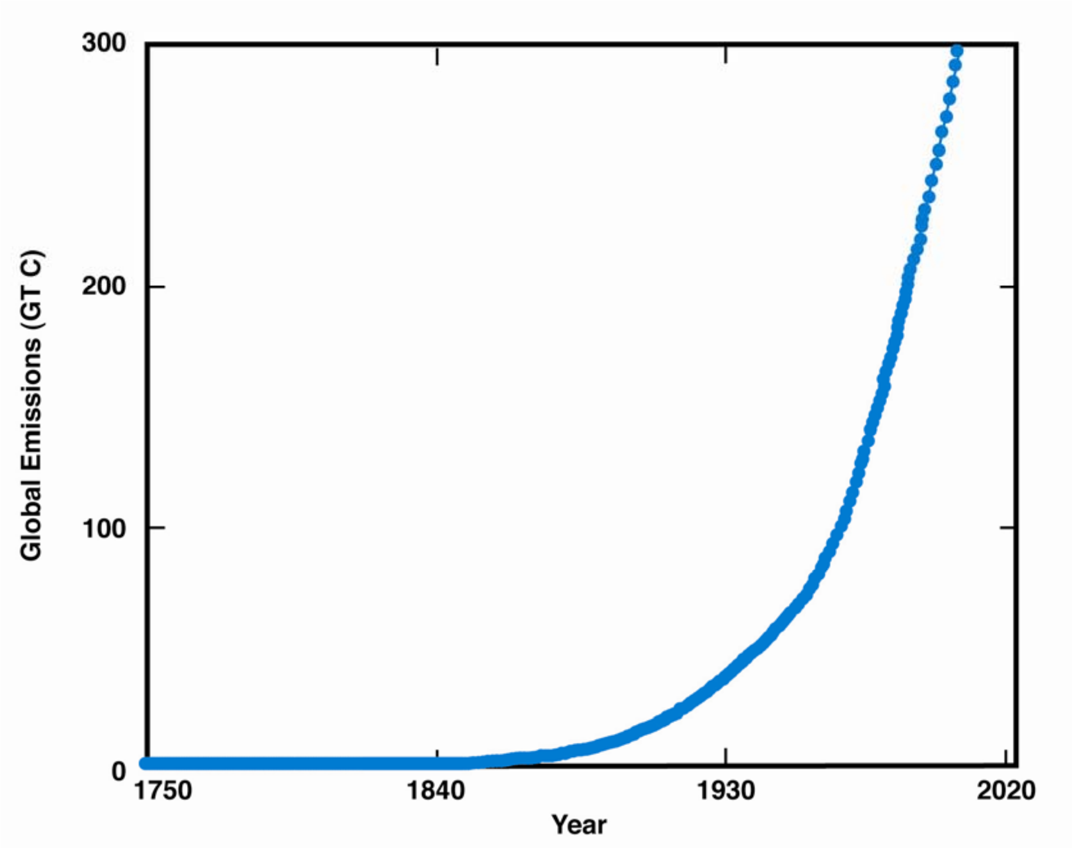


Fig. 1. Cumulative global emissions of CO_2 from fossil-fuel combustion and cement manufacture from 1751 to 2002 (data from Marland *et al.*, 2006).

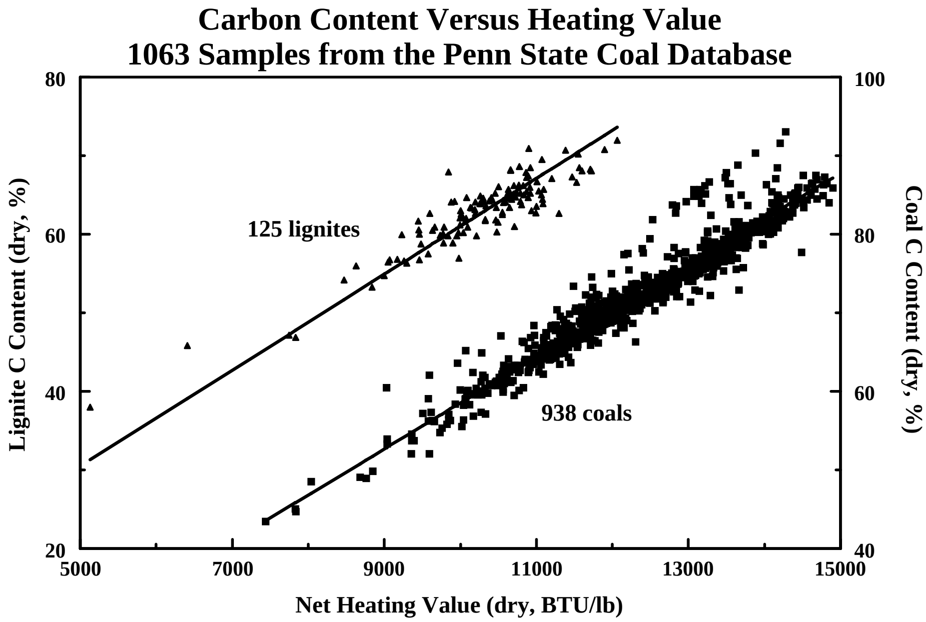


Fig. 2. The carbon content of coal varies with the heat content, shown here as the net heating value. To make them easier to distinguish, data for lignites and brown coals are shown on the left axis, while data for hard coals are offset by 20% and shown on the right axis. Heating value is plotted in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

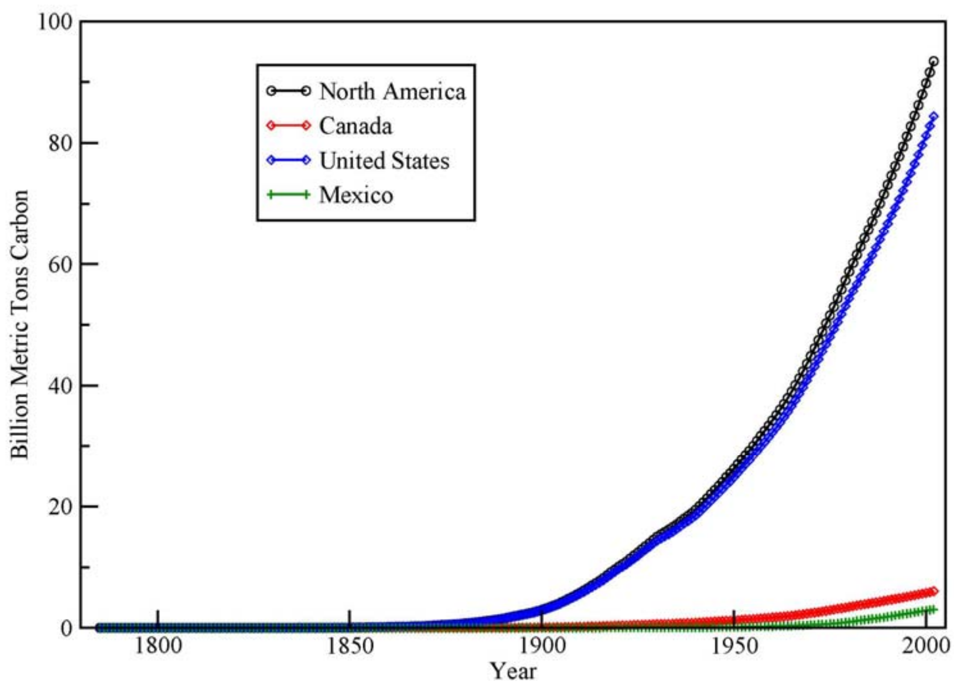


Fig. 3. The cumulative total of CO_2 emissions from fossil-fuel consumption and cement manufacture, as a function of time, for the three countries of North America and for the sum of the three (from Marland *et al.*, 2006).

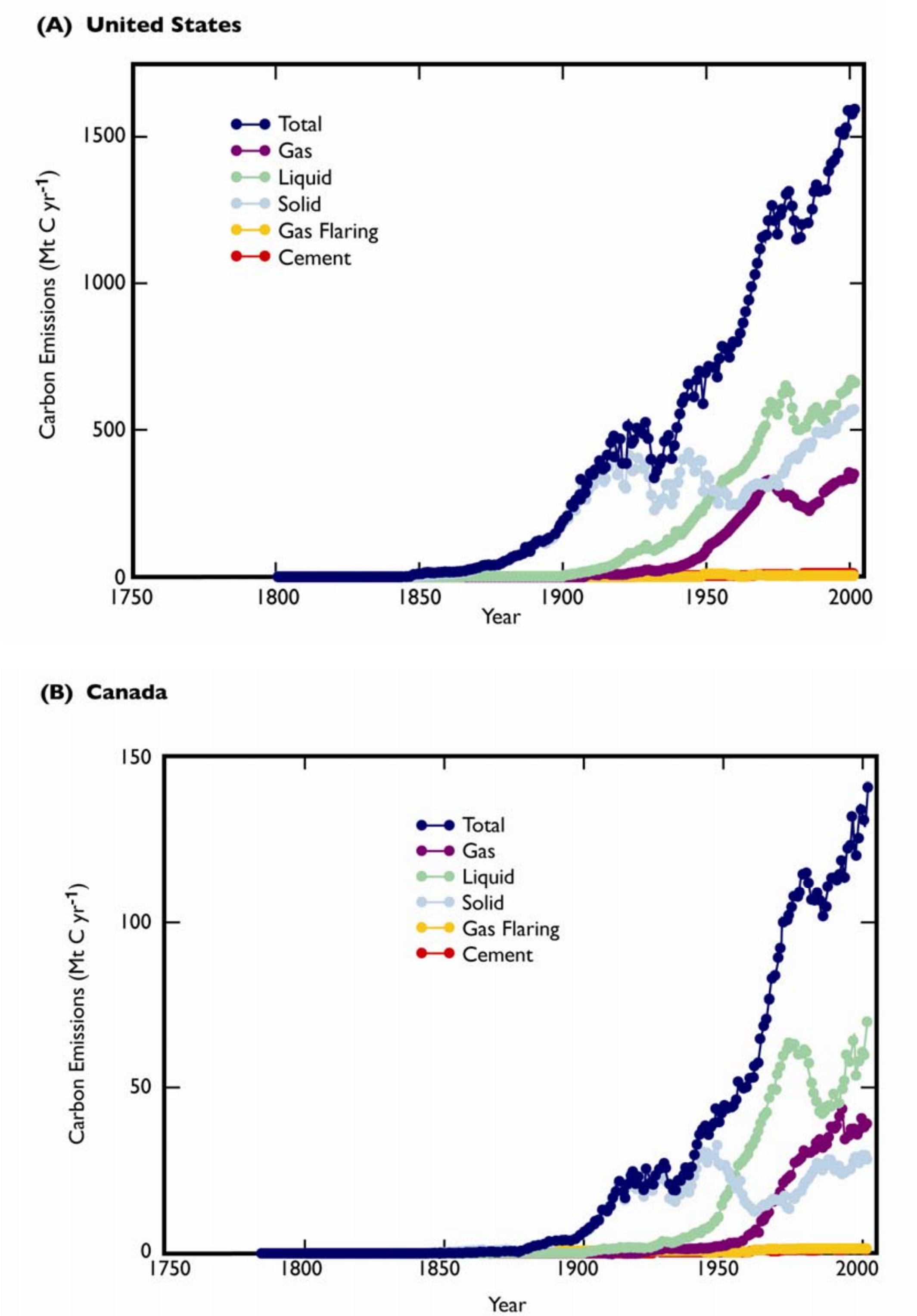
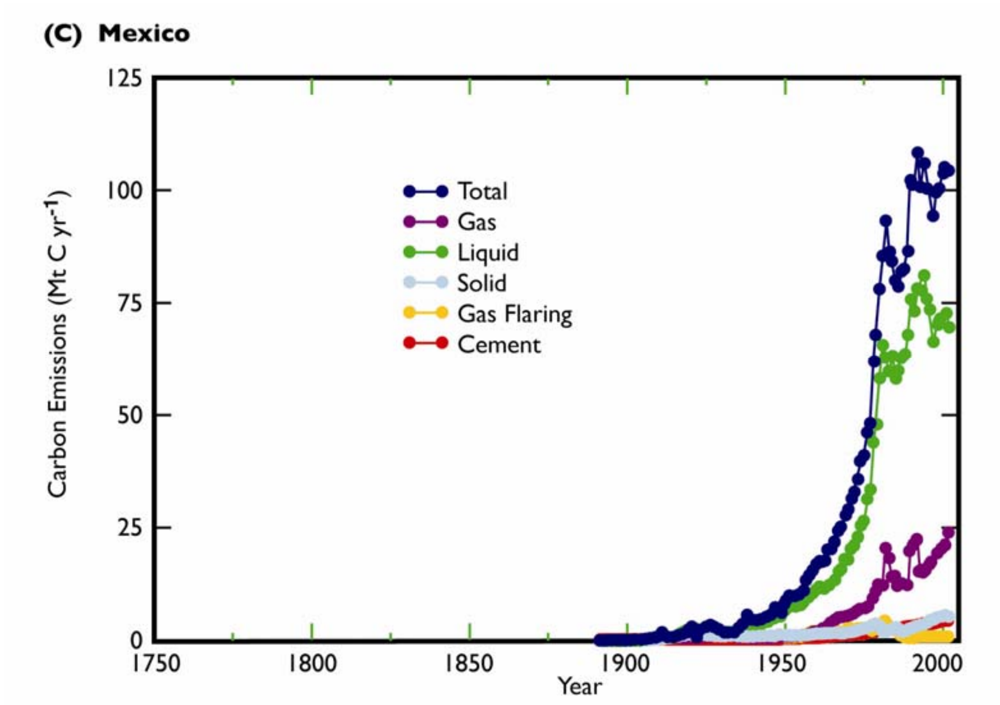


Fig. 4A and 4B. Annual emissions of CO_2 from fossil-fuel use by fuel type. Figure 4A is for the United States, Figure 4B is for Canada, Figure 4C is for Mexico, and Figure 4D is for the sum of the three. Note that in order to illustrate the contributions of the different fuels, the four plots are not to the same vertical scale (from Marland *et al*., 2006).



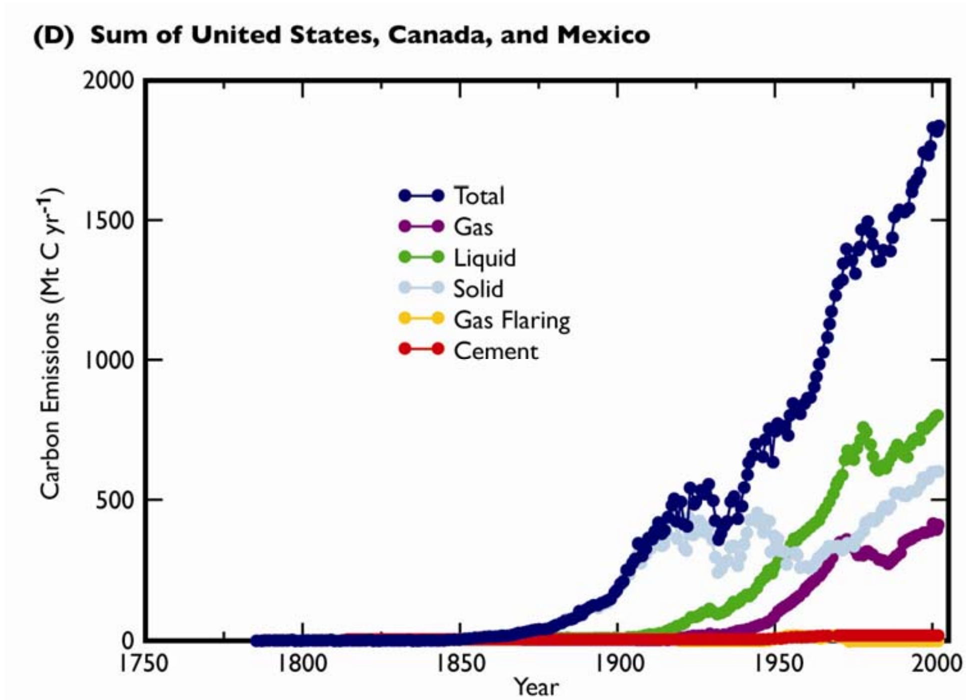


Fig. 4C and 4D. Annual emissions of CO_2 from fossil-fuel use by fuel type.
Figure 4A is for the United States, Figure 4B is for Canada, Figure 4C is for Mexico, and Figure 4D is for the sum of the three. Note that in order to illustrate the contributions of the different fuels, the four plots are not to the same vertical scale (from Marland *et al*., 2006).

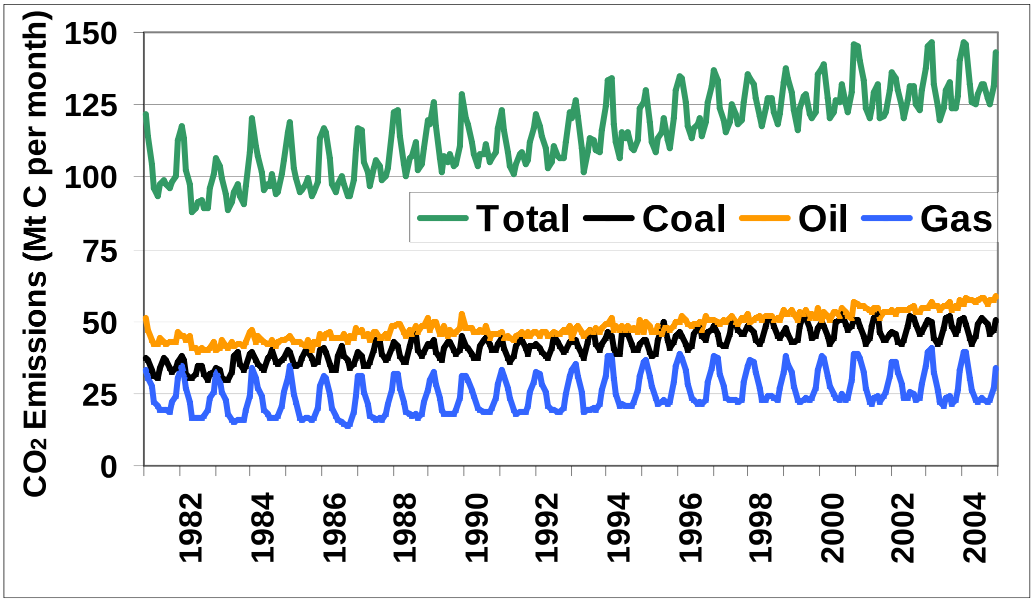


Fig. 5. Emissions of CO_2 from fossil-fuel consumption in the United States, by month. Emissions from cement manufacturing are not included (from Blasing *et al*., 2005a).

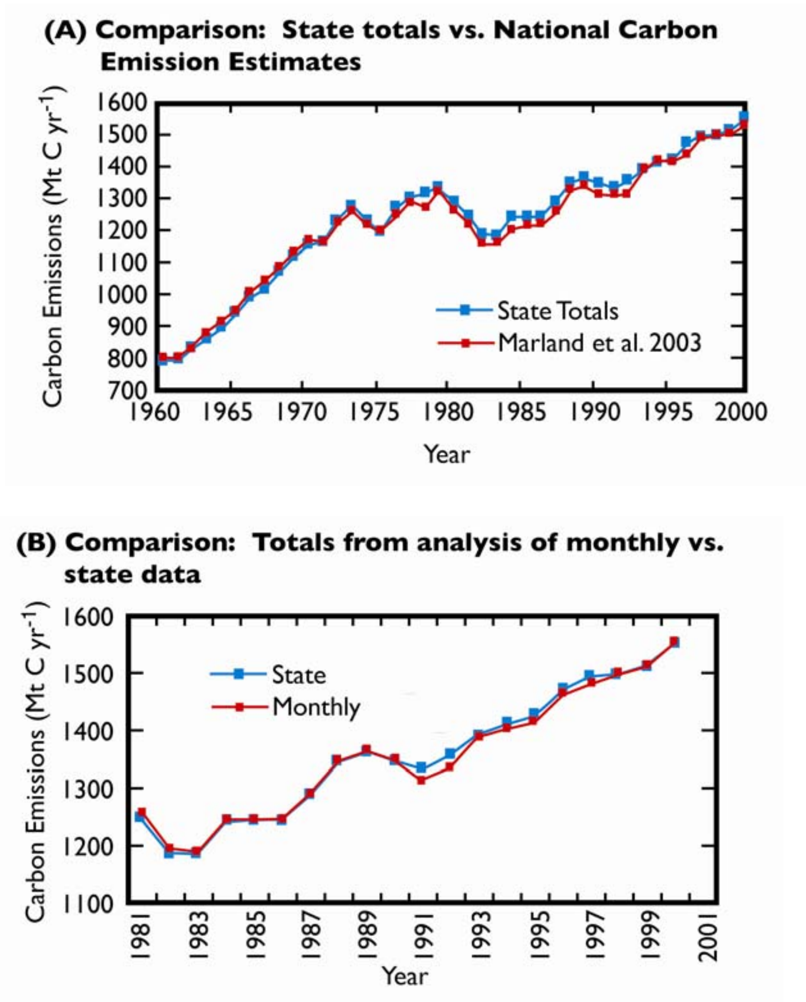


Fig. 6. A comparison of three different estimates of national annual emissions of CO_2 from fossil-fuel consumption in the United States. (6A) Estimates from U.S. Department of Energy data on fuel consumption by state (blue squares) vs. estimates based on UN Statistics Office data on apparent fuel consumption for the full United States (red squares) from Marland *et al*. (2003). (6B) 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 (from Blasing *et al.*, 2005b).

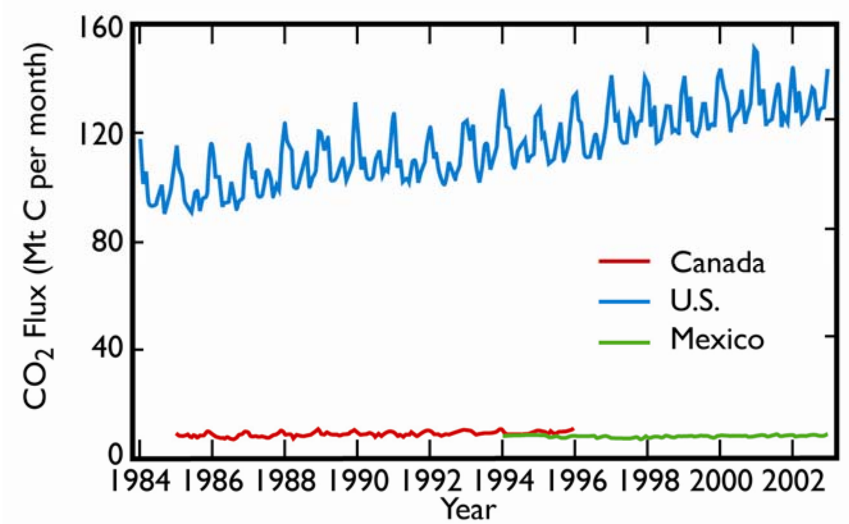


Fig. 7. CO_2 emissions from fossil-fuel consumption in North America, by month. Monthly values are shown where estimates are justified by the availability of monthly data on fuel consumption or sales (from Andres *et al*., 2005).

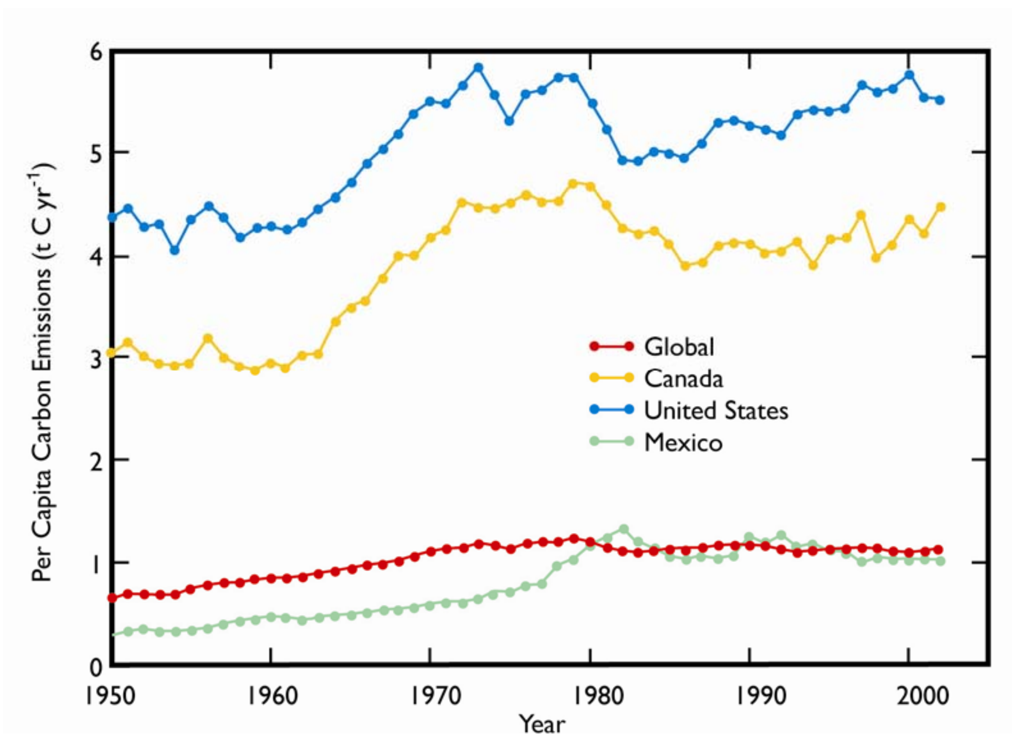


Fig. 8. Per capita emissions of CO_2 from fossil-fuel consumption (and cement manufacture) in the United States, Canada, and Mexico and for the global total of emissions (from Marland *et al*., 2005).

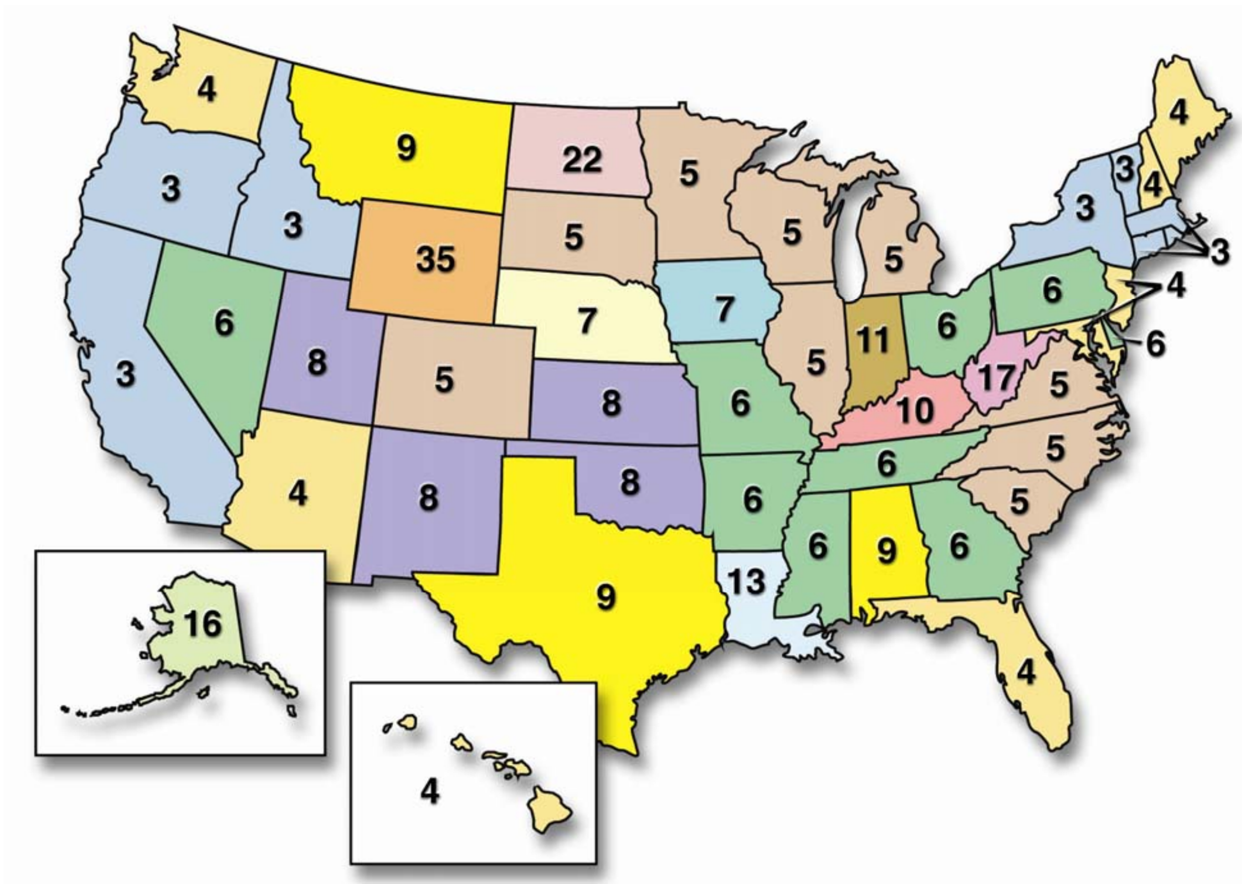


Fig. 9. Per capita emissions of CO_2 from fossil-fuel consumption for the 50 U.S. states in 2000. To demonstrate the range, values have been rounded to whole numbers of metric tons carbon per capita. A large portion of the range for extreme values is related to the occurrence of coal resources and inter-state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

Chapter 6. Energy Extraction and Conversion

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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 2700 Mt CO_2 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.
- The 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 CO_2 emissions from electricity generation alone will rise to above 3300 Mt CO_2 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.
- The prospects for major reductions in CO_2 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 (Fig. 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 sequestration, 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.

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. Also, 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.

CARBON EMISSIONS INVENTORY

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. 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.

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 (DOE, 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 in Mt CO_2 equivalents were 134 for electricity and heat generation and 71 for petroleum refining and upgrading and other fossil fuel production (Environment Canada, 2003). Although the mix of CO_2 and CH_4 in these figures is unclear, the carbon emission equivalent is probably in a 60-80 Mt C range.

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 UN United Nations Framework Convention on Climate Change in 2001, which included relatively comprehensive data from 1996 and some data from 1998. In 1998, total CO_2 emissions from "energy industries" were 47.3 Mt CO_2 (13 Mt C); from electricity generation they totaled 101.3 Mt CO_2 (27.6 Mt C), and "fugitive" emissions from oil and gas production and distribution were between 1.9 and 2.6 Mt of CH_4 (1.4 – 2 Mt C), depending on the estimated "emission factor" (Government of Mexico, 2001).

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 2299 Mt of CO_2 (627 Mt C), or 39% of a national total of 5890 (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 U.S. are about 40 Mt C per year (EIA, 2004: Ch. 2), while fugitive emissions from gas transmission and distribution pipelines in the U.S. are about 2.2 Mt C yr^{-1} (ORNL estimate). 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).

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*.

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 besides large-scale hydropower, and production costs of liquid and gas fuels are currently far lower than other sources, though rising. This is mainly due to the fact that 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 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.

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., Fig. 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.

Figure 6-2. U.S. carbon dioxide emissions from electricity generation, 1990–2004.

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).

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), but such factors 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).

United States

The Energy Information Administration (EIA, 2006a) projects that CO_2 emissions from electricity generation in the United States will rise between 2004 and 2030 from about 2299 (627 Mt C) to more than 3300 Mt (900 Mt C), 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 U.S. economy.

OPTIONS FOR MANAGEMENT OF 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.

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, 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* (CCTP, 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."

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), and 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 contributions to global emission reduction by energy supply technology initiatives between 2000 and 2100 range from about 25 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.

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 R&D, public-private sector R&D cost sharing, and electric utility restructuring. For a more comprehensive listing and discussion, see Chapter 6 in IPCC (2002, Chapter 6).

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.

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., Interlaboratory Working Group (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 IWG considered fifty policy/technology options (IWG, 2000; also see IPCC, 2001), most of which would affect both energy supply and energy use decisions.

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, on the whole, 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 through the use of generally accepted policies, generally at a positive direct cost of less than U.S.$100 per 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 760 Mt CO_2 (207 Mt C) 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% compared with a reference case, or 230 Mt CO_2 (63 Mt C), while a $50 price would reduce emissions by 17 to 19%, or 306 to 332 Mt CO_2 (83-91 Mt C). 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 at \$30 to \$70/t CO_2. With less optimistic assumptions, the cost could rise to above \$200/t.

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.

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 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.

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 it is possible that observed impacts of carbon cycle imbalances might change the political calculus for policy interventions in the future.

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:

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 can 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:

- the 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, and
- transitions from one energy system/infrastructure to another.

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.

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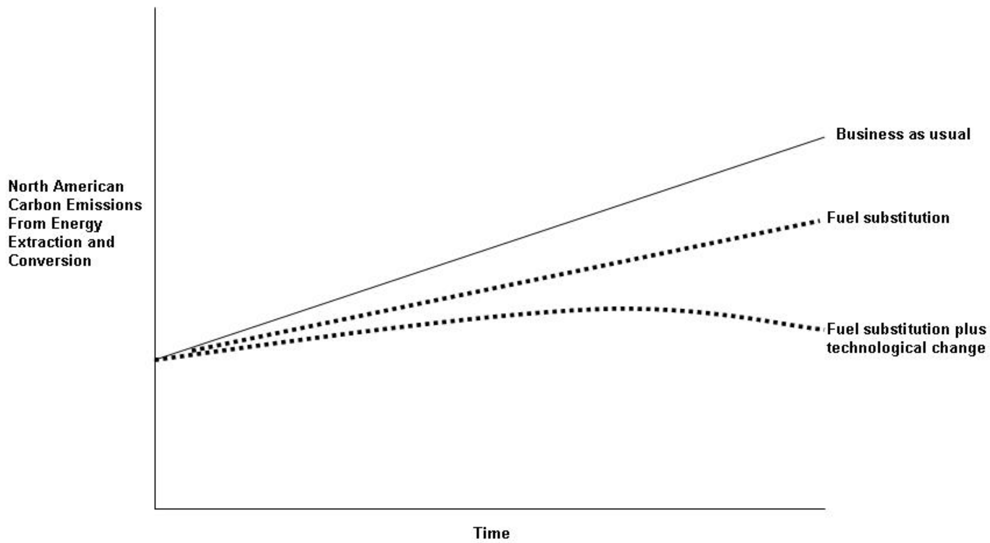

Fig. 6-1. Prospects for carbon emissions from energy extraction and conversion in North America, assuming substantial improvements in energy efficiency.

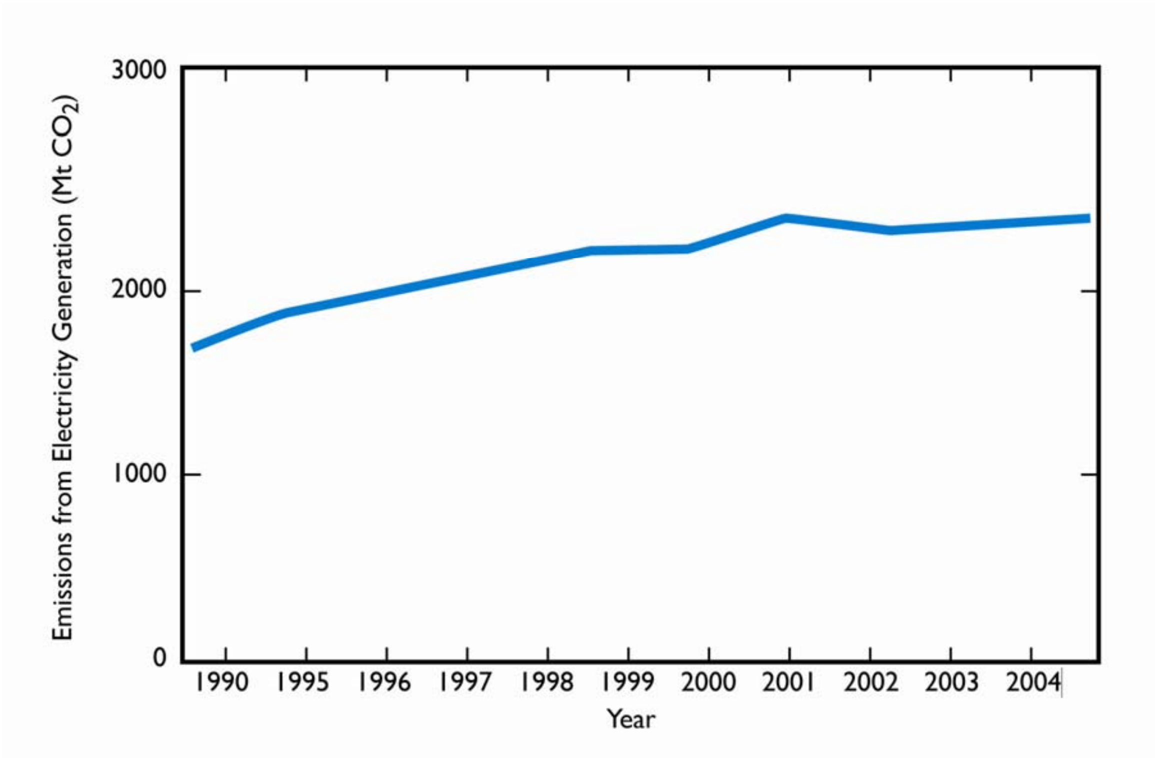

Fig. 6-2. U.S. carbon dioxide emissions from electricity generation, 1990–2004.

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Chapter 7. Transportation

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KEY FINDINGS

- The transportation sector of North America released 587 Mt of C into the atmosphere in 2003, nearly all in the form of carbon dioxide from combustion of fossil fuels. This comprises 37% of the total CO_2 emissions from worldwide transportation activity which, in turn, accounts for about 22% of total global CO_2 emissions.
- Transportation energy use in North America and the associated C 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 is assumed to remain the same, carbon dioxide emissions would increase from 587 Mt C in 2003 to 859 Mt C in 2025. Canada, the only one of the three countries in North America to have committed to specific GHG reduction goals, is expected to show the lowest rate of growth in C 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 biomass, and in the longer term, hydrogen produced from renewables, nuclear energy, or from fossil fuels with carbon sequestration. 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.

Transportation is the largest source of carbon emissions among North American energy end uses. 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 emissions: 6% below 1990 levels by 2012 (Government of Canada, 2005).

INVENTORY OF CARBON EMISSIONS

Worldwide, transportation produced about 22% (1.5 Gt C) of total global carbon dioxide 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. 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 gross domestic product (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% (Fig. 7-1) (see Table 4-1 in NATS, 2005). These differences in energy use are directly reflected in carbon emissions from the three countries' transportation sectors (Table 7-1).

Figure 7-1. Transportation energy use in North America, 1990–2003.

Table 7-1. Carbon emissions from transportation in North America in 2003.

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 greenhouse gas 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 carbon dioxide, the combustion of fossil fuels by transportation produces other greenhouse gases including methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane 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 carbon dioxide emissions from transportation activities (methane emissions are included in the totals presented in Table 7-1, but they are not included in any other estimates presented in this chapter).

Four main sources of information on carbon emissions are used in this chapter. The estimates shown in Table 7-1 were obtained from the greenhouse gas inventory reports of the three countries, estimated by environmental agencies in accordance with 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).

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 PJ). 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 PJ). Electricity, mostly for passenger rail transport, comprises only 0.1% of U.S. transport energy use. This pattern of energy use has persisted for more than half a century.

Table 7-2. Summary of North American transport energy use and carbon dioxide emissions in 2003 by fuel type.

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 (LPG), and less than 0.2% is electricity (Rodríguez, 2005). In Canada, natural gas use for natural gas pipelines accounts for 7.5% of transport energy use, 91.8% is petroleum, 0.5% is propane (LPG) and only 0.1% is electricity (see Table 1 in NRCan, 2006).

Mode of Transportation

Mode of transportation refers to how people and freight are moved about, whether by road, rail, or air, 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 Fig. 7-2.

Table 7-3. Summary of North American transport energy use and carbon dioxide emissions in 2003 by fuel type.

Figure 7-2. North American carbon emissions from transportation by mode; U.S.A and Canada 2003, Mexico 2001.

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 (Figs. 7-3A, 7-3B, 7-3C).

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.

In Mexico, trucking is the mode of choice for freight movements. Four-fifths of Mexican metric ton-km are 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 U.S. 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).

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.

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 that 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 (Fig. 7-4A) (motorcycle pkt, about 0.2% of the total, is included with passenger car). Air travel claims 10%; other modes are minor.

Figure 7-4A. Distribution of passenger travel in the United States by mode.

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 (Fig. 7-4B) (transit numbers for Canada were not available at the time these figures were compiled).

Figure 7-4B. Distribution of passenger travel by mode in Canada.

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 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.

Figure 7-5A. Evolution of transport energy use in Mexico.

Figure 7-5B. Evolution of transport energy use in the United States.

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 Figs. 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 U.S. 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. And 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.

Figure 7-6A. Transport CO_2 emissions in Canada.

Figure 7-6B. Transport CO_2 emissions in the United States.

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. As a consequence, 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 transportation over the next 25–50 years to occur in the developing economies (U.S. DOE/EIA, 2005b; IEA, 2004; WBCSD, 2004; Nakićenović, Grűbler, 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 (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 as a result 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, carbon dioxide emissions would increase from 587 Mt C in 2003 to 859 Mt C in 2025 (Fig. 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.

Figure 7-7. Projected carbon dioxide emissions from the North American transport sector in 2025, based on EIA IEO 2005 reference case.

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 greenhouse gas 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 (Fig. 7-8). Still, in 2050 North America accounts for 26.4% of global carbon dioxide emissions from transport vehicles (down from a 37.2% share in 2000).

Table 7-4. Global carbon emissions from transportation vehicles to 2050 by regions, WBCSD reference case projection (Mt C).

Figure 7-8. WBCSD projections of world transportation vehicle CO_2 emissions to 2050.

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; NAS, 2002, Ch. 5). 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 greenhouse gas 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 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 mpg (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 U.S. light-duty vehicles using proven technologies ranged from 12% for subcompact cars to 27% for large cars, and from 25% for small 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 U.S. 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.

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 U.S. 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 of 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 U.S. 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.

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 U.S. 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 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.

Table 7-5. Potential impacts of transportation GHG reduction policies in the United States by 2015 and 2030 based on the 2000 distribution of emissions by mode and fuel.

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 U.S. 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 U.S. 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 greenhouse gas 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 greenhouse gas emissions from highway vehicles through 2050 through greatly increased efficiency and biofuel and hydrogen use and, in one scenario, reduced demand for vehicle travel.

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), does not report emissions for pipelines but does report emissions from use of international bunker fuels. The U.S. and Canada report transport emissions in much greater modal detail, by vehicle type and fuel type within modes. The U.S. 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 (2005) 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 U.S. 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' greenhouse gas 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 interval for all carbon dioxide 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 greenhouse gas emissions on the order of +/- 10%. For carbon dioxide 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%).

Table 7-6. Uncertainty in estimates of carbon dioxide emissions from energy use in transport: Canada 2003.

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 (2005) 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's greenhouse gas emissions on a continuing basis (INE, 2003, p. 21). Knowledge of the magnitudes 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 lack of such studies for North America parallels a similar dearth of consistent and comprehensive global analyses noted by the Intergovernmental Panel on Climate Change (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 and measures 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. Technologies exist that could greatly reduce greenhouse gas emissions from other transport modes. For example, blended wing-body aircraft designs 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 greenhouse gas reduction benefits, biofuels must be made from plants' lingo-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.

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Table 7-1. Carbon emissions from transportation in North America in 2003

North American Carbon Emissions by Country and Mode, 2003/2001 (Mt C)				
	U.S.A. 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, 2005; INE, 2003.
Note: Data for Mexico is 2001, U.S.A. and Canada are 2003.

Table 7-2. Summary of North American transport energy use and carbon dioxide 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
Unalloc./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
Unalloc./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
Unalloc./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
Unalloc./error		
Total	1,685	31.0

Sources: Transportation energy use by fuel and mode from Rodriguez, 2005.

Source: Fulton and Eads, 2004, spreadsheet model, output worksheet.

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 greenhouse gases produced by transportation in CO_2 equivalents, while the U.S. 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 assumed that no transportation carbon emissions result from electricity use.

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
	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: Rodriguez, 2005.		

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 greenhouse gases produced by transportation in CO_2 equivalents, while the U.S. 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 emissions in end use.

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.

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 Schafer, 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.]

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, 2005, table A7-9.

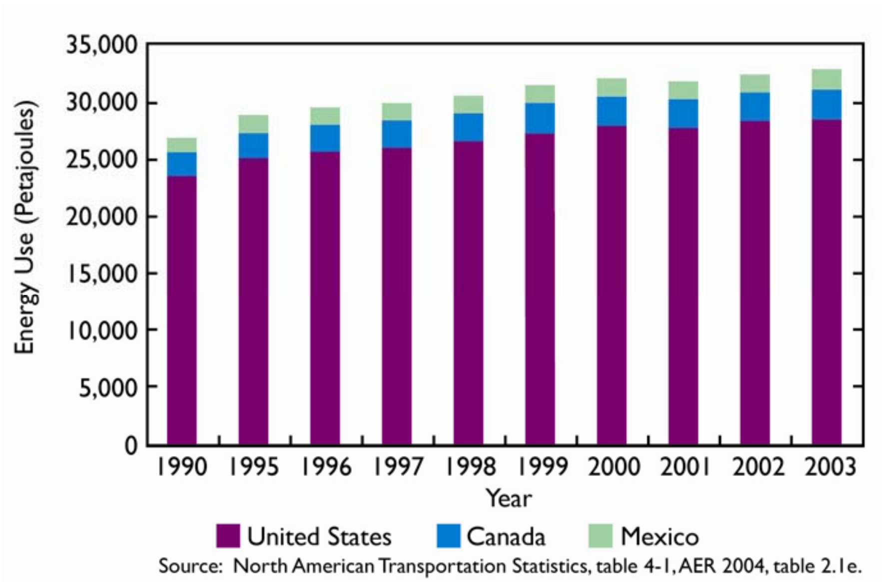

Fig. 7-1. Transportation energy use in North America, 1990–2003.

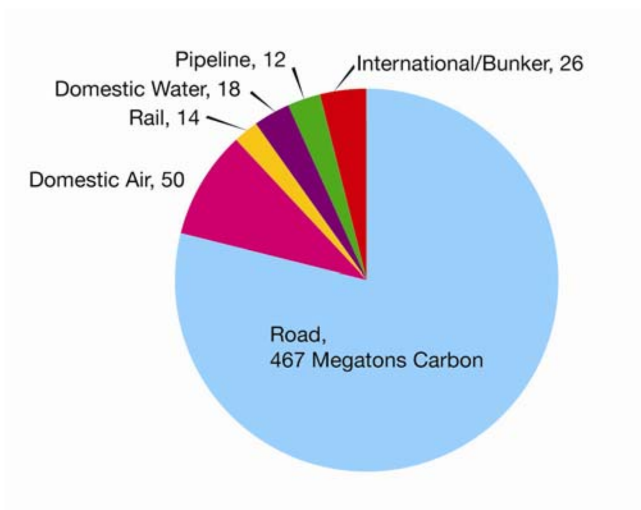

Fig. 7-2. North American carbon emissions from transportation by mode; U.S.A and Canada 2003, Mexico 2001. *Sources*: U.S. EPA, 2005; Environment Canada, 2005; INE, 2003.

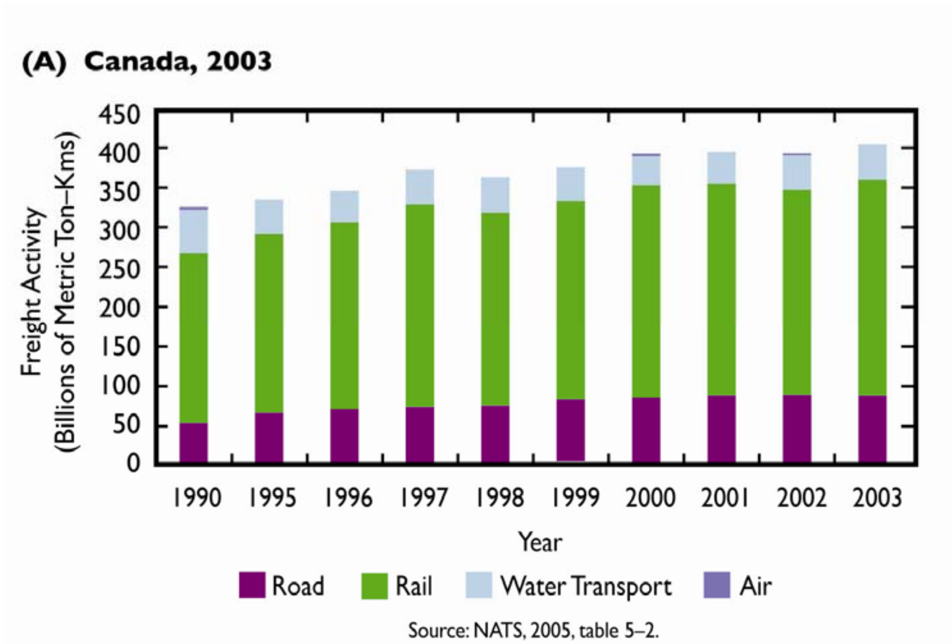

Fig. 7-3A. Freight activity by mode in Canada.

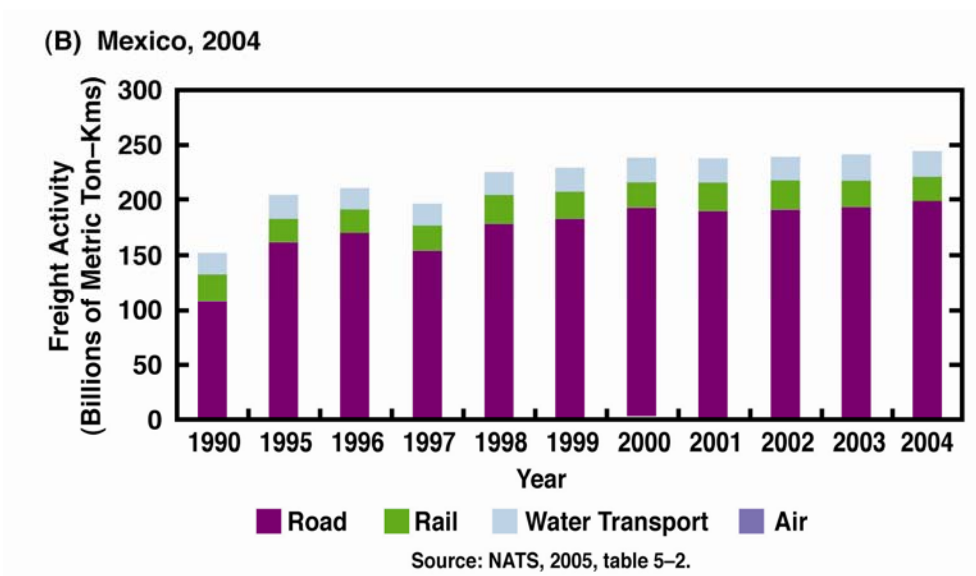

Fig. 7-3B. Freight activity by mode in Mexico.

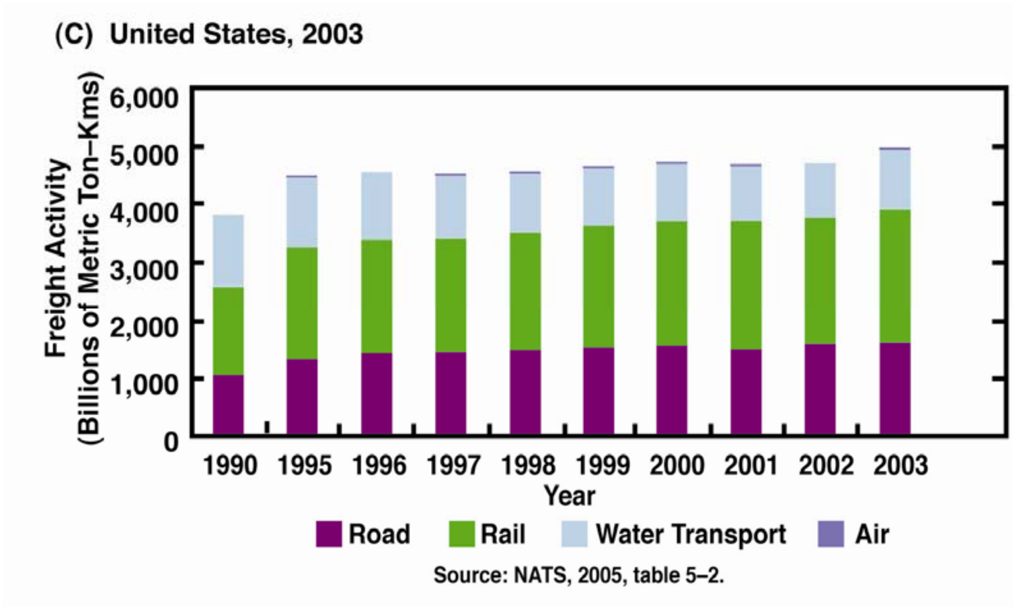

Fig. 7-3C. Freight activity by mode in the United States.

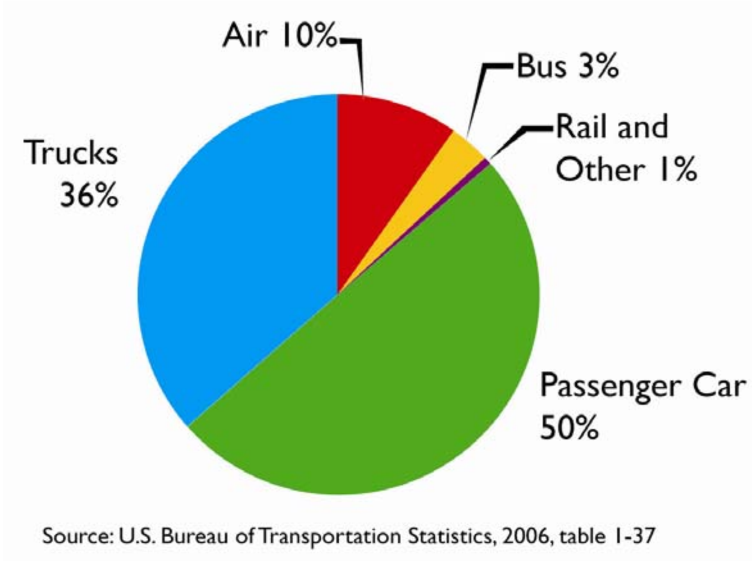

Fig. 7-4A. Distribution of passenger travel in the United States by mode.

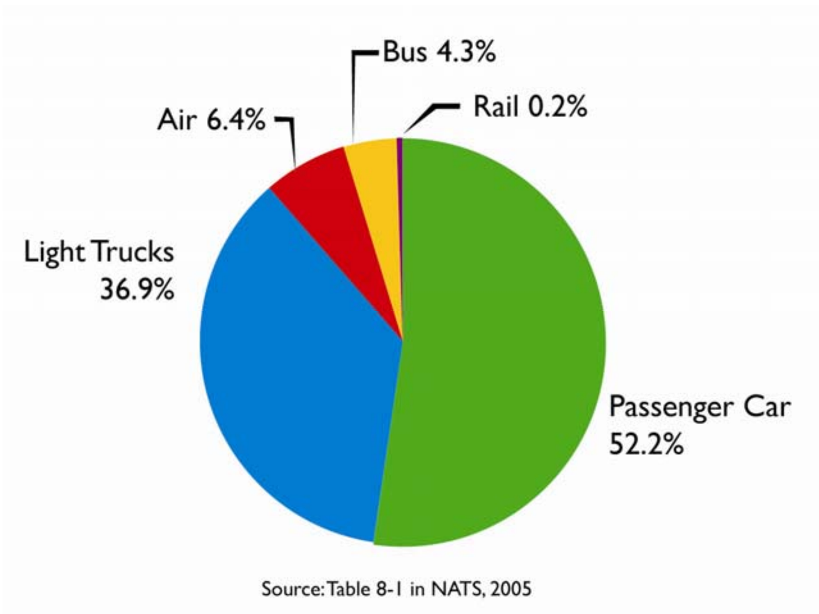

Fig. 7-4B. Distribution of passenger travel by mode in Canada. *Source*: Table 8-1 in NATS, 2005.

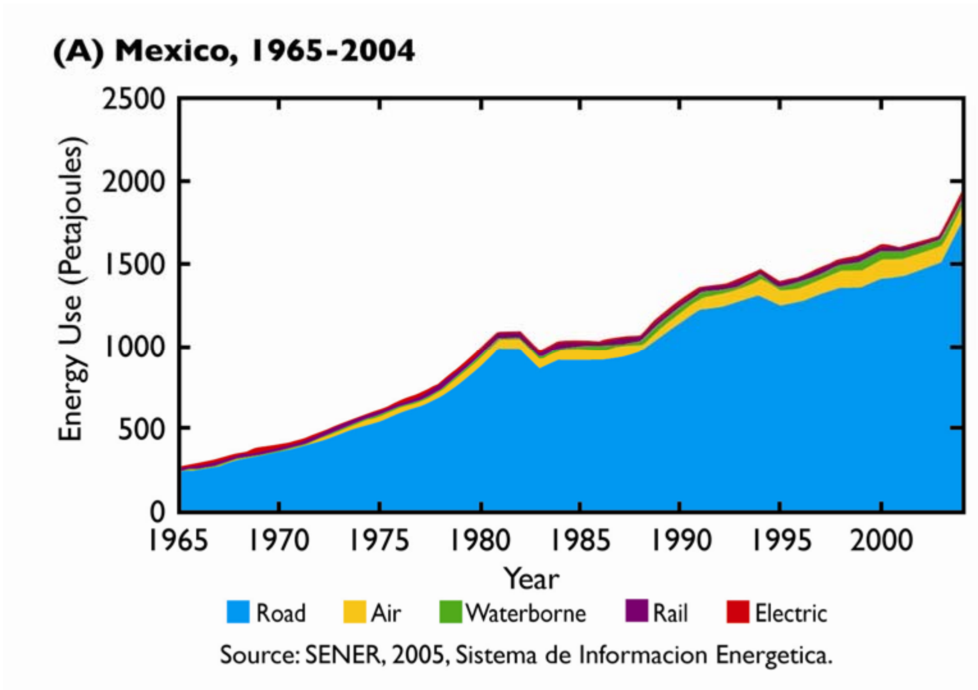

Fig. 7-5A. Evolution of transport energy use in Mexico.

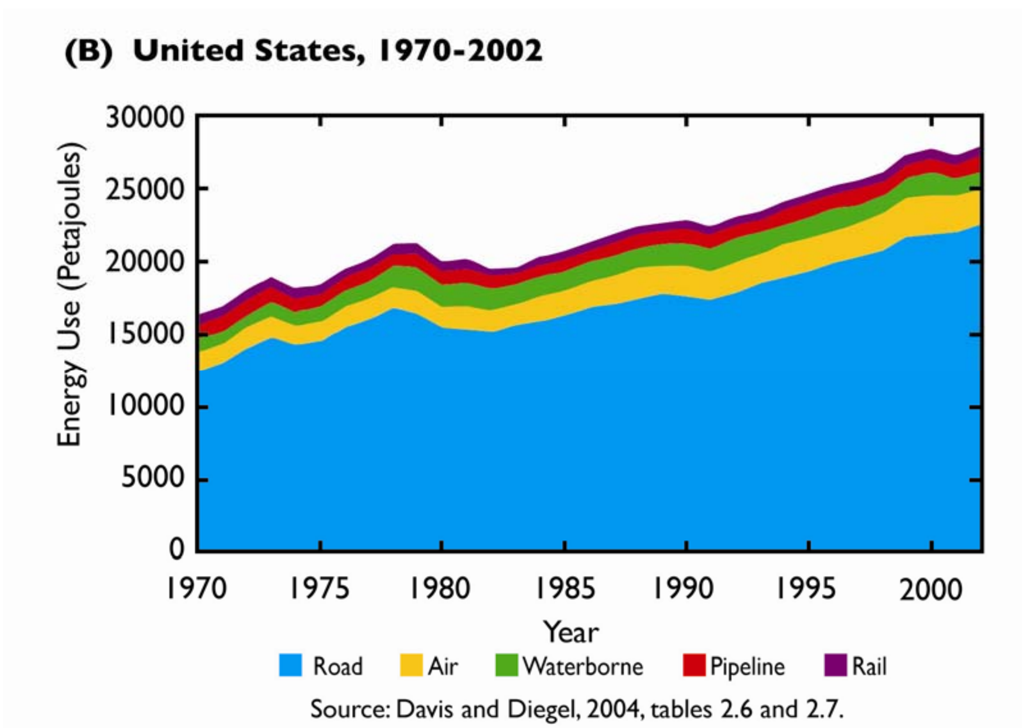

Fig. 7-5B. Evolution of transport energy use in the United States.

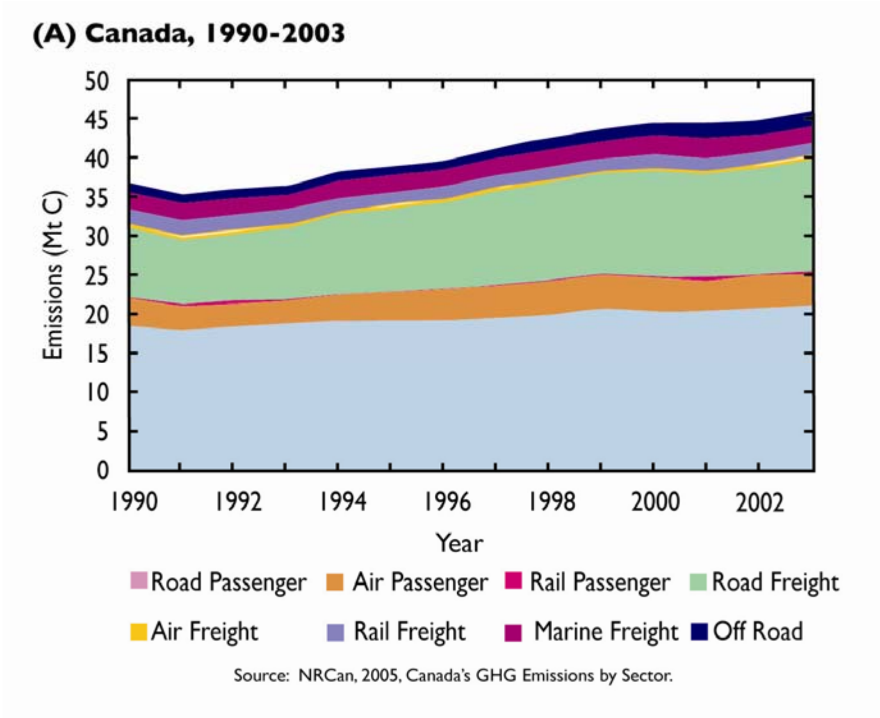

Fig. 7-6A. Transport CO_2 emissions in Canada.

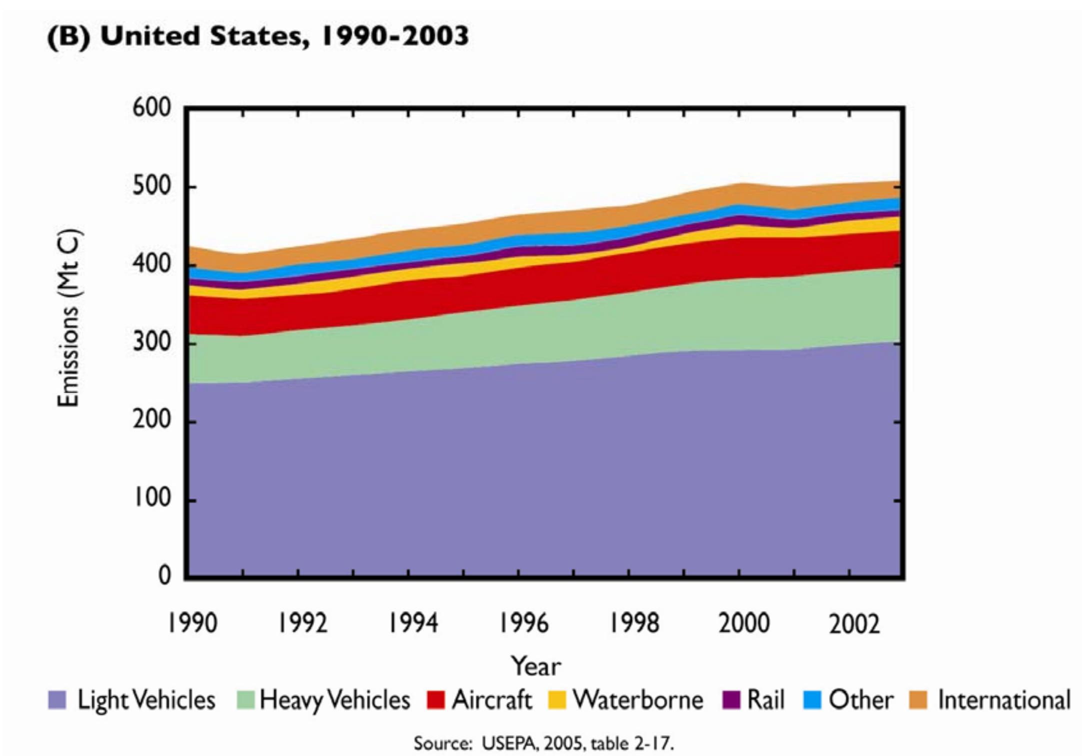

Fig. 7-6B. Transport CO_2 emissions in the United States.

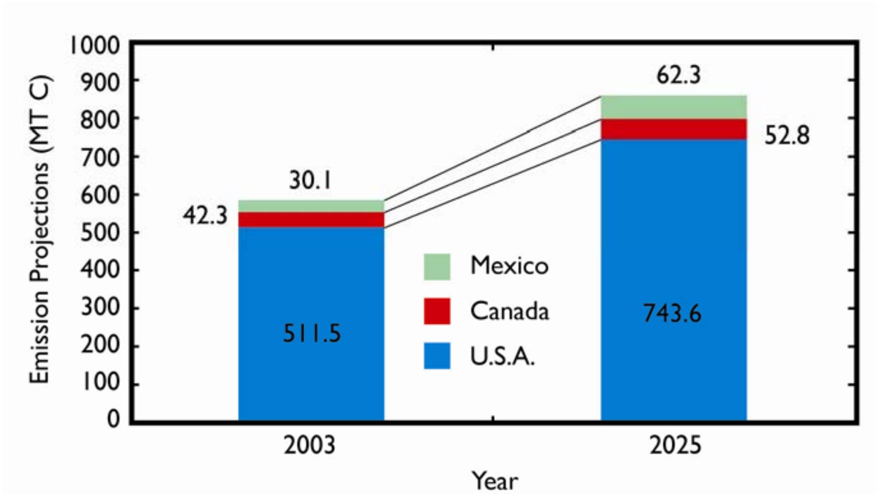

Fig. 7-7. Projected carbon dioxide emissions from the North American transport sector in 2025, based on EIA IEO 2005 reference case. *Source*: U.S. DOE Energy Information Administration, 2005b.

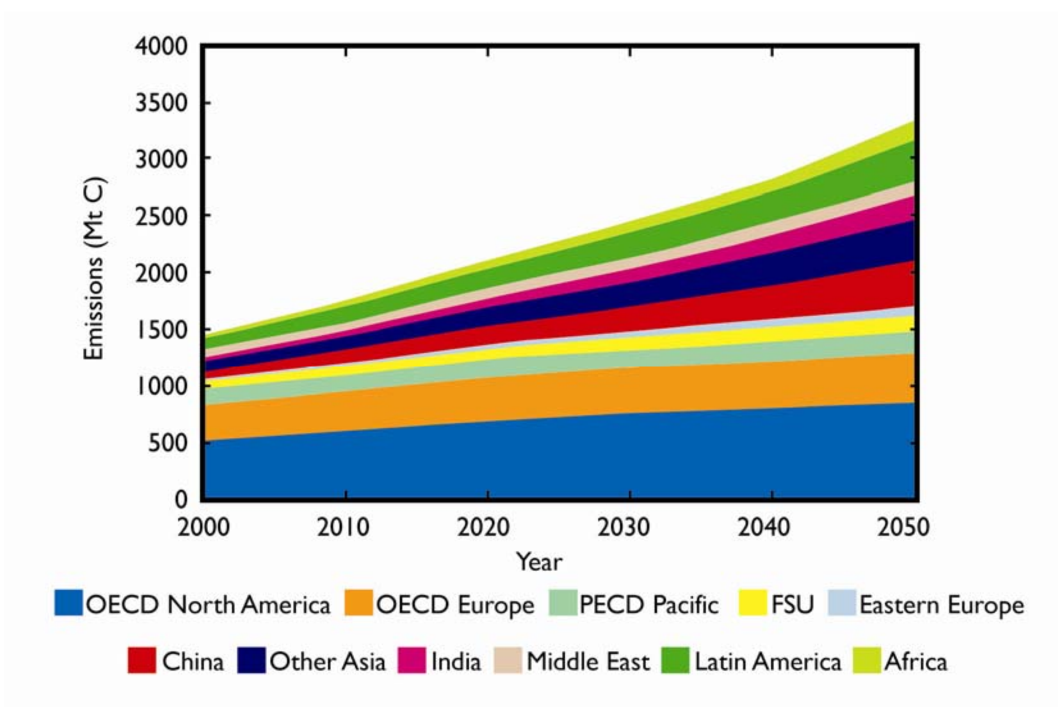

Fig. 7-8. WBCSD projections of world transportation vehicle CO_2 emissions to 2050. *Source*: Fulton and Eads, 2004.

Chapter 8. Industry and Waste Management

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KEY FINDINGS

- In 2002, North America's industry (not including fossil fuel mining and processing or electricity generation) contributed 826 Mt CO_2, 16% of the world's CO_2 emissions to the atmosphere from industry. Waste treatment plants and landfill sites in North America accounted for 13.4 Mt of CH_4 (282 Mt CO_2e), roughly 20% of global totals.
- Industrial CO_2 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 GDP growth.
- Changes in industrial CO_2 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 CO_2 emissions since 1997 in both Canada and the United States.
- An increase in CO_2 emissions from North American industry is likely to accompany the forecasted increase in industrial activity (2.3% yr^{-1} 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 and measures for reducing CO_2 emissions from North American industry can be broadly classified as methods to: (1) reduce process/fugitive emissions or converting currently released emissions; (2) increase energy efficiency, including combined heat and power; (3) change industrial processes (materials efficiency, recycling, substitution between materials or between materials and energy); (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 biomass feedstocks, of steel by aluminium in the transport sector, and of concrete by wood in the buildings sector. The prospects for greater energy efficiency technologies, including efficient Hall-Heroult cell retrofits in aluminium production, black liquor gasification in kraft pulp production, and shape casting in iron and steel industries are equally substantial.

INTRODUCTION

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

In 2002, industry was responsible for 5220.6 Mt of CO_2, 21% of anthropogenic CO_2 emissions to the atmosphere (4322.9 Mt from fuel combustion and 897.7 Mt from industrial processes). North America's industry contributed 758.7 Mt of combustion-sourced emissions and 66.8 Mt of process emissions for a total of 826 Mt, 16% of global totals. The manufacturing industry contributed 12% of total North American greenhouse gas (GHG) emissions, lower than in many other parts of the world. But 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 (see Fig. 8-1A).[2]

Figure 8-1A. CO_2 emissions by sector in 2002.

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 GDP growth (IEA, 2004).[3] 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. CO_2, 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

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

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

[3]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.

treatment plants and landfill sites, forms a substantial portion of carbon emissions to the atmosphere. Given its high global warming potential, methane plays an important role in the evaluation of possible climate change impacts (see Fig. 8-1B).[4] Globally, CH_4 emissions from waste amount to 66 Mt, or 1386 Mt CO_2 equivalent. North American activity accounts for 13.4 Mt of CH_4 (282 Mt CO_2 equivalent), roughly 20% of global totals.

Figure 8-1B. GHG emissions by sector in 2000, CO_2, CH_4, N_2O, PFCs, HFCs, and SF_6.

Substantial sequestration of carbon occurs in landfills.[5] Data on carbon buried there are poor. The Environmental Protection Agency (EPA), using data from Barlaz (1990, 1994), estimated that 30% of carbon in food waste and up to 80% of carbon in newsprint, leaves, and 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."

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.

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.

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

[4] While not carbon-based, N_2O from sewage treatment is shown in Fig. 2 to show its relative GHG importance.
[5] IPCC guidelines currently do not address landfill sequestration. Such guidelines will be in the 2006 publication.

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/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.

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.[6,7] The oxidation of carbon anodes generates about 1.5 tons CO_2 to produce a ton of aluminum. Striping hydrogen from methane to make ammonia releases about 1.6 tons CO_2 per ton of ammonia.

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 also be released (carbon monoxide, methane, volatile organic compounds). These often decompose into CO_2, but their life spans in the atmosphere vary.

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 8A. On the left side of Fig. 8-2, all carbon-

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

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.

Figure 8-2. Carbon flows for Canada, the United States, and Mexico combined.

Sectoral Trends in the Industrial Carbon Cycle

Figure 8-2 shows that energy-intensive industries differ significantly in their carbon cycle dynamics.

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.[8] Fuel handling difficulties and air quality concerns can arise from the use of biomass as a fuel.

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.

$$\underset{\text{calcium carbonate}}{CaCO_3} \rightarrow \underset{\text{calcium oxide}}{CaO} + \underset{\text{carbon dioxide}}{CO_2}$$

Outside of the combustion of fossil fuels, lime calcining is the single largest anthropogenic 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 and, as in glass production, in its utilization. Soda ash is used to produce pulp and paper, detergents and soft water.

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

$2NaHCO_3$	→	Na_2CO_3	+	CO_2	+	H_2O
sodium bicarbonate		sodium carbonate		carbon dioxide		water

Nonferrous Metal Smelting and Iron and Steel Smelting

Often metal smelting requires the reduction of metal oxides to obtain pure metal through the 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 aluminium oxide (alumina) in the production of aluminum. [9]

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.

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.

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.

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.[10] In aggregate, however, these various industries contribute significantly to total industrial CO_2 emissions. Industries in

[9] Ceramic anodes may soon be available to aluminum producers and significantly reduce process CO_2 emissions.
[10] Except, of course, the food, beverage and some textile industries.

this group include the automotive industry, electronic products, leather and allied products, fabricated metals, furniture and related products, and plastics and rubber products.

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 Modelling 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 average rate of 3.1% per year to 2025, industrial growth is forecast at 2.3% per year—an amalgam of manufacturing 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.

The International Energy Agency reviewed energy consumption and emissions during the last 30 years to identify and project underlying trends in carbon intensity.[11] The review's decomposition analysis (Fig. 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).

Figure 8-3. Decomposition of energy use, manufacturing section, 1990–1998.

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[12] 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.

[11] Most of the information in this section is obtained from this report (IEA, 2004a).

[12] 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.

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.[13]

Table 8-1. Energy reductions in recycling

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 are 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.

WASTE MANAGEMENT CARBON CYCLE

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

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

A portion of municipal solid waste is recycled: 31% in the United States, 27% in Canada. 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 methane) 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 methane (CH_4) by volume[14] 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,[15] a relatively small amount compared to total other (sub)sectors 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, 1990, 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, 2001; Mohareb *et al.*, 2003; EPA, 2003; 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.

Anaerobic digestion generates methane gases that can be captured and used in cogenerators. Many of the 1,800 municipal solid waste sites in 2003 in the United States captured and combusted landfill-generated methane; about half of all the methane produced was combusted or oxidized in some way (EPA, 2005). In Canada, about 23% of the methane emissions were captured and utilized to make energy in 2002 (Mohareb *et al.*, 2003). The resultant CO_2 released from such combustion is considered biological in origin. Thus, only methane 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.

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[14]Based on gas volumes, this means that roughly equivalent amounts of carbon are released as CO_2 as CH_4.

[15]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.

COSTS RELATED TO CONTROLLING ANTHROPOGENIC IMPACTS ON THE CARBON CYCLE

Defining costs associated with reducing anthropogenic impacts on the carbon cycle is a highly contentious issue. Different approaches to cost assessments (top-down, bottom-up, applicable discount rates, social 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 period 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.[16] Some studies focus on technical potential and don't 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.

Table 8-3. Approximate costs and reductions potential

[16]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* below Table 8-3 for a list.

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. gal). Diesel fuel cost would be nearly 2.7¢/L (10¢/U.S. gal). Costs per GJ[17] vary by fuel: coal rises about 90¢/GJ, depending on type, 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. But 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.

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.

Some Explanatory Notes

Data come from a variety of sources and do not delineate costs as per the categories describe here. Data sources can be notionally categorized into the following groups (with some references listed twice):[18]

- *General overviews*: Grubb *et al*., 1993; Weyant *et al*., 1999;[19] 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.*, 2003; 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.*, 2003; Jaccard, Nyboer, *et al.*, 2003; Edenhofer *et al.*, 2006.
- *Others*: Newell *et al.*, 1999; Sutherland, 2000; Jaffe *et al.*, 2002.

[17] A GJ is slightly smaller than 1 MMBtu (1 GJ = 0.948 MMBtu)

[18] 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.

[19] John Weyant, Stanford, is currently editing another similar analysis to this listed publication to be released some time in 2006. ***DETAILS FORTHCOMING…***

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 methane. The costs for this are quite low. EPA (2003a) estimates of between 40% and 60% of methane available for capture may generate net economic benefits.

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.*, 2003; Jaccard, Nyboer, *et al.*, 2003; Worrell *et al.*, 2004).

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.).

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.[20]

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

[20] 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 the difference between a fuel's higher heating value and its lower heating value.

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).

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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.

Table 8-2. Waste materials flows by region in North America, 2003

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

* Calculated estimate

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

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*	$\%Q_{red}$*	Cost category	$\%Q_{red}$	Cost category	$\%Q_{red}$	Cost category	$\%Q_{red}$
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

*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

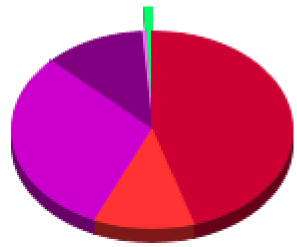
Carbon-Based: **A:** \$0–\$92/t C; **B:** \$92–\$180/t C; **C:** \$180–\$367/t C; **D:** >\$367/t C

World

Sector	Mt CO_2	%
Energy	23,432.1	96.3
Electricity & Heat	*10,731.8*	*44.1*
Manufacturing & Construction	*4,322.9*	*17.8*
Transportation	*4,964.5*	*20.4*
Other Fuel Combustion	*3,265.3*	*13.4*
Fugitive Emissions	*147.6*	*0.6*
Industrial Processes	897.7	3.7
Total	**24,329.8**	

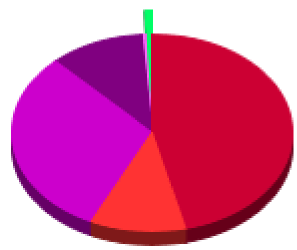
North America (w/ Mexico)

Sector	Mt CO_2	%
Energy	6,576.5	98.9
Electricity & Heat	*3,017.0*	*45.3*
Manufacturing & Construction	*758.7*	*11.3*
Transportation	*2,016.6*	*30.5*
Other Fuel Combustion	*757.1*	*11.6*
Fugitive Emissions	*27.2*	*0.4*
Industrial Processes	66.8	1.0
Total	**6,643.3**	



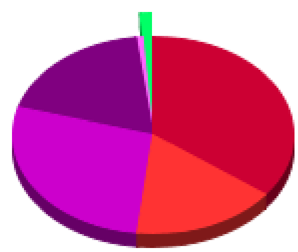
United States of America

Sector	Mt CO_2	%
Energy	5,675.4	99.2
Electricity & Heat	*2,645.0*	*46.2*
Manufacturing & Construction	*621.4*	*10.9*
Transportation	*1,761.4*	*30.8*
Other Fuel Combustion	*624.5*	*10.9*
Fugitive Emissions	*23.1*	*0.4*
Industrial Processes	44.7	0.8
Total	**5,720.1**	



Canada

Sector	Mt CO_2	%
Energy	535.9	98.8
Electricity & Heat	*191.7*	*35.3*
Manufacturing & Construction	*89.2*	*16.4*
Transportation	*150.5*	*27.7*
Other Fuel Combustion	*100.5*	*18.5*
Fugitive Emissions	*4.1*	*0.7*
Industrial Processes	6.6	1.2
Total	**542.5**	



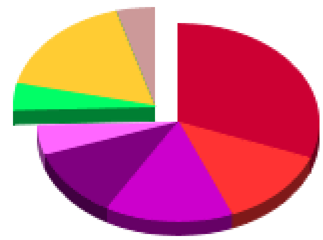
Mexico

Sector	Mt CO_2	%
Energy	365.2	95.9
Electricity & Heat	*180.3*	*47.4*
Manufacturing & Construction	*48.1*	*12.6*
Transportation	*104.7*	*27.5*
Other Fuel Combustion	*32.1*	*8.4*
Fugitive Emissions	*--*	*--*
Industrial Processes	15.5	4.1
Total	**380.6**	

Fig. 8-1A. CO_2 emissions by sector in 2002. *Source*: Climate Analysis Indicators Tool (CAIT) Version 3.0 (Washington, D.C.: World Resources Institute, 2005).

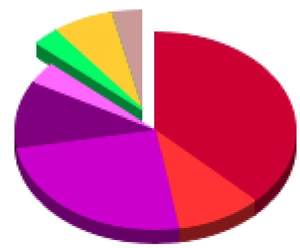
World

Sector	Mt CO_2	%
Energy	24,789.9	74.5
Electricity & Heat	*10,269.4*	*30.9*
Manufacturing & Construction	*4,327.9*	*13.0*
Transportation	*4,809.7*	*14.5*
Other Fuel Combustion	*3,742.4*	*11.2*
Fugitive Emissions	*1,640.5*	*4.9*
Industrial Processes	1,366.8	4.1
Agriculture	5,631.5	16.9
Waste	1,483.6	4.5
Total	**33,271.8**	



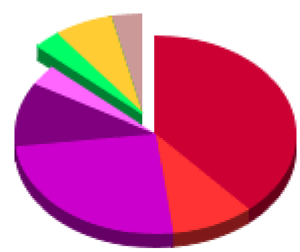
North America (w/ Mexico)

Sector	Mt CO_2	%
Energy	7,004.8	86.2
Electricity & Heat	*3,027.6*	*37.3*
Manufacturing & Construction	*809.6*	*10.0*
Transportation	*1,971.1*	*24.3*
Other Fuel Combustion	*877.2*	*10.8*
Fugitive Emissions	*319.2*	*3.9*
Industrial Processes	239.0	2.9
Agriculture	580.9	7.1
Waste	300.0	3.7
Total	**7,610.9**	



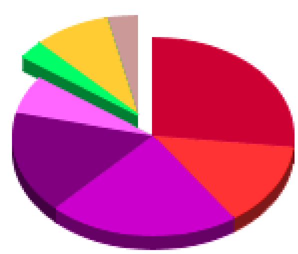
United States of America

Sector	Mt CO_2	%
Energy	6,005.5	86.8
Electricity & Heat	*2,670.6*	*38.6*
Manufacturing & Construction	*657.9*	*9.5*
Transportation	*1,719.9*	*24.9*
Other Fuel Combustion	*723.6*	*10.5*
Fugitive Emissions	*233.5*	*3.4*
Industrial Processes	198.4	2.9
Agriculture	469.9	6.8
Waste	243.3	3.5
Total	**6,917.1**	



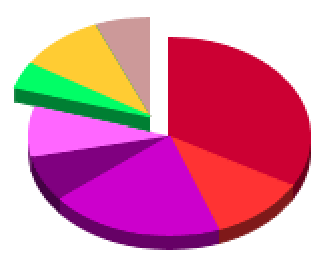
Canada

Sector	Mt CO_2	%
Energy	589.5	85.0
Electricity & Heat	*185.9*	*26.8*
Manufacturing & Construction	*94.6*	*13.6*
Transportation	*150.0*	*21.6*
Other Fuel Combustion	*115.3*	*16.6*
Fugitive Emissions [1]	*43.6*	*6.3*
Industrial Processes [2]	19.3	2.8
Agriculture	60.8	8.8
Waste	24.2	3.5
Total	**693.8**	



Mexico

Sector	Mt CO_2	%
Energy	409.8	79.8
Electricity & Heat	*171.1*	*33.3*
Manufacturing & Construction	*57.1*	*11.1*
Transportation	*101.2*	*19.7*
Other Fuel Combustion	*38.3*	*7.5*
Fugitive Emissions [1]	*42.1*	*8.2*
Industrial Processes [2]	21.3	4.2
Agriculture	50.2	9.8
Waste	32.5	6.3
Total	**513.8**	



[1] N_2O data not available. [2] CH_4 data not available.

Fig. 8-1B. GHG emissions by sector in 2000, CO_2, CH_4, N_2O, PFCs, HFCs, and SF_6. *Source*: Climate Analysis Indicators Tool (CAIT) Version 3.0 (Washington, D.C.: World Resources Institute, 2005).

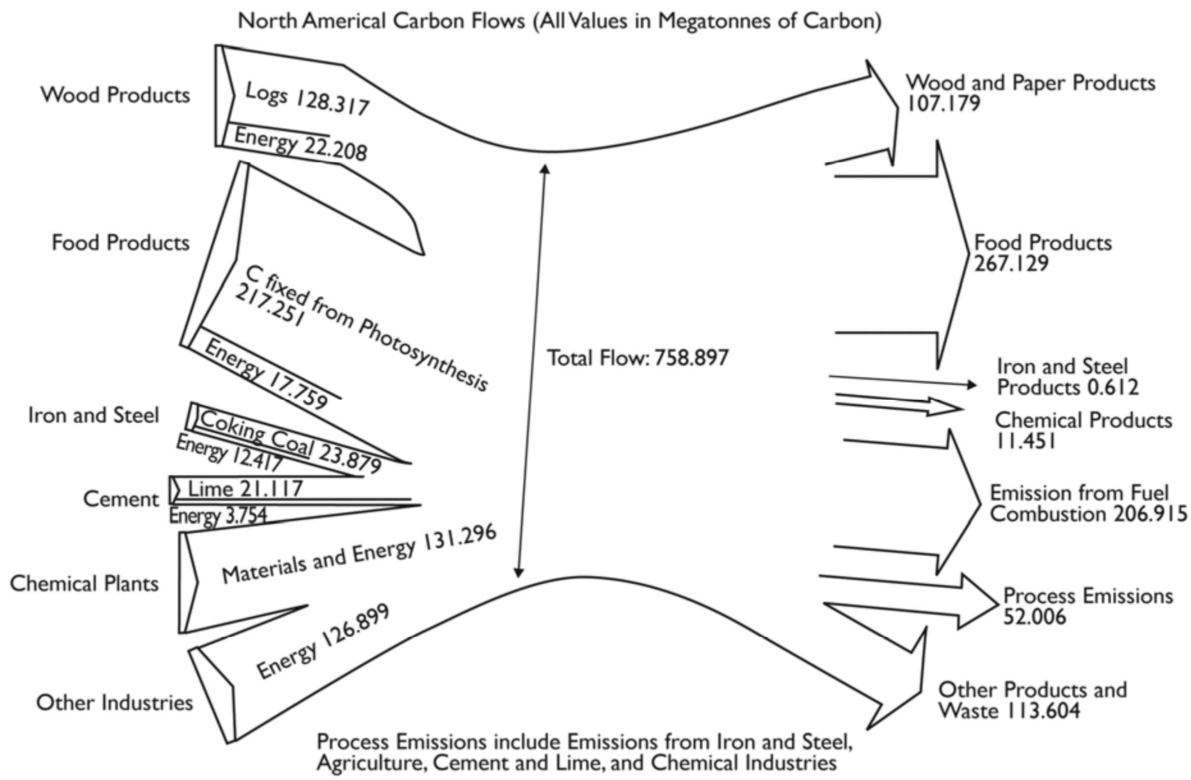


Fig. 8-2. Carbon flows for Canada, the United States and Mexico combined. Values in kilotons carbon can be converted to kilotons CO_2 equivalents by multiplying by 44/12, the ratio of carbon dioxide mass to carbon mass. Comparable diagrams for the individual countries are in Appendix 8A**.** *Source*: 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.

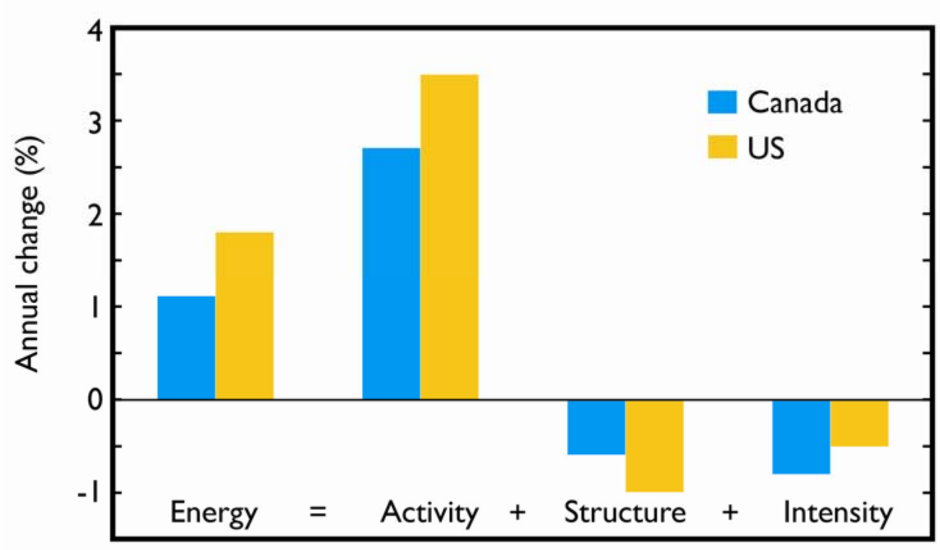
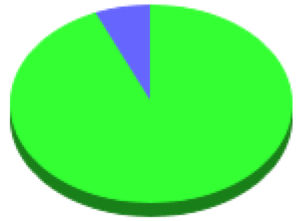


Fig. 8-3. Decomposition of energy use, manufacturing sector, 1990–1998. *Source*: IEA, 2004.

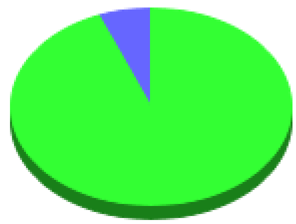
World

	Gas	Mt CO_2	%
■	CH_4	1,386.4	93.5
■	N_2O	97.2	6.5
	Total	**1,483.6**	



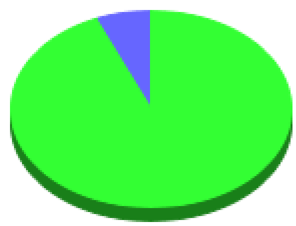
North America (w/ Mexico)

	Gas	Mt CO_2	%
■	CH_4	281.8	93.9
■	N_2O	18.2	6.1
	Total	**300.0**	



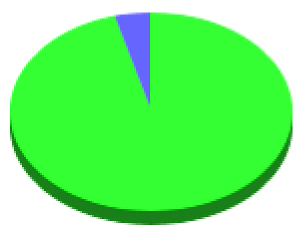
United States of America

	Gas	Mt CO_2	%
■	CH_4	227.7	93.6
■	N_2O	15.6	6.4
	Total	**243.3**	



Canada

	Gas	Mt CO_2	%
■	CH_4	23.2	95.8
■	N_2O	1.0	4.2
	Total	**24.2**	



Mexico

	Gas	Mt CO_2	%
■	CH_4	31.0	95.2
■	N_2O	1.6	4.8
	Total	**32.5**	

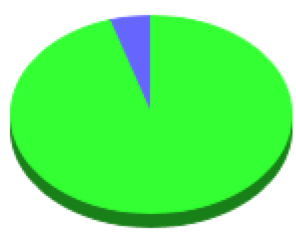


Fig. 8-4. GHG emissions by gas from waste in 2000. *Source*: Climate Analysis Indicators Tool (CAIT) Version 3.0 (Washington, D.C.: World Resources Institute, 2005).

Appendix 8A

Industry and Waste Management – Supplemental Material

This appendix presents diagrams of the carbon flows in Canada, the United States, and Mexico, respectively (Figs. 8A-1 through 8A-3). The numerical data in these figures are shown in thousands of metric tons of carbon, which can be converted into thousands of metric tons of CO_2 equivalents by multiplying the carbon values by 44/12 (i.e., the ratio of carbon dioxide mass to carbon mass). The combined carbon flows for all three nations are presented in Fig. 8-2 in Chapter 8 of this report.

Figure 8A-1. Carbon flows, Canada.

Figure 8A-2. Carbon flows, United States.

Figure 8A-3. Carbon flows, Mexico.

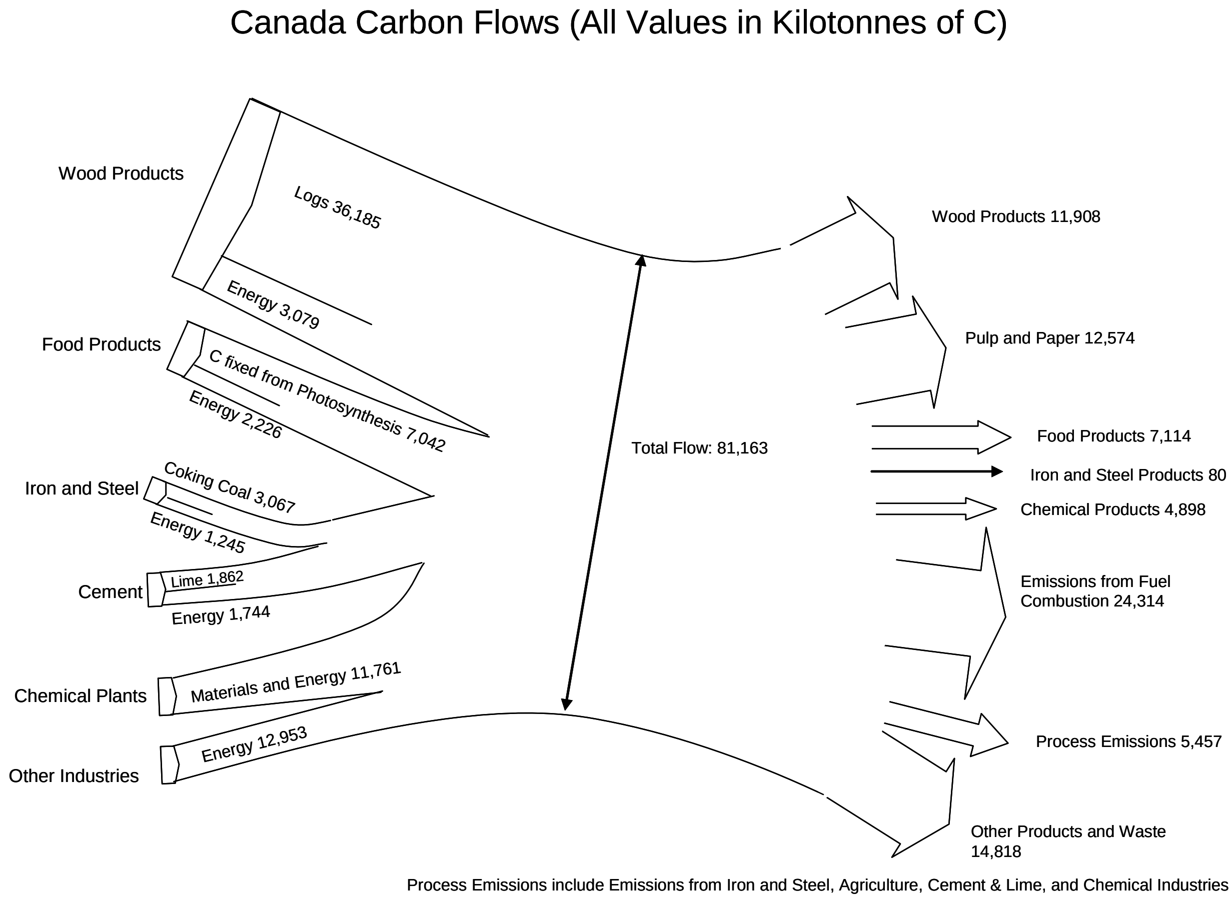


Fig. 8A-1. Carbon flows, Canada. *Source*: Energy data from Statistics Canada Industrial Consumption of Energy survey, conversion coefficients and process emissions from Environment Canada, *Canada GHG Inventory, 2002*. Production data from Statistics Canada, CANSIM Table 002-0010, Tables 303-0010, -0014 to -0021, -0024, -0060, Pub. Cat. Nos.: 21-020, 26-002, 45-002, Canadian Pulp and Paper Association on forestry products.

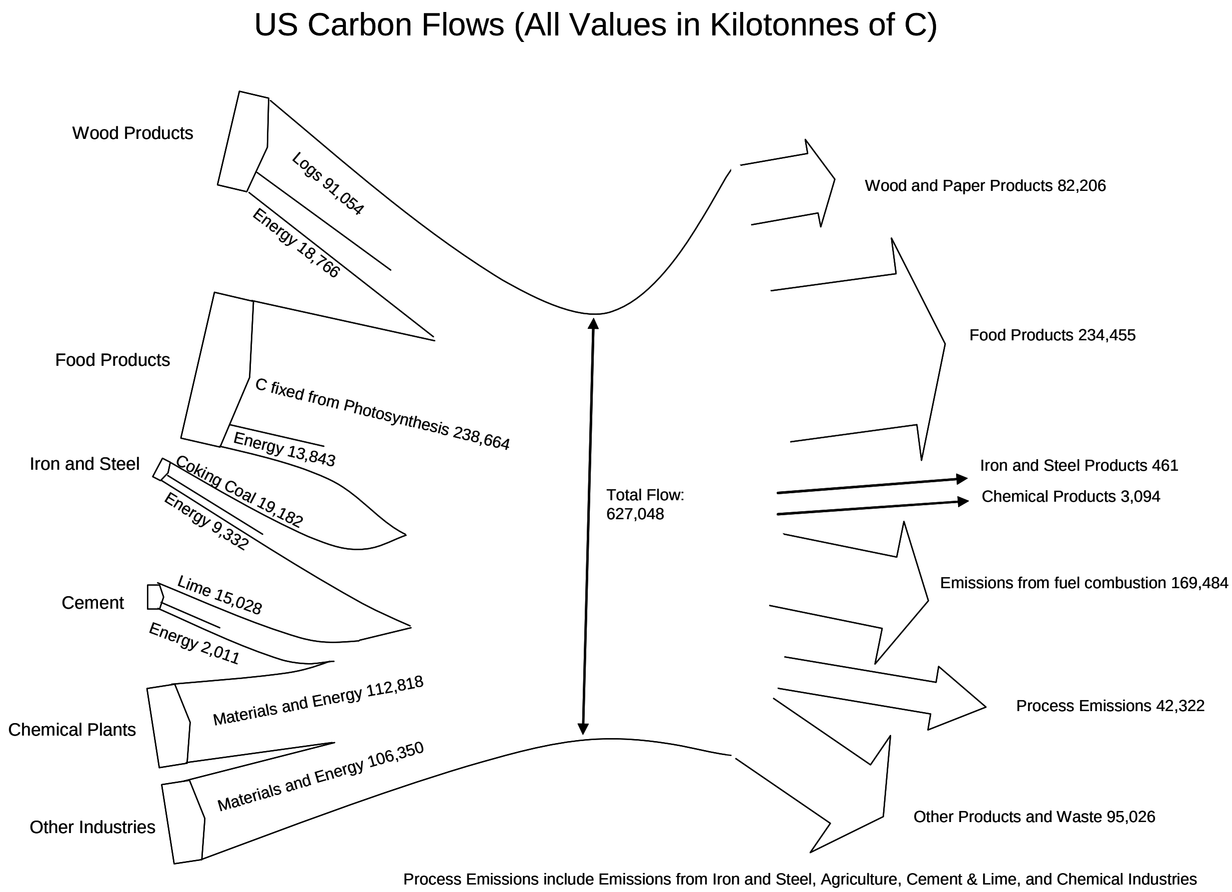


Fig. 8A-2. Carbon flows, United States. *Source*: Energy data from IEA Oil Information 2004, IEA Coal Information 2005, IEA Natural Gas Information 2004. Process emissions: EPA, U.S. Emissions Inventory. Production of forestry products: USDA Database; FO-2471000 and -2472010, U.S. Timber Production, 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.

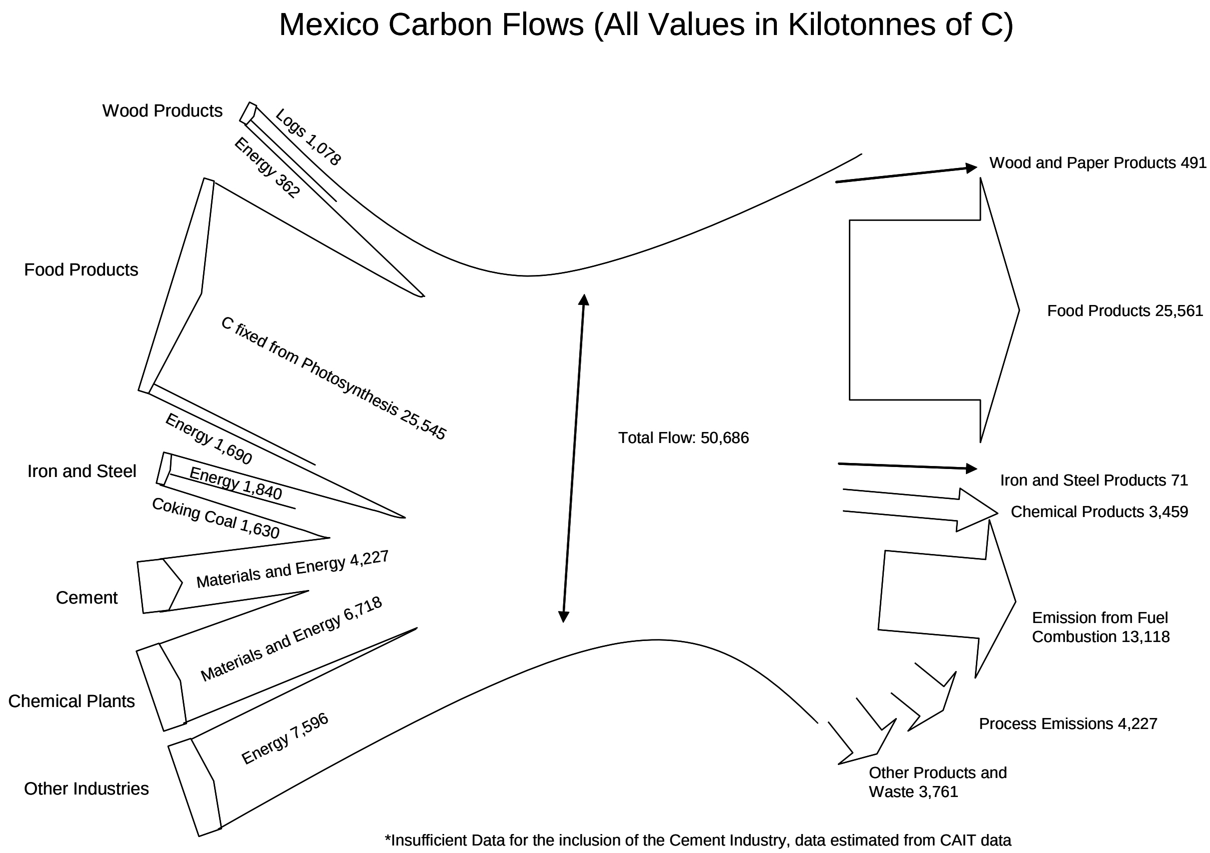


Fig. 8A-3. Carbon flows, Mexico. *Source*: Energy data from IEA Oil Information 2004, IEA Coal Information 2005, IEA Natural Gas Information 2004. Process emissions: EPA, U.S. Emissions Inventory. Production of forestry products: USDA Database; FO-2471000, -2472010, -2482000, -2483040, -6342000, -6342040. Production of organic products (e.g., food): USDA PS&D Official Statistical Results. Steel: International Iron and Steel institute, World steel in figures 2003.

Chapter 9. Buildings

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KEY FINDINGS

- The buildings sector of North America was responsible for annual carbon dioxide (CO_2) emissions of 671 Mt C in 2003, which is 37% of total North American CO_2 emissions and 10% of global emissions. U.S. buildings alone are responsible for more CO_2 emissions than total CO_2 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 CO_2 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 need to be supported by a portfolio of policy options that take advantage of synergies, avoid unduly burdening certain sectors and are cost effective.
- Because reducing CO_2 emissions from buildings is currently secondary to reducing building costs, continued improvement of energy efficiency in buildings and reduced CO_2 emissions from the building sector will require a better understanding of the total societal cost of CO_2 emissions as an externality of building costs, including the costs of mitigation compared to the costs of continued emissions.

In 2003, buildings were responsible for 615 Mt C[1] in the United States (DOE-EIA, 2005), 40 Mt C in Canada (Natural Resources Canada, 2005) and 17 Mt C in Mexico (SENER México, 2005), for a total of 671 Mt C in North America. According to the International Energy Agency, total energy-related emissions in North America in this year were 1815 Mt (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. U.S. buildings alone are responsible for more CO_2 emissions than total CO_2 emissions of any other country in the world except China (Kinsey *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 U.S. electricity consumption and 54% of natural gas consumption (DOE/EERE, 2005).[2] 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 (see Chapter 6). 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.

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[3] and up to 70% for homes.[4] 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)[5]. 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.

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

[1]Carbon dioxide emissions only.
[2]See Tables 1.1.6 and 1.1.7 in DOE/EERE (2005).
[3]Leadership in Energy and Environment Design (LEED) Gold Certification (USGBC, 2005).
[4]U.S. DOE Building America Program (DOE/EERE, 2006).
[5]A recent study estimates a potential of 711 GW generation capacity from rooftop installation of photovoltaic systems (Chaudhari *et al*., 2004).

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[6] of carbon per year in the United States, 1.7 metric tons[7] per year in Canada, and 0.6 metric tons[8] in Mexico (DOE/EIA, 2005; Natural Resources Canada, 2005; 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).[9] Energy consumption includes electricity as 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).[10] The equivalent amount of energy from natural gas or other fuels contributed about 52 g of carbon (DOE/EIA, 2005).[11] 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).[12]

Buildings-sector CO_2 emissions and the relative contribution of each end use are shown in Fig. 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).[13] 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).[14] Water heating is the second-highest energy consumer in the United States and Canada, while lighting is the second-highest source of carbon dioxide emissions, due to the higher emissions per unit of electricity compared to natural gas.

[6]U.S. residential sector emissions of 334 Mt CO_2 divided by 114 million households in 2004; the numerical value given for "tons of carbon" is for carbon dioxide emissions only.
[7]Canada residential sector emissions of 20.6 Mt CO_2 divided by 12.2 million households in 2003.
[8]Mexico residential sector emissions of 13.2 Mt CO_2 divided by 23.8 million households in 2004.
[9]U.S. commercial sector emissions per m^2 in 2003 times 500 m^2.
[10]U.S. emissions from electricity divided by delivered energy.
[11]U.S. emissions from electricity divided by delivered energy.
[12]See Table 1.5.4 and Summary Table 2 in DOE/EERE (2005).
[13]Does not include adjustment EIA uses to relieve differences between data sources.
[14]Table 1.2.3 and Table 1.3.3 in DOE/EERE (2005); available at http://buildingsdatabook.eere.energy.gov (2003 data).

Fig. 9-1. U.S. carbon emissions by sector and—for commercial and residential buildings—by end use.

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 U.S. households own an air conditioner; and, although air-conditioner ownership has been historically low Mexico,[15] sales of this equipment are now growing significantly, 14% per year over the past 10 years.[16] 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 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.

Residential and commercial buildings in the United States are responsible for 38% of CO_2 emissions from energy nationally and 33% 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 is comparable with that of Canada, about

[15]Air conditioners have typically been used only in the northern and coastal areas of Mexico.
[16]Air conditioner sales 1995–2004 from Asociacion Nacional de Fabricantes de Aparatos Domesticos (ANFAD).

40 GJ equivalent per person per year. This is about six times higher than in Mexico, where 7 GJ is consumed per person per year.

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 twice as many emissions as all other fuels combined in the United States and Mexico (2.2 and 2.1 times as much, respectively). In Canada, natural gas is on par with electricity (1.03 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.

Table 9-1. Carbon dioxide emissions from energy consumed in buildings.

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-m^2 (2200-ft^2) house requires about 20 metric tons of wood and creates 2 to 7 metric tons of construction waste (DOE/EERE, 2005).[17] 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.

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, 2005),[18] 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—the amount of living area per capita is increasing in all three countries in North America. On one hand, total population growth is

[17]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).

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

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, and 1.7% in Mexico. In the period from 1970 to 1990 it was 1.0%, 1.2%, and 2.5%, respectively.[19] 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[20]—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.[21] Per capita energy consumption generally grows with economic development, since wealthier people live in larger dwellings and use more energy.[22] 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. As a result 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 Stages, 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 U.S. single-family home has grown from 160 m^2 (1720 ft^2) for a house built in 1980 to 216 m^2 (2320 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).[23] Certain end uses once considered luxuries have now become commonplace. Only 56% of U.S. 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.

Table 9-2. Principal drivers of buildings emissions trends

[SIDEBAR 1 TEXT BOX HERE]

[19] *Source:* UN Department of Economic and Social Affairs.
[20] See household size statistics in Table 9-2.
[21] For example, whether biomass, natural gas or electricity is used for space heating and cooking.
[22] See Table 4.2.6 in DOE/EERE (2005).
[23] See Tables 2.1.6 and 2.2.1 in DOE/EERE (2005). Residential data are from 1981.

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 with 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.

Options for Management

A variety of alternatives exist 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 adequately curtail emissions growth 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[24]), nonprofit organizations, building owners and occupants.

- **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

[24]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.

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) Energy Star Appliances and Homes], public-private partnerships [such as the U.S. Department of Energy's (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, nongovernment organizations and professional societies (such as 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.

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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, but 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 home builders, providing research and development toward goals to decrease primary energy consumption by 30% for participating projects by 2007, and by 50% by 2015.

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, including carbon emissions? Energy resources in North America have been abundant and affordable, but externality 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 seriously consider a set of options, 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.

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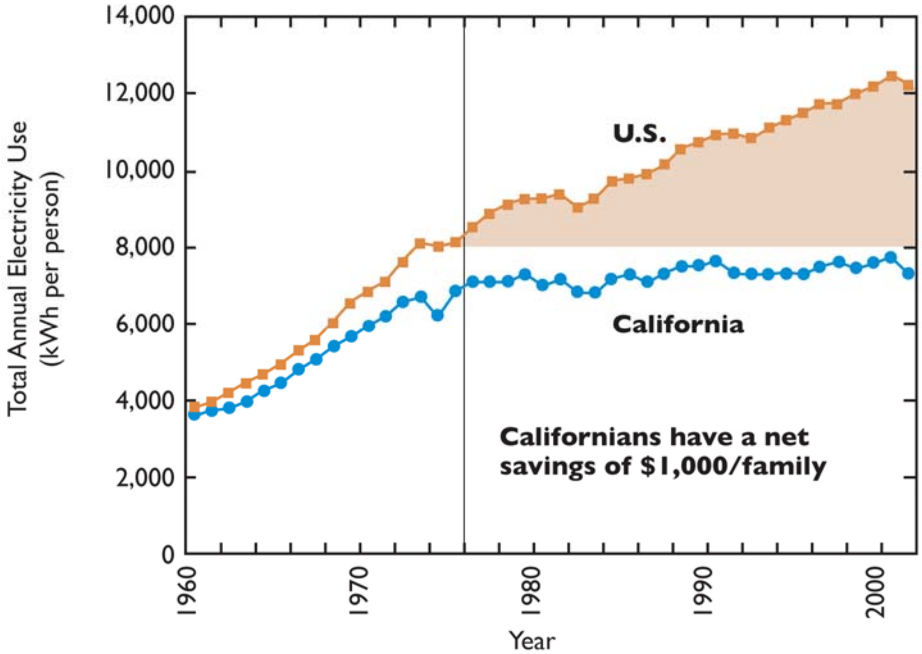
Electricity Consumption in the United States and in California

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

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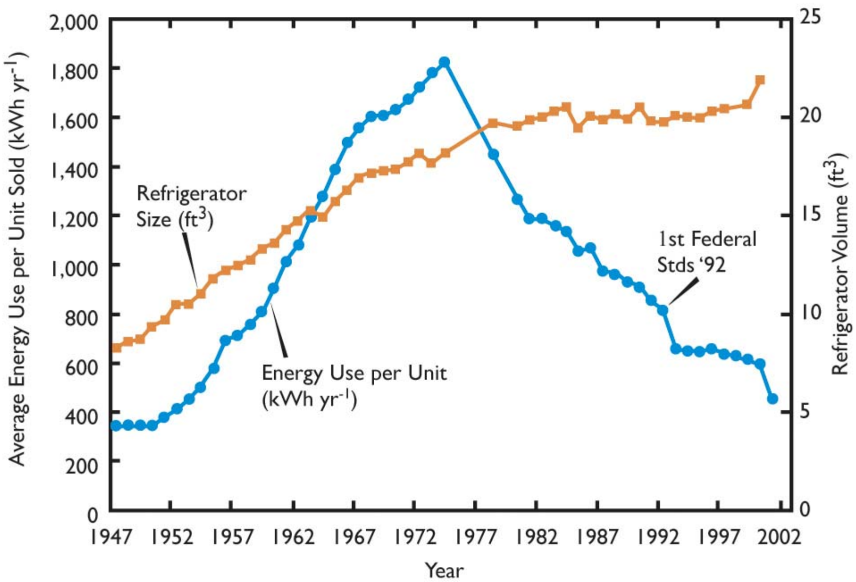
Impact of Efficiency Improvements

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

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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	3.5	0.1	0.1	3.7

Table 9-2. Principal drivers of buildings emissions trends

	United States		Canada		Mexico	
Driver	**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 $US 1995)	31.7	2.0%	23.0	1.8%	3.8	1.8%
Residential Floor space (billion m^2)	15.7	0.0%	1.5	2.4%	0.85	N/A
Commercial Floor space (million m^2)	6.4	0.6%	0.5	1.6%	N/A	N/A
Building Energy Emissions per GDP (g C/$US)	70	-0.5%	59	-0.9%	N/A	N/A

Source: Population - UNDESA; Household Size - UNDP; GDP - World Bank

Source: Floorspace - EIA-EERE (2005), Natural Resources Canada (2005). Mexican residential floor space estimated from Table 1.8 in CONAFOVI (2001)

Source: Emissions - EIA-EERE (2005), Natural Resources Canada (2005)

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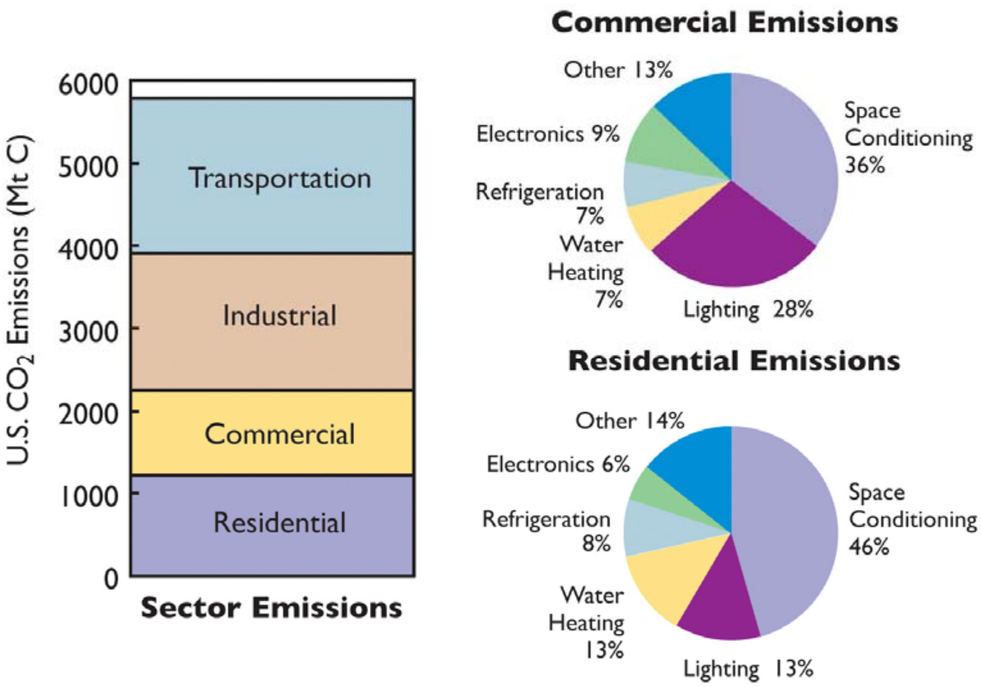

Fig. 9-1. U.S. carbon emissions by sector and—for commercial and residential buildings—by end use.

2

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