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 fuel is burned. Fossil fuels are composed primarily of compounds of hydrogen and carbon. 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 continuing to grow as population grows and demand for energy grows. Looking back from the end of 2005, fully half of the CO_2 released from fossil-fuel burning globally has occurred since 1980 (Figure 1).

Figure 1. Cumulative global emissions of CO_2 from fossil-fuel combustion and cement manufacture from 1751 to 2002.

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 manufacturing now releases less than 1% of the CO_2 released by fossil-fuel combustion. However, cement manufacturing is the largest anthropogenic (of human origin) 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 in 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 manufacturing in North America, and discusses some scenarios for emissions in the future. 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 that 38.4% of CO_2 emissions from North America come from enterprises whose primary business is to provide electricity and heat and another 30.8% 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 processes motivating their use.

Estimating CO_2 Emissions

If we have estimates of the consumption of fossil fuels, it is relatively straightforward to estimate the amount of CO_2 released to the atmosphere when they 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 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 products such as highway asphalt, lubricants, waxes, solvents, and plastics and thus may not soon be converted to CO_2. Some of these long-lived carbon-containing products will release the carbon they contain to the atmosphere as CO_2 during use or during processing of the materials as 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 ways they deal with the carbon in these carbon-containing 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, petroleum, 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 billion J for coal, 20 kg C per billion J for petroleum, and 15 kg C per billion J 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 kg C per billion J of coal (measured on a net heating value basis[1]), with a standard error of the mean at 2.09%. The value is slightly higher for lignite and brown coals (26.23 kg C per billion J ±2.33%, also shown in Figure 1). 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 from measures of fossil-fuel use. The differences between the values in Table 1 and those in Figure 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. To make them easier to distinguish, data for lignites and brown coals are shown on the left axis, and 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).

Table 1. A sample of the coefficients used for estimating CO_2 emissions from the amount of fuel burned (from IPCC, 1996).

Data on fossil-fuel production, trade, consumption, and so on 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

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

estimates of fuel consumption. All of the emissions estimates in this chapter are in terms of 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 countries like the United States—with good data on fuel production, trade, and consumption—the uncertainty in national emissions of CO_2 is probably on the order of ±5% or less. In fact, the U.S. Environmental Protection Agency (EPA) (2005) suggests its 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 its estimates for Canada are within –4 to 0 %. The Mexican National Report (Mexico, 2001) does not provide estimates of uncertainty, but our analyses using 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 are inclined to 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.

The Magnitude of National and Regional CO_2 Emissions

Figure 3 shows that from the beginning of the fossil-fuel era (1750 in these graphs) to the end of 2002, there were 93.5 Gt C released as CO_2 from fossil-fuel consumption (and cement manufacturing) 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 is 31.5 % of the global total. Among all countries, the United States, Canada, and Mexico rank as the first, eighth, and eleventh largest emitters of CO_2 from fossil-fuel consumption, respectively (for 2002) (Marland *et al.*, 2005). 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 manufacturing as a function of time, for the three countries of North America and for the sum of the

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

three. Figure 3a is for the United States, Figure 3b is for Canada, Figure 3c is for Mexico, and Figure 3d 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.*, 2005).

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

The long time series of emissions estimates illustrated in Figures 2 and 3 are from CDIAC (Marland *et al.*, 2005). 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, 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, http://unfccc.int). The latter two sets of estimates are based on data on actual fuel combustion 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. However, they do represent different manipulations of these 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. 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 earlier.

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 manufacturing 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 a correction is made for non-fuel usage of fossil-fuel resources, the conversion from mass or volume to energy units, and/or the way estimates of carbon content are derived. Because the national estimates from CDIAC do not include emissions from the non-fuel uses of

[3]IEA 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.

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 difference among the multiple sources: the emissions from Mexico in 1990. Losey (2004) has suggested, based on other criteria, that there is an inaccuracy in the UN energy data set for Mexican natural gas for the three-year period 1990–1992; these kinds of analyses result in reexamination of some of the fundamental data.

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

IEA (2005, p. 1.4) has systematically compared its estimates with those reported to the UNFCCC by the different countries, and it finds that the differences for most developed countries are within 5%. 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 the 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
- a different split between what is identified as emissions from energy and emissions from industrial processes.

Emissions by Month and/or State

With interest increasing in the details and processes of the global carbon cycle, there is also 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 there is considerable variation in United States emissions by month, and preliminary analyses by Gurney *et al.* (2005) reveal that proper recognition of this variability can be very important in some exercises to model the details of the global carbon cycle.

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

Figure 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).

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 United States 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. It 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. Monthly values are shown where estimates are justified by the availability of monthly data on fuel consumption or sales (from Andres *et al.*, 2005).

Emissions by Economic Sector

To understand how CO_2 emissions from fossil-fuel use enter and 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 in this brief discussion. 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 more detail at how the fuels are used and at the economic sectors in which the fuels are used and from which the CO_2 is emitted. This is the goal of the next four chapters of this volume.

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 additional 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 (Figure 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 such as climate, population density, and access to resources (Blasing *et al.*, 2005b; Neumayer, 2004).

Chapters 6 through 9 of this volume 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 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 numeric differences, however, the 4 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 50% of its electricity from coal, Mexico gets 73% from petroleum and natural gas, and Canada gets 60% from hydroelectric stations. Partially as a reflection of this difference, 40% of United States CO_2 emissions are from enterprises whose primary business is to generate electricity and heat, while this number is only 31% in Mexico and 23% in Canada (for 2002, from IEA, 2004). 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 International Energy Agency allows us to summarize CO_2 emissions for the 3 countries according to sectors that closely correspond to the sectoral division of chapters 6 through 9 (Table 4).

Figure 8. Per capita emissions of CO_2 from fossil-fuel consumption (and cement manufacturing) 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 manufacturing and gas flaring are not included) per unit of GDP for the United States, Canada, and Mexico and worldwide.

Figure 9. Per capita emissions of CO_2 from fossil-fuel consumption for the 50 U.S. states in 2000. To demonstrate the range of values, values have been rounded to whole numbers of metric tons 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).

CONCLUSION

There are a variety of reasons 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.

REFERENCES

Andres, R.J., D.J.Fielding, G. Marland, T.A.Boden, N. Kumar, and A.T. Kearney, 1999. Carbon dioxide emissions from fossil-fuel use, 1751-1950. Tellus 51:759-765.

Andres, R.J., J.S. Gregg, L.M. Losey, and G. Marland, 2005. Monthly resolution fossil-fuel-derived carbon dioxide emissions for the countries of the North American Carbon Program, Proceedings of the Seventh International Carbon Dioxide Conference, Bloomfield, Colorado, September, 2005, pp. 157-158.

Blasing, T. J., C.T. Broniak, and G. Marland, 2005a. The annual cycle of fossil-fuel carbon dioxide emissions in the United States. Tellus 57B: 107-115. (data available at http://cdiac.esd.ornl.gov)

Blasing, T.J., C. Broniak, and G. Marland, 2005b. State-by-state carbon dioxide emissions from fossil-fuel use in the United States 1960-2000. Mitigation and Adaptation Strategies for Global Change 10: 659-674.

Environment Canada, 2005. Canada's Greenhouse Gas Inventory: 1990-2003, National Inventory Report – April 15, 2005, Greenhouse Gas Division, Environment Canada.

EPA, 2005. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2003, EPA 430-R-05-003, United States Environmental Protection Agency, Washington D.C.

Gregg, J.S., 2005. Improving the temporal and spatial resolution of carbon dioxide emissions estimates from fossil-fuel consumption, A thesis submitted to the graduate faculty of the University of North Dakota, August, 2005, 404 pp. (data available at http://cdiac.esd.ornl.gov)

Gurney, K.R., Y.H Chen, T. Maki, S.R. Kawa, A. Andrews, and Z. Zhu, 2005. Sensitivity of atmospheric CO_2 inversion to seasonal and interannual variations in fossil-fuel emissions," J. Geophys. Res. 110 (D10), 10308.

IEA, 2005. CO_2 emissions from fuel combustion: 1971-2003. International Energy Agency, OECD/IEA, Paris.

IPCC (Intergovernmental Panel on Climate Change), 1997. revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (3 volumes), IPCC Technical Support Unit, Bracknell,UK.

Losey, L.M., 2004. Monthly and seasonal estimates of carbon dioxide emissions from fossil fuel consumption in Canada, Mexico, Brazil, The United Kingdom, France, Spain, Italy, and Poland. A thesis submitted to the graduate faculty of the University of North Dakota, May, 2004, 328 pp. (data available at http://cdiac.essd.ornl.gov)

Marland, G., T. Boden, and R.J. Andres, 1995. Carbon dioxide emissions from fossil fuel burning: emissions coefficients and the global contribution of eastern European countries. Időjárás 99:157-170.

Marland, G., T.A. Boden, and R.J. Andres. 2005. Global, Regional, and National CO_2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. (data available at http://cdiac.esd.ornl.gov)

Mexico, 2001. México: Segunda comunicación nacional ante la Convención Marco de las Naciones Unidas sobre el cambio climático. Comité intersecretarial sobre cambio climático, Secretaria de Medio Ambiente y Recursos Naturales (Semarnat), 374 pp., Mexico City.

Neumayer, E., 2004. National carbon dioxide emissions: geography matters. Area 36.1: 33-40.

Table 1. A sample of the coefficients used for estimating CO_2 emissions from the amount of fuel burned
(from IPCC, 1996)

Fuel	Emissions coefficient (kg carbon/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. 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
	U.S. EPA	1316	U.S. EPA	1478	U.S. EPA	1534
Canada	CDIAC	112	CDIAC	119	CDIAC	139
	IEA	117	IEA	136	IEA	145
	U.S. EPA	117	U.S. EPA	133	U.S. EPA	144
Mexico	CDIAC	99	CDIAC	96	CDIAC	100
	IEA	80	IEA	96	IEA	100
	U.S. EPA	81	U.S. EPA	96	U.S. EPA	NA

Notes:

These data have been multiplied by 12/44 to get the mass of carbon for the comparison here.

Many of these data were published in terms of the mass of CO_2.

Values for the United States, Canada and Mexico represent consumption data as reported by CDIAC (Marland *et al.*, 2005), IEA (2005), and by the National Reports to the United Nations Framework Convention on Climate Change [United States (EPA, 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 manufacturing and gas flaring are not included) per unit of GDP for the United States, Canada, and Mexico and worldwide

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 2002

Sector	United States	Canada	Mexico	North America
Energy extraction and conversion[a]	46.8	36.0	49.4	46.1
Transportation[b]	31.2	28.3	28.7	30.8
Industry[c]	11.0	16.8	13.2	11.6
Buildings[d]	11.0	18.9	8.8	11.6

[a]The sum of three IEA categories, "public electricity and heat production," "unallocated autoproducers," and "other energy industries." (IEA, 2004)

[b]IEA category "transport." (IEA, 2004)

[c]IEA category "manufacturing industries and construction." (IEA, 2004)

[d]IEA category "other sectors." (IEA, 2004)

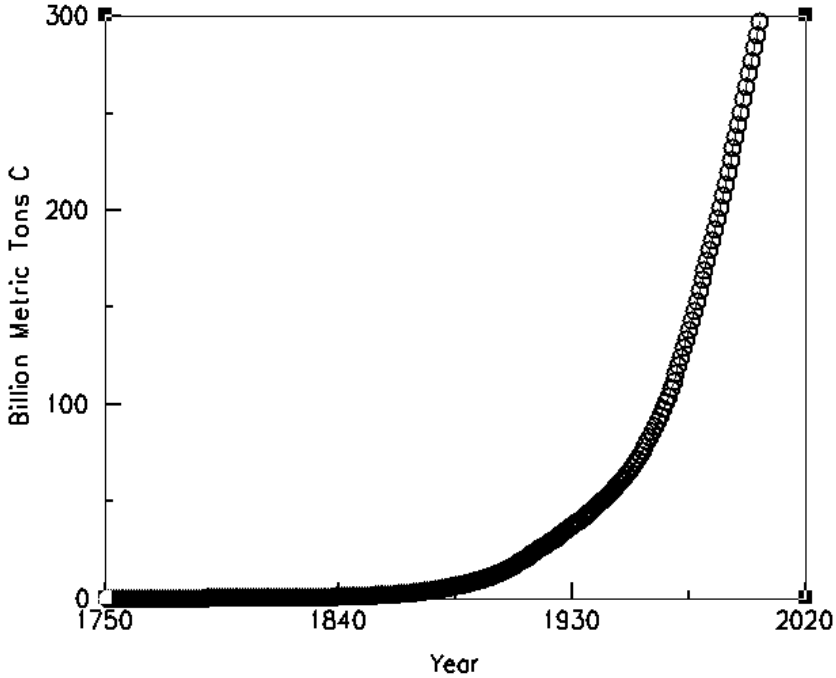
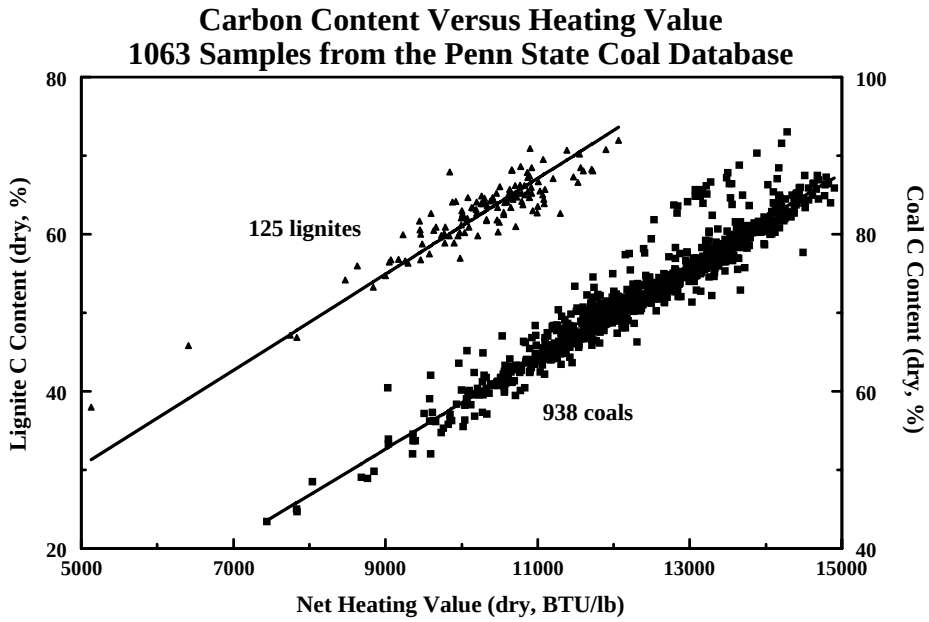


Figure 1. Cumulative global emissions of CO_2 from fossil-fuel combustion and cement manufacture from 1751 to 2002.



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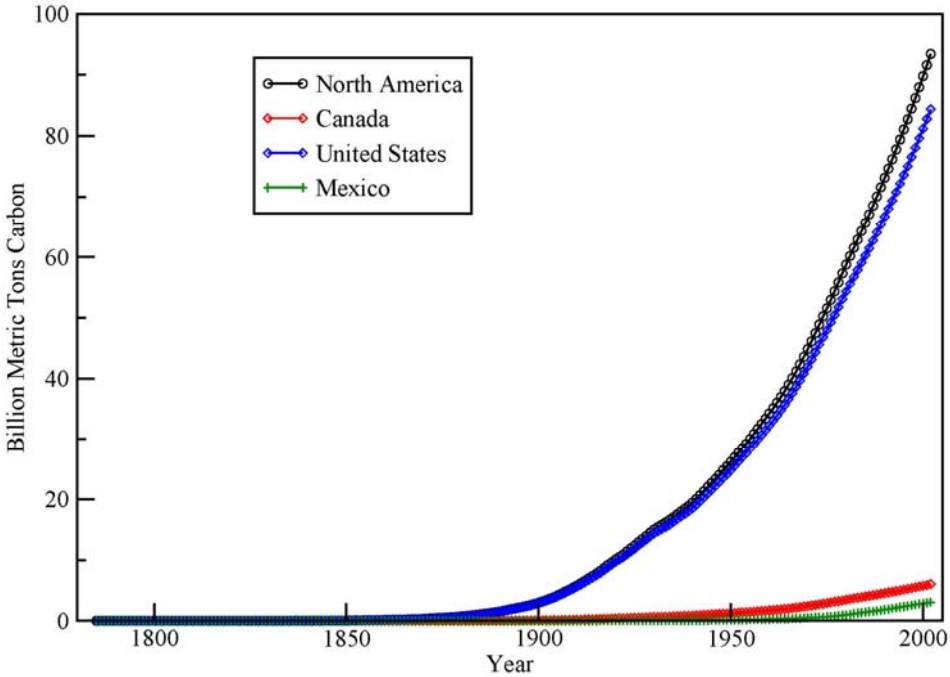

Figure 3. The cumulative total of CO_2 emissions from fossil-fuel consumption and cement manufacturing as a function of time, for the three countries of North America and for the sum of the three.

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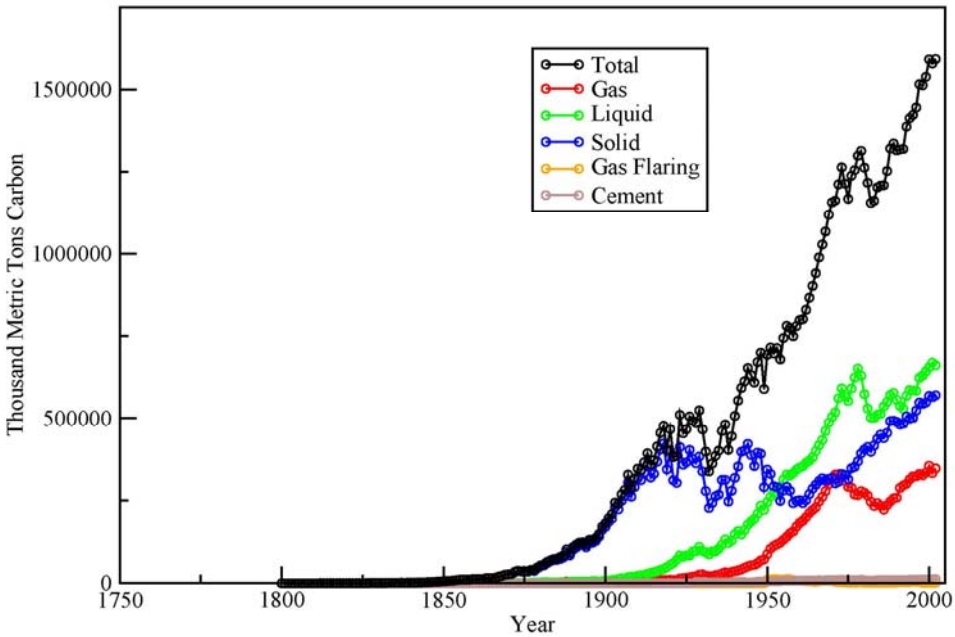

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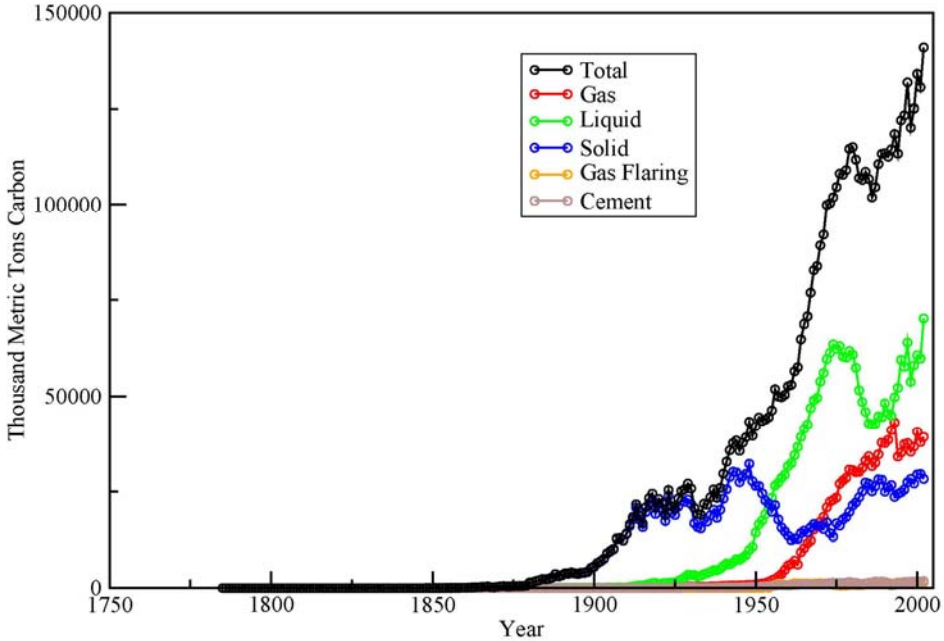

Figure 4a and 4b. Annual emissions of CO_2 from fossil-fuel use by fuel type. Figure 4a is for the United States, Figure 4b is for Canada, Figure 4c is for Mexico, and Figure 4d is for the sum of the three. Note that in order to illustrate the contributions of the different fuels, the four plots are not to the same vertical scale (from Marland et al. 2005).

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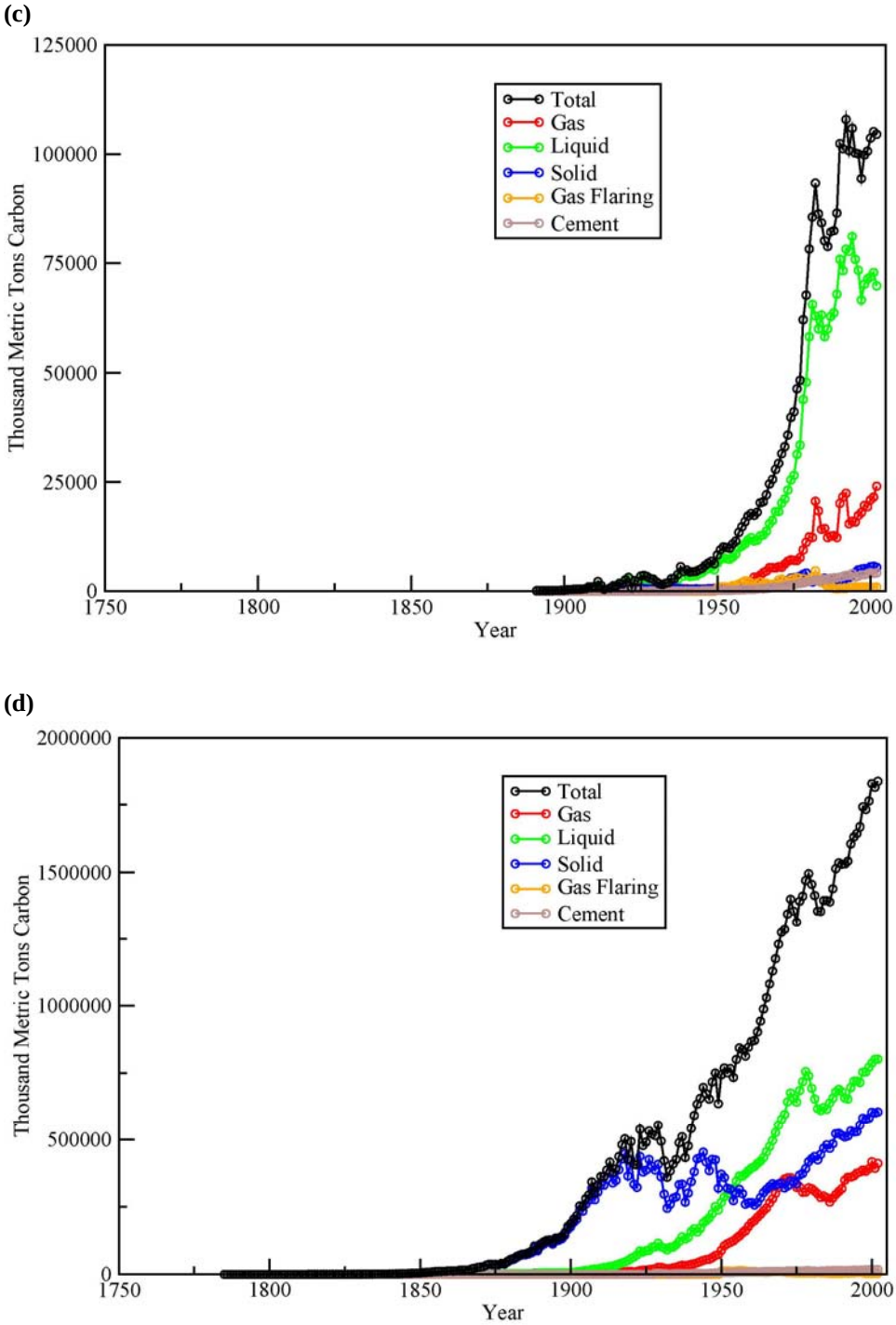

Figure 4c and 4d. Annual emissions of CO_2 from fossil-fuel use by fuel type.
Figure 4a is for the United States, Figure 4b is for Canada, Figure 4c is for Mexico, and Figure 4d is for the sum of the three. Note that in order to illustrate the contributions of the different fuels, the four plots are not to the same vertical scale (from Marland et al. 2005).

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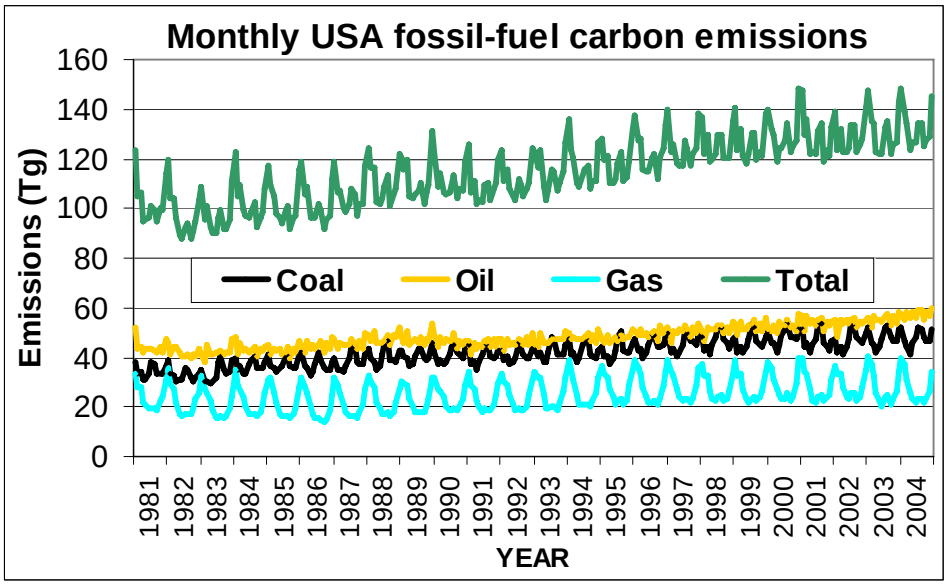
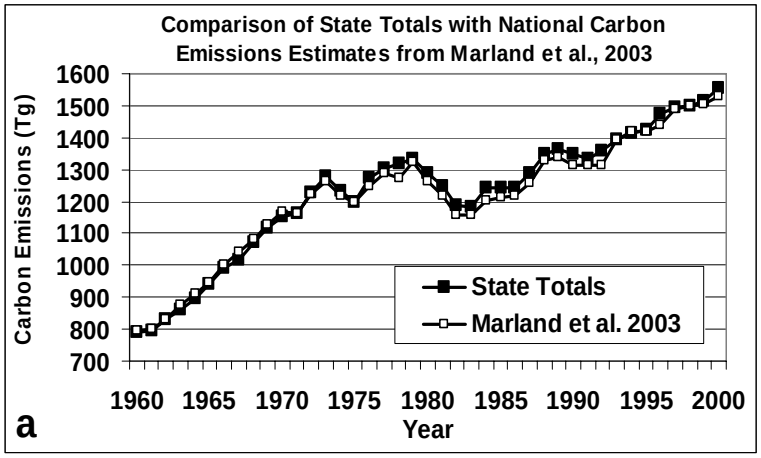
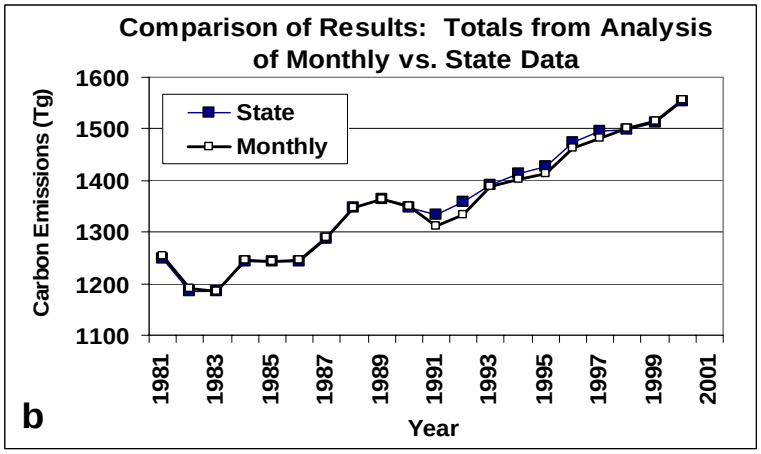


Figure 5. Emissions of CO_2 from fossil-fuel consumption in the United States, by month. Emissions from cement manufacturing are not included (from Blasing et al. 2005a).



Estimates from DOE data on fuel consumption by state (black squares) vs estimates based on the UN Statistics Office data on apparent fuel consumption for the full United States (open squares).



Estimates based on DOE data on fuel consumption in the 50 U.S. states (black squares) vs estimates based on national fuel consumption for each of the 12 months (open 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).

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

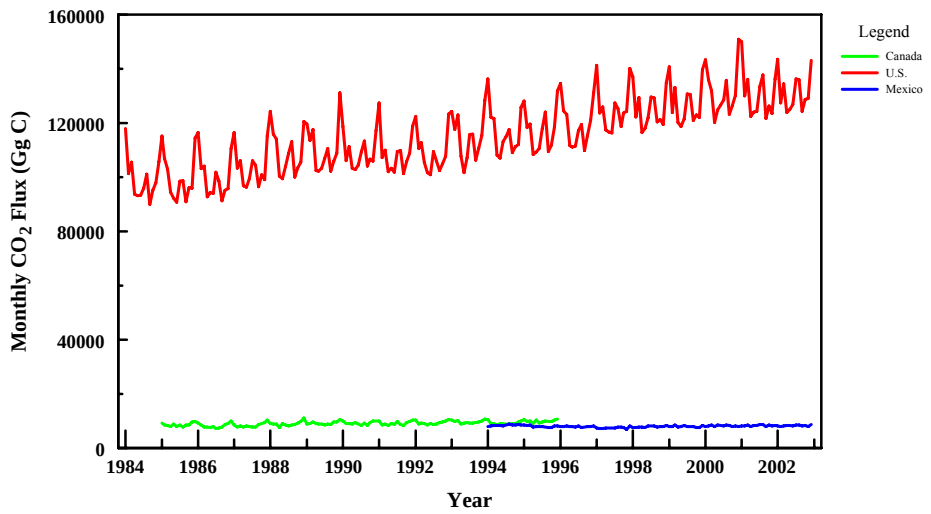


Figure 7. CO_2 emissions from fossil-fuel consumption in North America, by month. Monthly values are shown where estimates are justified by the availability of monthly data on fuel consumption or sales (from Andres et al. 2005).

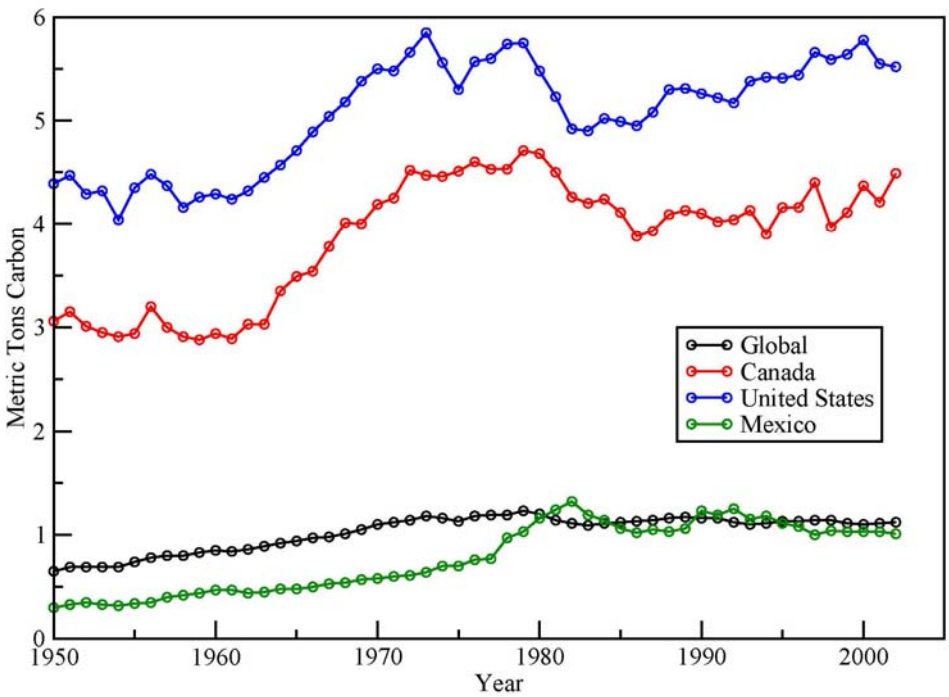


Figure 8. Per capita emissions of CO_2 from fossil-fuel consumption (and cement manufacturing) in the United States, Canada, and Mexico and for the global total of emissions (from Marland et al. 2005).

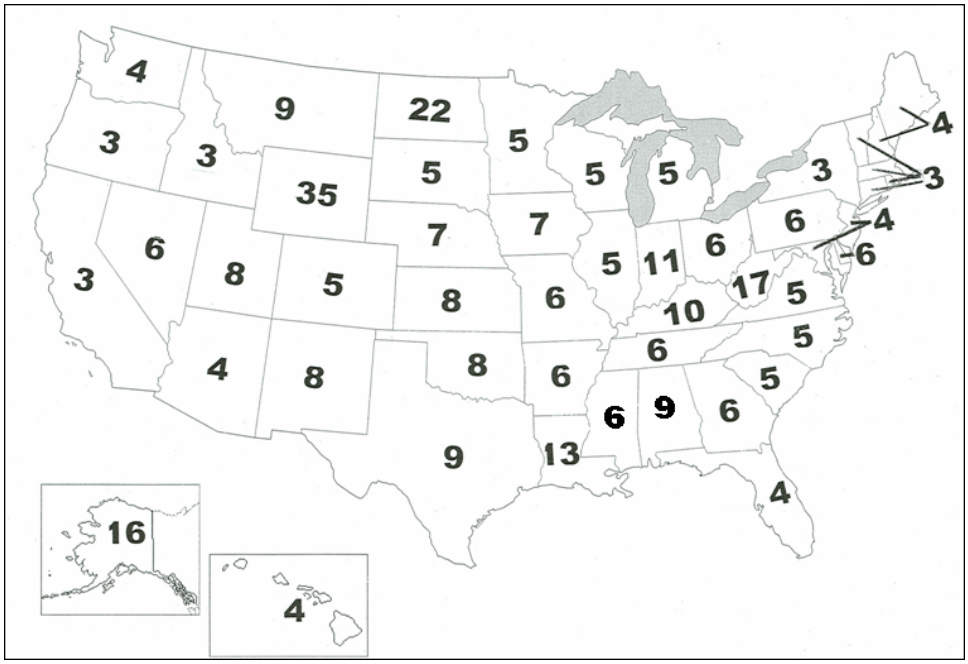


Figure 9. Per capita emissions of CO_2 from fossil-fuel consumption for the 50 US states in 2000. To demonstrate the range of values, values have been rounded to whole numbers of metric tons per capita. A large portion of the range for extreme values is related to the occurrence of coal resources and 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, extraction of primary energy sources and their conversion into energy delivery forms (solid, liquid, gas, and electric) in North America released on the order of 2800 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 most (90–95%) of North America's energy extraction and conversion emissions.
- Carbon dioxide emissions from energy extraction and conversion in North America are currently rising.
- The principal drivers behind carbon emissions from energy extraction and conversion are (1) the growing appetite for energy services such as comfort, convenience, mobility, and labor productivity, so closely related to economic and social progress, and (2) the market competitiveness of fossil energy sources compared with alternatives.
- Emissions from energy extraction and conversion in North America are projected to increase in the future. Projections vary among the countries, but increases approaching 50% or more appear likely. Projections for the United States., for example, indicate that CO_2 emissions from electricity generation alone will rise to about 3314 Mt CO_2 by 2025, a 45% increase over emissions in 2003, 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 extraction and conversion in North America appear dependent upon 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.
- Research and development priorities for managing carbon emissions from energy extraction and conversion 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 energy sources associated with carbon emissions.

INTRODUCTION

A significant component of the North American carbon cycle is the extraction of primary energy sources and their conversion into energy delivery forms (solid, liquid, gas, and electric) because both energy resource extraction and energy conversion activities in North America emphasize fossil fuels and their associated emissions of greenhouse gases. This chapter summarizes the knowledge bases related to 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, as when industry practices co-generation as an energy-efficiency strategy, and biomass energy extraction/conversion is directly related to agriculture and forestry. In addition, in addressing options and measures, policy alternatives are often directed at both supply and demand responses, i.e., involving not only emission reductions from supply systems 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 extraction (e.g., mining and oil/gas production) and conversion (e.g., electricity generation and refining) are one of the “big three” sectors accounting for most of total emissions from human systems, along with industry and transportation. The largest share of total emissions from energy supply (not including energy end use) are from (a) coal and other fossil fuel use in producing electricity and (b) fossil fuel conversion activities such as oil refining. Other emission sources are less well-defined but generally small, such as 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.

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, it seems more appropriate to report inventories by country in whatever forms are available than to try to construct a North American inventory that is consistent across all three major countries (which appears unattainable). 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 other fossil fuel production (Environment Canada, 2003).

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, CO_2 emissions from "energy industries" were 47.3 Mt CO_2; from electricity generation they totaled 101.3 Mt CO_2, and "fugitive" emissions from oil and gas production and distribution were between 1.9 and 2.6 Mt of CH_4, depending on the estimated "emission factor" (Government of Mexico, 2001). An estimate for, say, 2003 might be constructed by increasing these totals in proportion to 1998–2003 gross domestic product growth.

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 2003 account for 2409 Mt of CO_2, or 41% of a national total of 5870 (EIA, 2004). Emissions from oil refining, natural gas transmission, and other fossil energy supply activities are also substantial, though harder to document because they are grouped with aggregate industrial emissions. Oil refineries are known to be a major source of methane as well as CO_2 emissions; natural gas supply systems emit methane as well. For example, 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 scale (AAG, 2003).

Carbon Sinks Associated with Energy Extraction and Conversion

Generally, energy extraction and conversion are based heavily on mining hydrocarbons from carbon sinks accumulated over millions of years, but carbon sequestration occurs in connection with energy production from biomass during plant growth. Limited strictly to energy sector applications, the total contribution of these sinks to the North American carbon cycle is potentially nontrivial but probably relatively small.

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. In some cases reinforced by policy conditions, 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. 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 from 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., Figure 6.1). National trends and drivers are as follows.

Figure 6.1. United States CO_2 emissions from electricity generation, 1990–2003, in million metric tons CO_2 (Source: EIA, 2004).

Canada

Canada is the only Annex I country that 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 would increase 2000–2020 from about 90 Mt of CO_2 equivalent to about 150, while emissions from fossil fuel production would remain relatively stable at about 100 Mt.

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, 2005b).

United States

The Energy Information Administration (EIA, 2005a) projects that CO_2 emissions from electricity generation in the United States will rise between 2003 and 2025 from about 2286 to about 3314 Mt, a 45% increase, with three-quarters of the increase associated with greater coal use in electric power plants. EIA projects that technology advances could reduce the increase by as much as 7%. Projections of other emissions from energy supply systems appear to be unavailable.

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 resource extraction, conversion, and energy production (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). Examples include very real 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 currently available or 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 wedges 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 wedge 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 some 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 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, although the prospects remain speculative at this time.

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 between about 100 and 325 Gt. 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 summary of policy options because 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).

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

[TEXT BOX HERE]

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. 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 global 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. It estimated that the cost of emission reducing technologies for power generation, compared with coal-fired power, range from 3 to 8 cents/kWh, except for more expensive photovoltaic and solar thermal technologies. According to the IPCC report, based on DOE/EIA analyses in 2000, advanced coal generation technologies such as integrated gasification combined cycle technology would

cost between 3 and 4 cents/kWh in the United States without CO_2 capture. CO_2 capture would raise costs to between 5 and 7 cents. Nuclear energy costs would rise 5 to 6 cents/kWh. Solar energy options would rise from 3 to 5 cents for wind power, 4 to 8 cents for biomass, and 9 to 25 cents for photovoltaics and thermal solar. 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 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, while a $50 price would reduce emissions by 17 to 19%, or 306 to 332 Mt CO_2. Both cases assume a doubling of United States government appropriations for cost-shared clean energy research, design, and development.

For carbon capture and sequestration, IPCC (2006) concluded that this option could contribute 15 to 55% to global mitigation between now and 2100 if technologies develop as projected in relatively optimistic scenarios and very large-scale geological carbon sequestration is publicly acceptable. Under these assumptions, the cost is projected 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; see page 3-19 in that report) 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,

- other 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 wedges of available technology to transform the capacity to manage carbon emissions from energy supply systems, if that is a high priority for North America.

REFERENCES

AAG, 2003. Global Change and Local Places: Estimating, Understanding, and Reducing Greenhouse Gases, Association of American Geographers, Cambridge: Cambridge University Press.

Caldeira, K., *et al.*, 2005. Climate Change Technology Exploratory Research. Working paper. Washington, DC: Climate Policy Center.

EIA, 2004. Annual Energy Review, 2004. Washington: Energy Information Administration.

EIA, 2005a. Annual Energy Outlook, 2005. Washington: Energy Information Administration.

EIA, 2005b. International Energy Outlook, 2005. Washington: Energy Information Administration

Environment Canada, 2003. Canada's Greenhouse Gas Inventory, 1990–2003 (see: http://www.ec.gc.ca/pdb/ghg/inventory_report/2003_report/ts_2_e.cfm).

Environment Canada, 2005. The Green Lane: Climate Change: The Greenhouse Gas Emissions Outlook to 2020 (see: http://www.ec.gc.ca/climate/overview_2020-e.html)

Government Accountability Office (GAO), 2004. Climate Change: Analysis of Two Studies of Estimated Costs of Implementing the Kyoto Protocol. Washington: January 2004.

Government of Canada, 2005. Project Green: Moving Forward on Climate Change, April 2005.

Government of Mexico, 2001. Second National Communication. Submitted to UNFCCC by the Secretaria de Medio Ambiente y Recursos, Naturales. Mexico City.

Hoffert, M. I. *et al*., 2002. Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet, *Science*, 298 (1 November 2002): 981–87.

Interlaboratory Working Group, 1997. Scenarios of U.S. Carbon Reductions. Prepared by Lawrence Berkeley National Laboratory (LBNL-40533) and Oak Ridge National Laboratory (ORNL/CON-444) for the U.S. Department of Energy.

Interlaboratory Working Group, 2000. Scenarios for a Clean Energy Future. Prepared by Lawrence Berkeley National Laboratory (LBNL-44029) and Oak Ridge National Laboratory (ORNL/CON-476) for the U.S. Department of Energy.

IPCC, 2001. Climate Change, 2001: Mitigation. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

IPCC, 2006. Carbon Dioxide Capture and Storage. IPCC Special Report. Cambridge University Press.

Lewis, N., 2005. Global Energy Perspective, Paper presented to the U.S. DOE Laboratory Energy and Development Working Group (LERDWG), Washington, DC: September 2005.

National Academy of Sciences (NAS), 1992. Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base. Washington.

National Academy of Sciences (NAS), 1999. Our Common Journey: A Transition Toward Sustainability. Washington, DC: National Academy Press.

National Commission on Energy Policy, 2004. Ending the Energy Stalemate: A Bipartisan Strategy to Meet America's Energy Challenges, Washington, DC, NCEP, December 2004.

National Laboratory Directors, 1997. Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions. Prepared for the U.S. Department of Energy.

Office of Technology Assessment (OTA), 1991. Changing By Degrees: Steps to Reduce Greenhouse Gases, OTA-0-482. Washington.

Pacala, S. and R. Socolow, 2004. Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies, *Science*, 305 (13 August 2004): 968–72.

Pew Center on Global Climate Change, 2002. Climate Change Mitigation in Developing Countries. Report prepared by W. Chandler, *et al.* Washington.

Tremblay, A., 2004. Greenhouse Gas Emissions – Fluxes and Processes: Hydroelectric Reservoirs and Natural Environments, New York: Springer.

U.S. Climate Change Technology Program, (2005). *Strategic Plan: Draft for Public Comment*, September 2005. (see http://www.climatetechnology.gov/stratplan/draft/index.htm).

U.S. Department of Energy, 2004. National Energy Policy/Overview/Canada, in *Energy Trends*. (see http://energytrends.pnl.gov/Canada/ca004.htm).

Wilbanks, T., 1992. "Energy Policy Responses to Concerns about Global Climate Change," in S. Majumdar and others, eds., *Global Climate Change: Implications, Challenges and Mitigation Measures.* Easton, PA: Pennsylvania Academy of Sciences: 452–70.

[BEGIN TEXTBOX]

THE CARBON MITIGATION INITIATIVE AT PRINCETON

In September 2000, British Petroleum and Ford Motor Company established a partnership with the Princeton Environmental Institute to explore pathways for capturing and sequestering a large fraction of the carbon emissions from fossil fuels, with $20 million in industry funding over a ten-year period. This program assesses the potential of low-carbon energy technologies, studies the feasibility of long-term underground carbon storage, considers impacts of carbon dioxide on the carbon cycle, and analyzes possible pathways for carbon mitigation.

[END TEXTBOX]

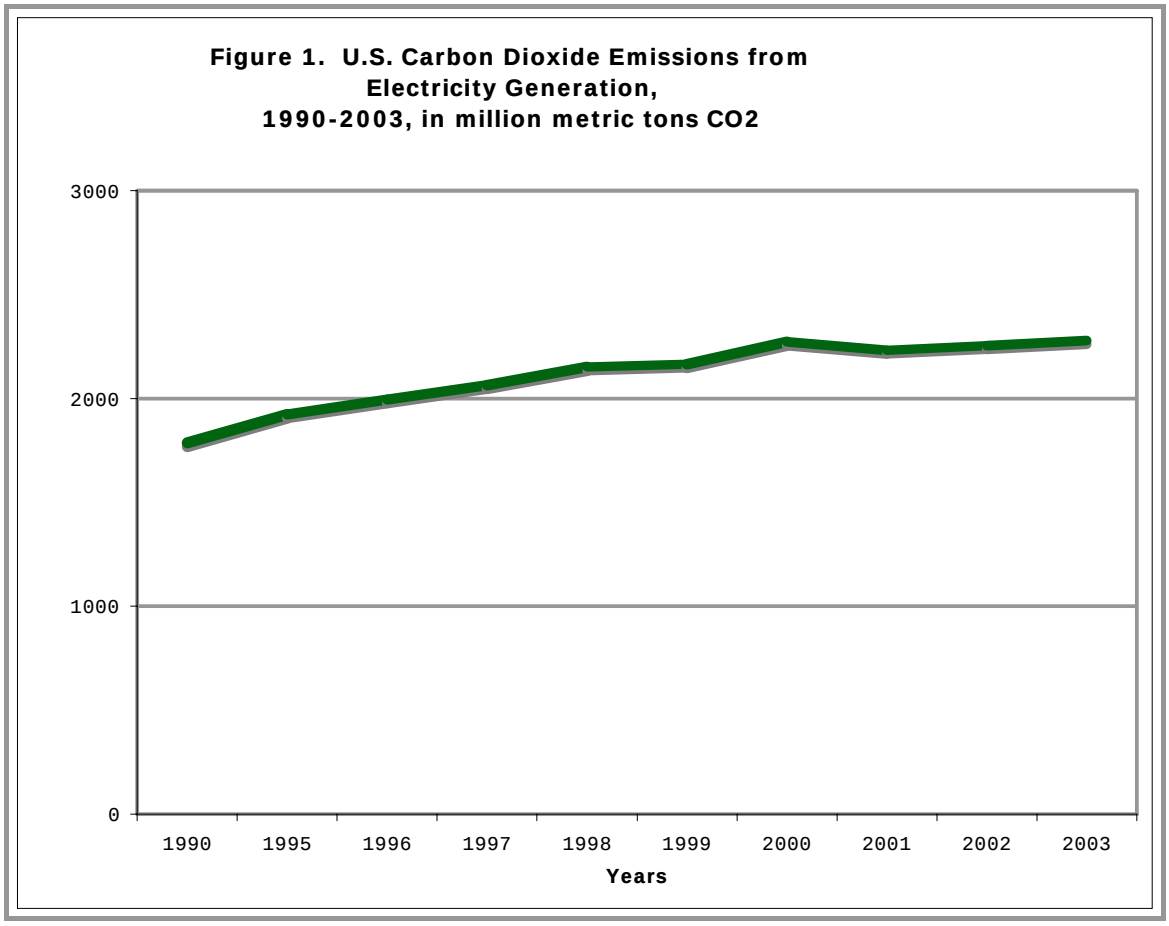

Figure 6.1. United States CO_2 emissions from electricity generation, 1990–2003, in million metric tons CO_2 (Source: EIA, 2004).

Chapter 7. Transportation

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KEY FINDINGS

- The transportation sector of North America released 2120 Mt of CO_2 into the atmosphere in 2003, 37% of the total CO_2 emissions from worldwide transportation activity and about 22% of total global CO_2 emissions.
- Transportation energy use in North America and the associated CO_2 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 2151 Mt CO_2 in 2003 to 3149 Mt CO_2 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 CO_2 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 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. There is also a need for improved data, particularly the provision of data to complete the country-specific histories of emissions from transportation, and a consistent description of the accuracy of each country's data.

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% (5.36 Gt yr^{-1}) of total global carbon dioxide emissions from the combustion of fossil fuels (24.2 Gt CO_2) 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% (an estimated 2120 Mt CO_2 in 2005) of the total carbon emissions from worldwide transportation activity (an estimated 5846 Mt CO_2 in 2005) (Fulton and Eads, 2004).

Transportation activity is driven 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 reflected in carbon dioxide emissions from the North American transportation sector (Table 7-1).

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

Table 7-1. Carbon dioxide 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 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, 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. 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 minor in comparison to the volume of CO_2 emissions. For example, in the United States, mobile sources including international bunker fuels produced only 132,000 Mt CH_4 (or 2.8 Mt CO_2 equivalents) in 2003. This is a tiny fraction of the 1770.4 Mt of CO_2 emitted by the transportation sector (see Tables 2-3, 2-4, and 2-7 in U.S. EPA, 2005). This chapter will therefore address only the carbon dioxide emissions from transportation activities.

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 (Fig. 7-1).

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, 2003.

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, 7-3b, and 7-3c. Freight activity by mode in Canada, Mexico, and 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. 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, 88% was by light-duty personal vehicles, roughly equally split between passenger cars and light trucks (Fig. 7-4a) (motorcycle pkt, about 0.2% of the total, is included with passenger car). Air travel claims almost 9%; 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 large 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

In all three countries, transportation energy use has grown substantially and relatively steadily. 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 is also visible, especially with respect to energy use for air travel.

Figure 7-5a and 7-5b. Evolution of transport energy use in Mexico and 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 were effective in restraining 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 and 7-6b. Transport CO_2 emissions in Canada and the United States, 1990–2003.

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). With rising per capita income comes increased vehicle ownership, 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).

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 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).

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 (2005). 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 does in the IEO 2005 Reference Case projection, carbon dioxide emissions would increase from 2151 Mt CO_2 in 2003 to 3149 Mt CO_2 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.

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 CO_2 emissions from transportation vehicles to 2050 by regions, WBCSD reference case projection.

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. 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 dioxide emissions by 10% from 826 Mt C in the reference case to 744 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 (CAFÉ) 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 1,419 Mt of CO_2 emissions, then a 10% reduction amounts to 142 Mt CO_2. 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 $21/t CO_2.

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 (510 Mt CO_2) 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 (246 Mt CO_2), or an implied cost of $12/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 sugar cane or cellulose or liquid hydrocarbon fuels produced via biomass gasification and synthesis, appear to be a promising near- and

long-term option, while hydrogen could become an important energy carrier after 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 up 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). 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 7-4). The study's premises assumed no change in the year 2000 distribution and efficiency 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). 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 (5) 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.

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 1752 Mt CO_2 in 1997 to 2567 Mt CO_2 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 569 Mt CO_2 to 1998 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.

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. The North American Transportation Statistics project made a start at producing comprehensive and consistent estimates for all three countries. However, there are many items of missing data, and the country-specific time series are incomplete. 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. A consistent description of the accuracy of each country's data is also needed.

The most pressing research need is for comprehensive, consistent, and rigorous assessments of carbon emissions mitigation potential for North America. The lack of such studies for North America parallels a similar dearth of 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.

Highly promising technologies for reducing transportation GHG emissions include hybrid vehicles, plug-in hybrid vehicles capable of accepting electrical energy from the grid, and 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.

REFERENCES

(CIA) Central Intelligence Agency, 2005: *The World Factbook*, http://www.cia.gov/cia/publications/factbook , Washington, DC, November 8.

(CBO) Congressional Budget Office, 2003: "The Economic Costs of Fuel Economy Standards Versus a Gasoline Tax," Congress of the United States, Washington, DC, December.

Davis, S.C. and S.W. Diegel, 2004: *Transportation Energy Data Book: Edition 24.* ORNL-6973, Oak Ridge National Laboratory, Oak Ridge, Tennessee, December.

Fulton, L. and G. Eads, 2004: "IEA/SMP Model Documentation and Reference Case Projection." World Business Council for Sustainable Development, http://www.wbcsd.ch/web/publications/mobility/smp-model-document.pdf , July.

General Motors Corporation, Argonne National Laboratory, ExxonMobil and Shell, 2001: *Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems: North American Analysis, vol. 2.* Published by Argonne National Laboratory, Argonne, Illinois, June.

Government of Canada, 2005. *Moving Forward on Climate Change: A Plan for Honouring our Kyoto Commitment*, available at www.climatechange.gc.ca, Ottawa, Canada.

Greene, D.L. and A. Schafer, 2003: *Reducing Greenhouse Gas Emissions from U.S. Transportation*. Pew Center on Global Climate Change, Arlington, Virginia, May.

Greene, D.L., P.D. Patterson, M. Singh and J. Li, 2005: "Feebates, Rebates and Gas-guzzler Taxes: A Study of Incentives for Increased Fuel Economy." *Energy Policy*, **33**(6), 757-776.

Harrington, W. and V. McConnell, 2003: *Motor Vehicles and the Environment*. RFF Report, Resources for the Future, Washington, DC, April.

(IEA) International Energy Agency, 2005: *World Energy Outlook 2005*. OECD, Paris.

(IEA) International Energy Agency, 2004: *Biofuels for Transport*. OECD, Paris.

(IEA) International Energy Agency, 2001: *Saving Oil and Reducing CO_2 Emissions in Transport*, OECD, Paris.

(ILWG) Interlaboratory Working Group, 2000: *Scenarios for a Clean Energy Future*. ORNL/CON-476, LBNL-44029, Oak Ridge National Laboratory, Oak Ridge, TN, Lawrence Berkeley National Laboratory, Berkeley, CA, November.

Marland, G., T. Boden, and R.J. Andres, 2005: *Global CO_2 Emissions from Fossil Fuel Burning, Cement Manufacture and Gas Flaring, 1751-2002*, http://cdiac.esd.ornl.gov/ftp/ndp030/global.1751_2002.ems , November 8.

Moomaw, W.R. and J.R. Moreira, 2001: "Technological and Economic Potential of Greenhouse Gas Emissions Reduction." Chapter 3 in Metz, Davidson, Swart and Pan, eds., *Climate Change 2001: Mitigation*, Cambridge University Press, Cambridge, UK.

Nakićenović, N., A. Grűbler, and A. McDonald, 1998: *Global Energy Perspectives*, Cambridge University Press, Cambridge, UK.

(NAS) National Academy of Sciences, 2004: *The Hydrogen Economy*, National Academies Press, Washington, DC.

(NAS) National Academy of Sciences, 2002: *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards*, National Academy Press, Washington, D.C.

(NATS) North American Transportation Statistics, 2005: Various tables, found at http://nats.sct.gob.mx/lib/series , a joint project of the U.S. Bureau of Transportation Statistics, Statistics Canada and Instituto Nacional de Estadistica Gegrafica Informatica (INEGI), Mexico.

(NRCan) Natural Resources Canada, 2006. "Comprehensive Energy Use Data Base Tables," Transportation Sector, Table 1 Secondary Energy Use by Source, Table 8, GHG Emissions by Transportation Mode, available on the Internet at http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/trends_tran_ca.cfm.

(NRTEE) National Round Table on the Environment and the Economy, 2005: *Economic Instruments for Long-term Reductions in Energy-based Carbon Emissions*. Renouf Publishing Co., Ltd., Ottawa, Ontario, Canada.

Patterson, P., D. Greene, E. Steiner, S. Plotkin, M. Singh, A. Vyas, M. Mintz, D. Santini, S. Folga, J. Moore, P. Reilly-Roe, K. Cliffe, R. Talbot, P. Khannna, V. Stanciulescu, 2003: *Joint DOE/NRCan Study of North American Transportation Energy Futures*. Energy Efficiency and Renewable Energy, U.S. Department of Energy, Washington, DC, May, available at www.eere.energy.gov/ba/pdfs/final_**2050**_pres.pdf .

Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, D.C. Erbach, 2005. *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*, DOE/GO-102995-2135, U.S. Department of Energy, Washington, D.C., April.

Rodriíguez, H.M., 2005: "Perspectivas del Uso de los Hidrocarburos a Nevel México." Presentation, *Subsecretario de Hidrocarburos*, Mexico City, Mexico, April 14.

(U.S. DOE) U.S. Department of Energy, 2005: *Hydrogen, Fuel Cells and Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plann*. DOE/GO-102003-1741, Energy Efficiency and Renewable Energy, available at www.eere.energy.gov , January.

(U.S. DOE/EIA) U.S. Department of Energy, Energy Information Administration, 2005a: *Annual Energy Review 2004*. DOE/EIA-0384(2004), Washington, DC, August. . Also available on line at www.eia.doe.gov .

(U.S. DOE/EIA)U.S. Department of Energy, Energy Information Administration, 2005b: *International Energy Outlook 2005*. DOE/EIA-0484(2005), Washington, DC.

(U.S. DOE/EIA) U.S. Department of Energy, Energy Information Administration, 2003: *Analysis of S.139, the Climate Stewardship Act of 2003*. SR/OIAF/2003-02, Washington, DC, June.

(U.S. DOT) U.S. Department of Transportation, 1998: *Transportation and Global Climate Change: A Review and Analysis of the Literature*. Federal Highway Administration, Washington, DC, June.

(U.S. EPA) U.S. Environmental Protection Agency, 2005: *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*. EPA 430-R-05-003, Office of Atmospheric Programs, Washington, DC, April 15.

Wang, M.Q., 2005: Argonne Expert Addresses Energy and Environmental Impacts of Fuel Ethanol. *TransForum*, vol. 5, no 2, Transportation Technology R&D Center, Argonne National Laboratory, Argonne, Illiniois, November.

Weiss, M.A., J.B. Heywood, E.M. Drake, A. Schafer and F.F. AuYeung, 2000. "On the Road in 2020", Energy Laboratory Report #MIT EL 00-003, Energy Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts, October.

Williams, R.H., 2005: *CO_2 Capture and Storage Strategies for Coal and Biomass to Reduce GHG Emissions for Synfuels*. Princeton Environmental Institute, Princeton University, Princeton, New Jersey, March.

(WBCSD) World Business Council for Sustainable Development, 2004: *Mobility 2030*. The Sustainable Mobility Project, Geneva Switzerland, available at www.wbcsd.org .

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

	Carbon dioxide emissions ($Mt\ CO_2$)
North America	2151
Canada	1865
United States	169
Mexico	117

Note: Summarized from Table 7-3 in this chapter.

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 CO_2)
Gasoline	20,923	1,314
Diesel/distillate	7,344	475
Jet fuel/kerosene	2,298	251
Residual	681	53
Other fuels	124	5
Natural gas	926	36
Electricity	36	3
Unalloc./error	466	0
Total	32,798	2,137
United States		
Gasoline	18,520	1,146
Diesel/distillate	6,193	393
Jet fuel/kerosene	1,986	229
Residual	612	48
Other fuels	50	1
Natural gas	748	35
Electricity	20	3
Unalloc./error	466.2	
Total	28,595.2	1,855
Sources: U.S. EPA, 2005, Tables 3-7 and 2-17; Davis and Diegel, 2004, Tables 2.6 and 2.7.		
Canada		
Gasoline	1,337	96
Diesel/distillate	704	51
Jet fuel/kerosene	206	16
Residual	66	5
Other fuels	17	1
Natural gas	178	0
Electricity	12	0
Unalloc./error	0	
Total	2,518	169
NRCan, 2005, Tables 1 and 8.		
Mexico		
Gasoline	1,066	72
Diesel/distillate	447	31
Jet fuel/kerosene	106	7
Residual	4	0
Other fuels	57	3
Natural gas	1	0
Electricity	4	
Unalloc./error		
Total	1,685	114
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. Electricity is assumed to produce no carbon emissions in end 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 CO_2)
Road	25,830	1,698
Air	2,667	194
Rail	751	50
Waterborne	1,386	68
Pipeline	990	57
	0	84
Total	31,624	2,151
United States		
Road		
Light vehicles	17,083	1,113
Heavy vehicles	5,505	350
Air	2,335	171
Rail	655	43
Waterborne	1,250	58
Pipeline/other	986	47
Internatl./Bunker		84
Total	27,814	1,865
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	87
Heavy vehicles	491	46
Air	226	16
Rail	74	6
Waterborne	103	8
Pipeline/other		7
Total	2,126	169
Source: NRCan, 2005; Tables 1 and 8.		
Mexico		
Road	1,518	102
Light vehicles		
Heavy vehicles		
Air	107	7
Rail	22	2
Waterborne	33	2
Electric	4	4
Total	1,684	117
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 CO_2 emissions from transportation vehicles to 2050 by regions, WBCSD reference case projection

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
OECD North America	1995.6	2119.7	2285.0	2447.4	2594.4	2706.1	2814.8	2917.9	3021.1	3125.6	3232.5
OECD Europe	1146.3	1224.1	1314.7	1395.7	1438.1	1474.6	1510.7	1525.5	1540.2	1554.9	1569.7
OECD Pacific	489.2	499.5	521.9	542.2	560.5	574.4	589.0	603.7	620.1	637.7	656.4
FSU	176.9	203.7	234.1	274.3	324.2	361.1	401.2	444.0	484.4	523.2	561.5
Eastern Europe	84.1	92.7	103.3	115.6	130.2	142.0	154.6	172.2	191.9	214.4	240.4
China	251.9	314.8	394.9	488.8	599.0	702.7	826.8	967.8	1130.0	1316.2	1530.0
Other Asia	360.6	412.5	480.0	554.6	639.4	715.8	806.1	913.1	1037.7	1182.5	1350.1
India	137.6	163.9	199.6	242.1	292.0	338.8	395.2	457.8	534.2	628.1	743.5
Middle East	215.3	236.7	261.5	288.6	323.5	355.2	387.0	417.3	447.1	476.5	505.6
Latin America	348.2	397.8	467.0	543.1	630.5	703.1	792.0	892.2	1008.6	1141.2	1290.2
Africa	159.4	181.0	211.7	248.8	293.7	337.2	378.1	419.0	464.3	516.8	579.5
Total—All regions	**5364.9**	**5846.3**	**6473.6**	**7141.4**	**7825.4**	**8411.1**	**9055.5**	**9730.3**	**10479.7**	**11317.1**	**12259.4**

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 ($Mt\ CO_2$) 2000	2015	2030	2015	2030
Research, development and demonstration					
Light-duty vehicles (LDVs)	1061	11[b]	38[b]	7[b]	23[b]
Heavy trucks	294	11[b]	24[b]	2[b]	4[b]
Commercial aircraft	196	11[b]	27[b]	1[b]	3[b]
Efficiency standards					
Light-duty vehicles	1061	9	31	6	18
Heavy trucks	294	9	20	2	3
Commercial aircraft	196	9	22	1	2
Replacement and alternative fuels					
Low-carbon replacement fuels (~10% of LDV fuel)	100	30	100	2	7
Hydrogen fuel (All LDV fuel)	1061	1	6	1	4
Pricing policies					
Low-carbon replacement fuels (~10% of LDV fuel)	100	30	100	2	6
Carbon pricing (All transportation fuel)	1792	3	6	3	6
Variabilization (All highway vehicle fuel)	1355	8	12	6	9
Behavioral					
Land use and infrastructure (2/3 of highway fuel)	903	5	10	3	5
System efficiency (25% LDV fuel)	265	2	5	0	1
Climate change education (All transportation fuel)	1792	1	2	1	2
Fuel economy information (All LDV fuel)	1061	1	2	1	1
Total	**1792**			**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.]

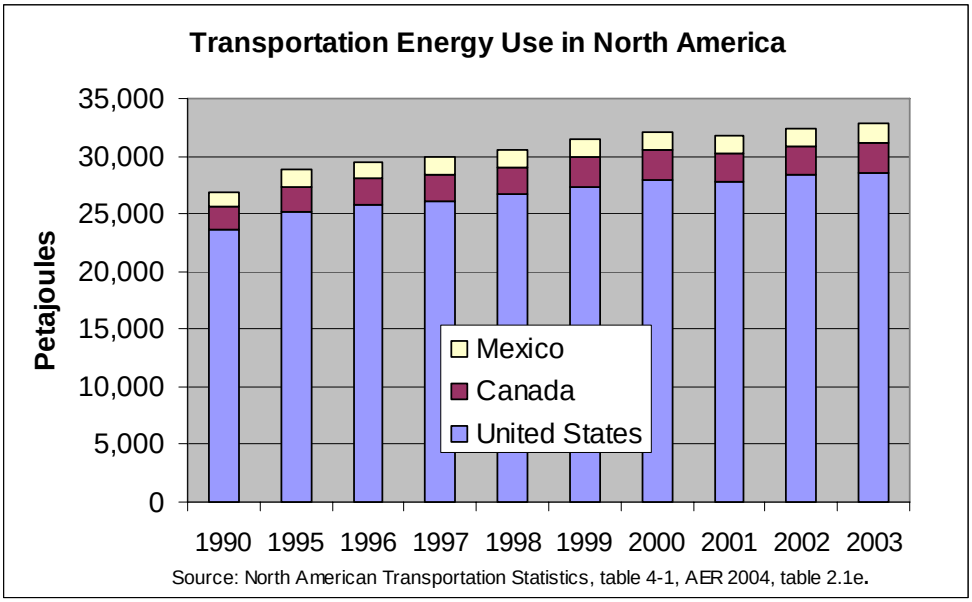

Fig. 7-1. Transportation energy use in North America, 1990–2003.

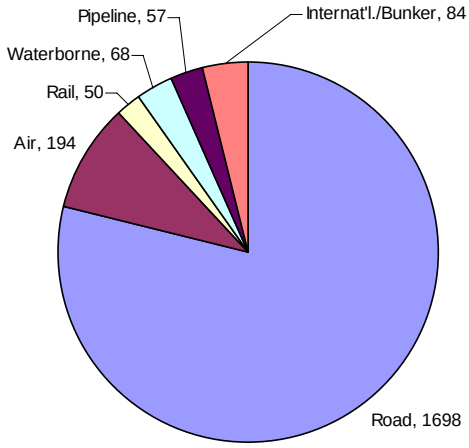

Fig. 7-2. North American carbon emissions from transportation by mode (million metric tons CO_2) 2003. *Source*: Table 7-3, this chapter.

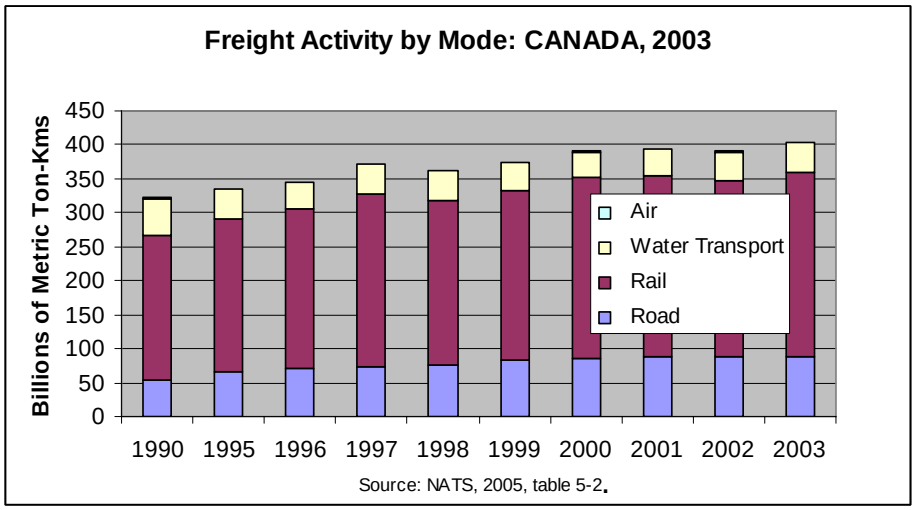

Fig. 7-3a. Freight activity by mode in Canada, Mexico, and the United States.

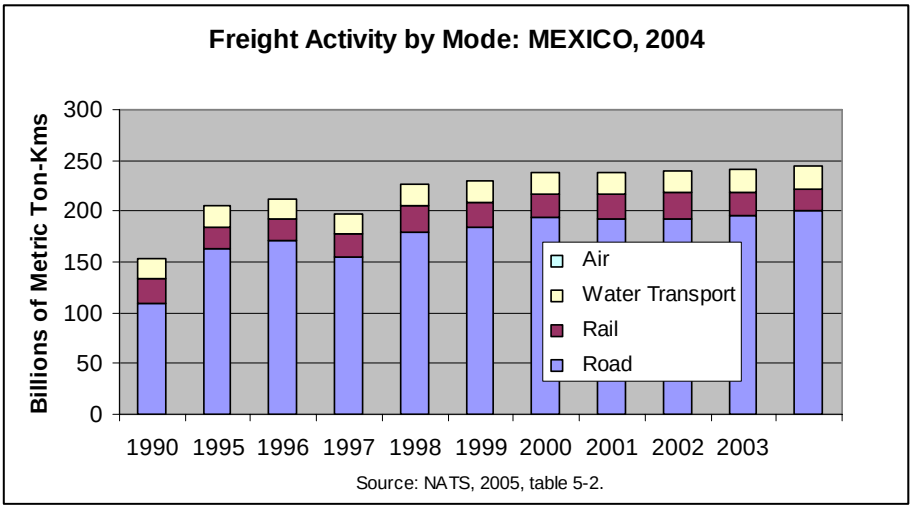

Fig. 7-3b. Freight activity by mode in Canada, Mexico, and the United States.

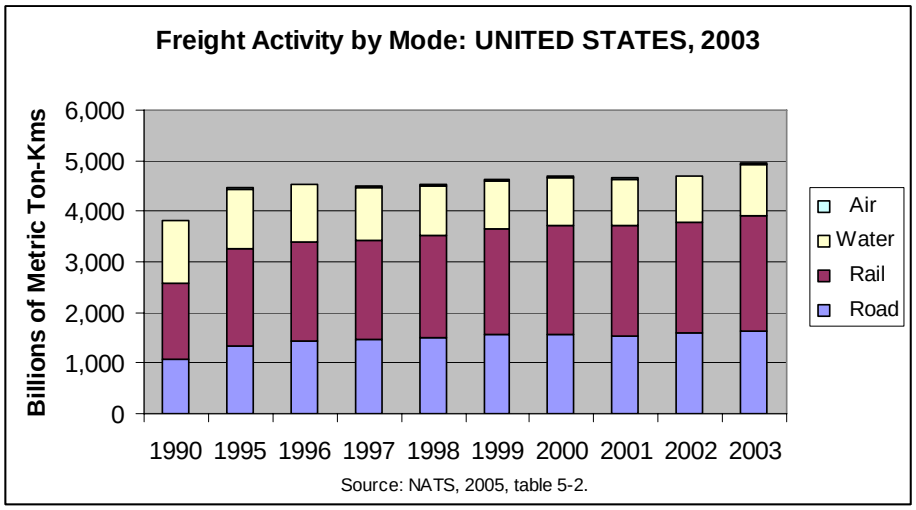

Fig. 7-3c. Freight activity by mode in Canada, Mexico and the United States.

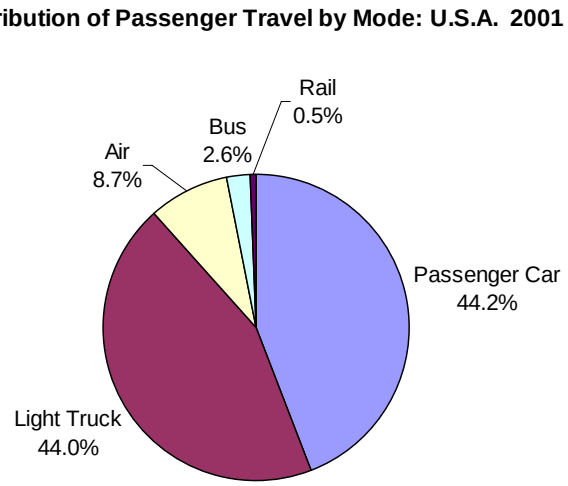

Fig. 7-4a. Distribution of passenger travel in the United States by mode. *Source*: Table 8-1 in NATS, 2005.

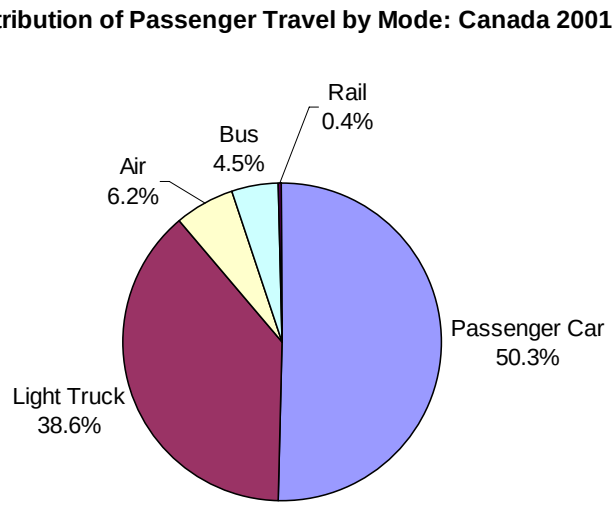

Fig. 7-4b. Distribution of passenger travel by mode in Canada. *Source*: Table 8-1 in NATS, 2005.

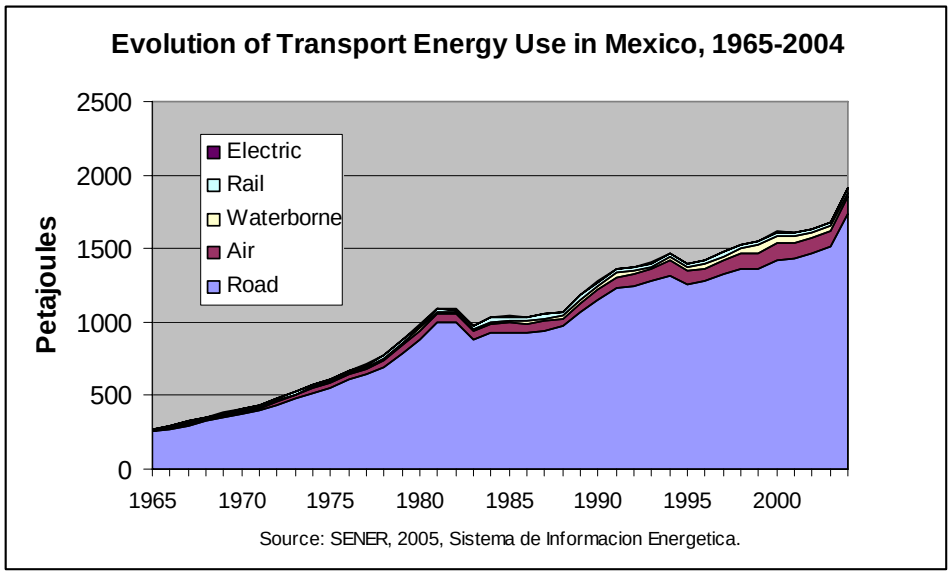

Fig. 7-5a. Evolution of transport energy use in Mexico and the United States.

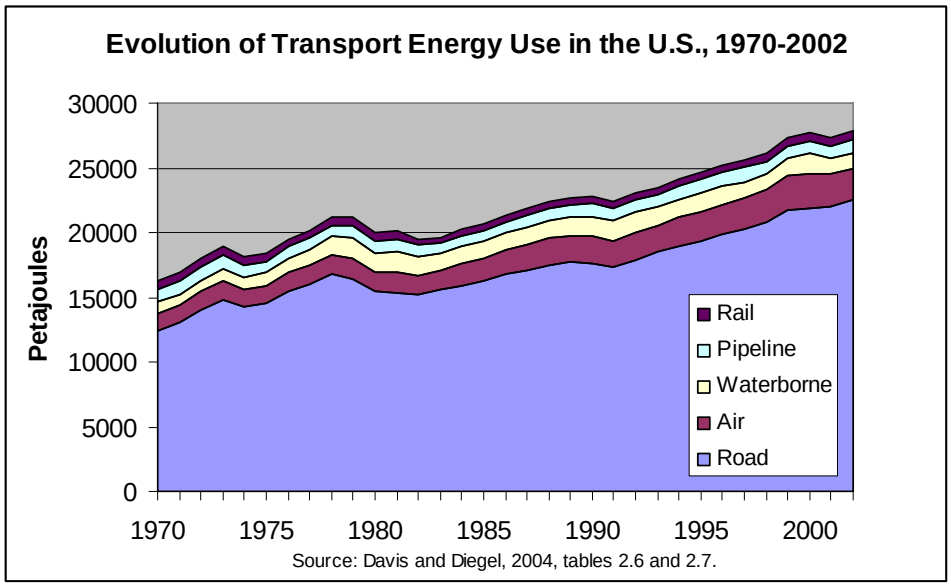

Fig. 7-5b. Evolution of transport energy use in Mexico and the United States.

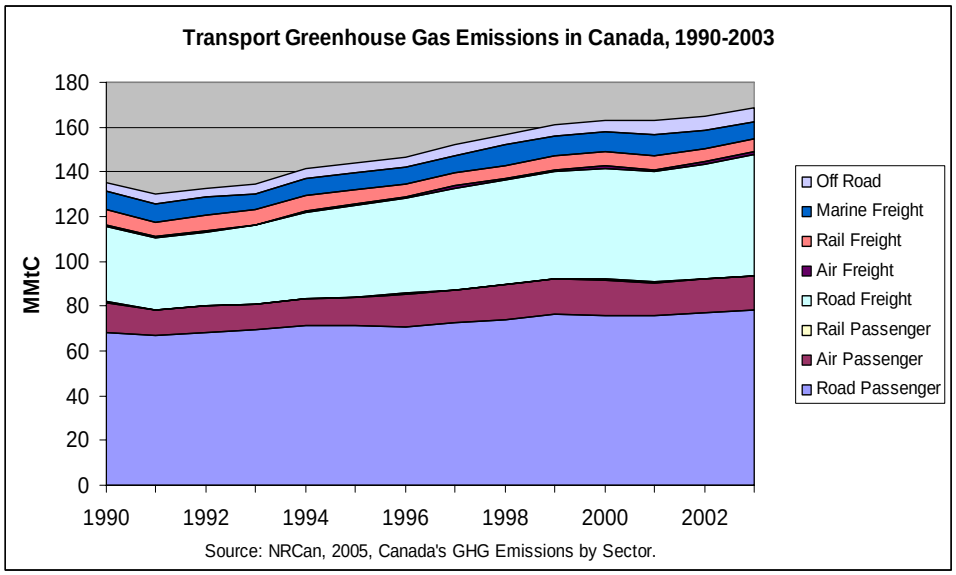

Fig. 7-6a. Transport CO_2 emissions in Canada and the United States, 1990–2003.

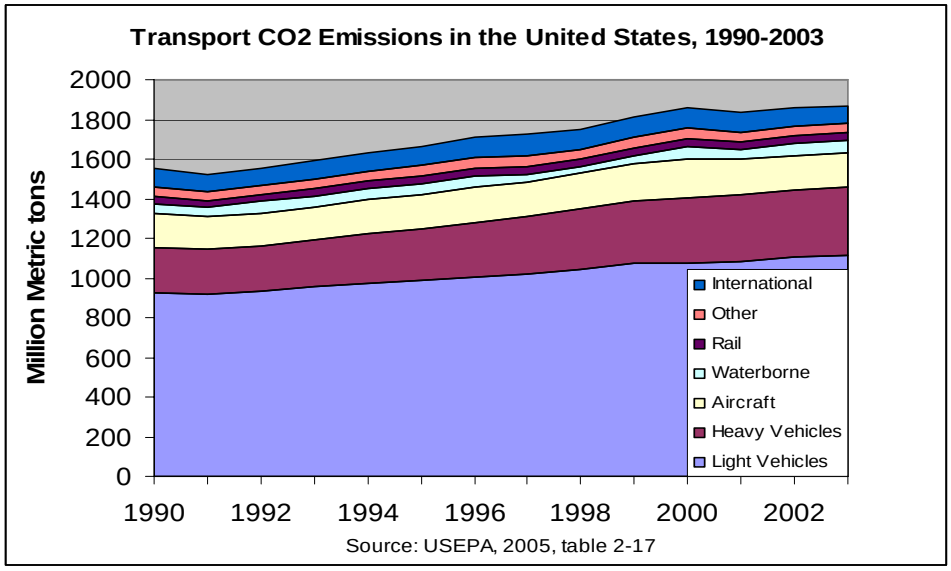

Fig. 7-6b. Transport CO_2 emissions in Canada and the United States, 1990–2003.

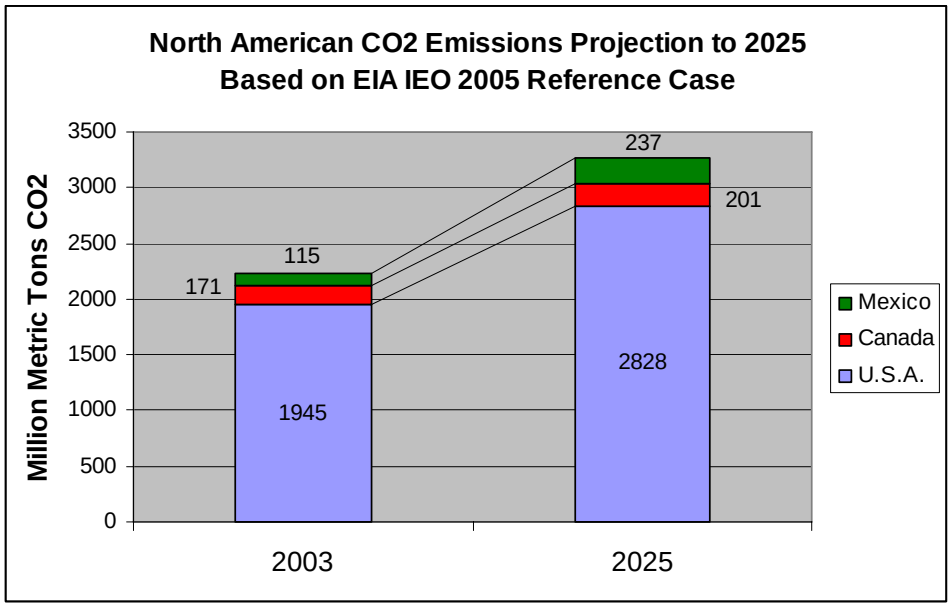

Fig. 7-7. Projected carbon dioxide emissions from the North American transport sector in 2025. *Source*: Fulton and Eads, 2004.

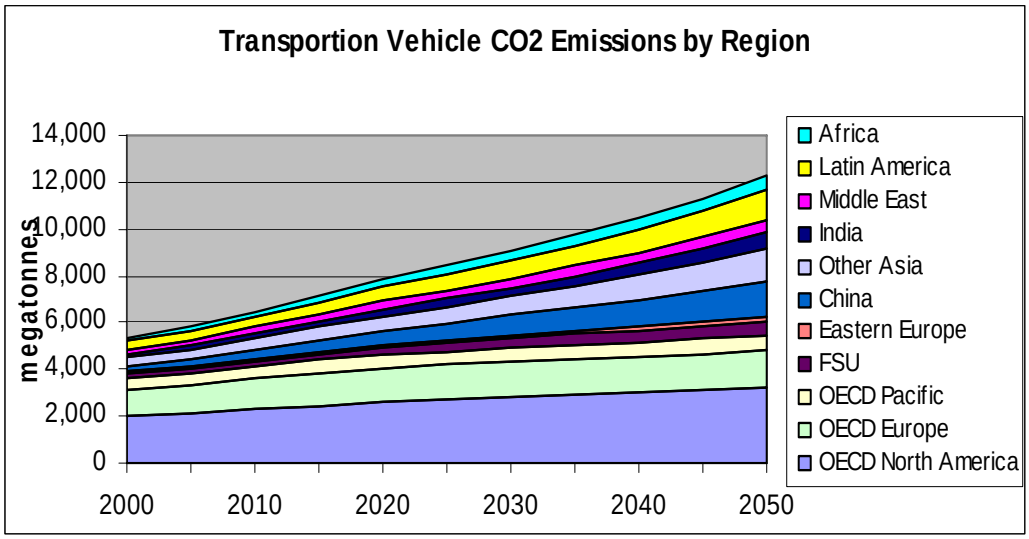

Fig. 7-8. WBCSD projections of world transportation vehicle CO_2 emissions to 2050.
Source: Fulton and Eads, 2004.

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 accounts 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 presents two components of the carbon cycle. The first section assesses carbon flows through industry (manufacturing, construction, and industry process emissions, but excluding fossil fuel mining, and processing).[1] The second section assesses municipal waste disposal (primarily landfills) for its impact on the fate of carbon and the release of methane and other carbon-based gases.

In 2002, industry was responsible for 5220.6 Mt of CO_2, 21% of anthropogenic CO_2 emissions to the atmosphere worldwide (this includes 4322.9 Mt from fuel combustion and 897.7 Mt from the industrial processes described later in this chapter). North America's industry contributed 758.7 Mt of combustion-sourced emissions and 66.8 Mt of process emission for a total of 826 Mt, 16% of global totals. The manufacturing industry and its process emissions contributed only 12% of total North American GHG emissions, lower than in many other parts of the world, because of the high CO_2 intensity of the continent's transportation sector and the significance of heating and cooling energy demands. But with North America's population at 6.8% of the world total, the continent's industry contributed a proportionally larger share of total industrial emissions than the rest of the world (see comparative tables and graphs, 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% during that period (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 energy demand growth lower than industrial GDP

[1]This includes direct flows only. Indirect carbon flows, such as the carbon released due to electricity generation, are not associated with the industry that consumed the electricity but with power generation (see Chapter 6).

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

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 is generated from aerobic metabolism in waste removal and storage processes. Because this CO_2 arises from biological material, it is considered neutral in terms of GHG emissions. Methane (CH_4), released from anaerobic activity at waste treatment plants and landfill sites, forms a substantial portion of carbon emissions to the atmosphere. Given its much higher rating as a GHG gas in terms of 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.

Landfills are not "efficient" aerobic or anaerobic digesters; substantial sequestration of carbon occurs.[5] Data on carbon buried in landfills are poor. The Environmental Protection Agency (EPA) used 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 and are assumed to remain in the landfill site as sequestered carbon. In all, more than 80% of the carbon entering a landfill site may be sequestered, depending on moisture, aeration, and other conditions of the site. In another paper, Bogner and Spokas (1993) estimate that "in general, more than 75% of the carbon deposited in landfills remains in sedimentary storage."

INDUSTRY CARBON CYCLE

Carbon may enter industry as a fuel, providing energy for the completion of industrial processes, or as a feedstock where the carbon becomes entrained in the final product generated by that industry. Thus, carbon exits industrial sites either as a constituent of a product or as a waste. Carbon in the waste stream can be distinguished as atmospheric and non-atmospheric, the former being comprised of process and combustion-related emissions. Process emissions refer to CO_2 emitted as a result of the transformation of the material inputs to the production process (i.e., a non-combustive source). For example, cement

[3]Decomposition analyses assess the changes in the overall energy consumption or emissions release in terms of the major factors affecting such a change. Changes in energy consumption, for example, can result from increase industry activity, changes in relative productivity to or from more intense industry subsectors, or changes in material or energy efficiency in industrial processes.

[4]While not carbon-based, N_2O from sewage treatment is shown in Fig. 2 to show its relative importance as a GHG.

[5]IPCC guidelines currently do not provide a methodology for addressing landfill sequestration. Such guidelines are to be included in the 2006 guidelines.

production involves the calcination of lime, a process that chemically alters limestone to form calcium oxide and releases CO_2. Combustion-related emissions such as CO_2 occur when carbon-based fuels provide thermal energy to industrial processes.

Overview of Carbon Inputs and Outputs

Relatively speaking, industry as it is here defined 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 in the form of biomass (primarily wood), limestone, soda ash, oil products, coal/coke, natural gas, and natural gas liquids. These inputs are converted to dimension lumber and other wood products, various types of paper and paperboard, cement and lime, glass, and a host of chemical products, plastics, and fertilizers based on oil, coal, natural gas, and natural gas liquids.

While the bulk of the input raw material leaves the industrial site as a product, some of the carbon leaves the process as CO_2 (e.g., from limestone in cement production), and some is converted to fuel combusted in the plant. Waste wood (or hog fuel) and black liquor, a product generated in the production of chemical pulps, are burned to provide process heat or steam for digesting wood chips in the production of chemical pulp and for drying paper or wood products. In some cases, electricity is cogenerated from this biomass energy. Chemical processes utilizing natural gas or natural gas liquids often generate off-gases that can be mixed with conventional fuels to 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 in a process known as "reduction." In most of the literature, such carbon is considered an input to the process even though it acts as a fuel (i.e., it unites with oxygen to form CO_2 and releases heat, just as it would in combustion processes). For example, in metal smelting and refining processes, a carbon-based reductant is used to separate oxygen from the metal atoms. Coke, a product of the destructive distillation of high-quality coal, enters a blast furnace with iron ore to strip off the oxygen associated with the iron, leaving pig iron at the bottom of the blast furnace with CO_2 exiting at the top. Carbon anodes in electric arc furnaces in steel mills and in the 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 (wood, paper, chemical products), as a waste product (waste wood, pulp mill sludge), or as a gas, usually CO_2. The carbon in the commodities generated may, in turn, be utilized by other industries to be released as another commodity or as a waste product or emission.

Process emissions are CO_2 emissions that occur as a result of the process itself—the calcining of limestone releases about 0.5 Mt CO_2 per metric ton of clinker (unground cement) or about 0.8 Mt per metric ton of lime,[6] depending on the degree to which limestone or dolomite is used as a feedstock.[7] The oxidation of carbon anodes generates about 1.5 Mt CO_2 in the production of a metric ton of aluminium.[8] Striping hydrogen from methane to make ammonia releases about 1.6 Mt CO_2 per metric ton of ammonia.

Combustion of carbon-based fuels results in the release of CO_2 to the atmosphere. In many cases, the combustion process is not complete, and other carbon-based compounds may also be released, such as carbon monoxide, methane, or mixtures of more complex carbon products known as volatile organic compounds (VOCs). 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 industrial sites as per the industry categories in Sect. 2.2. Numbers for the full North American budget are defined in the figure. Comparable diagrams for the individual countries are presented in Appendix 8A. On the left side of Fig. 8-2, all carbon-based material is accounted for by industry sector, 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 input to industry, as well as some of the feedstock materials, leave in the waste stream as emissions from fuel combustion, process emissions, or as other products and waste. The potential for carbon capture and storage is 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

Energy-intensive industries differ significantly in their carbon cycle dynamics. Figure 8-2 shows the current contribution to the carbon cycle of different industries.

[6] In these industries, more CO_2 is generated from the process of limestone transformation than from the fossils fuels combusted to drive the transformation.

[7] The calcination of limestone also takes place in the iron and steel, pulp and paper, glass and sugar industries.

[8] Ceramic anodes may soon be available to aluminum producers and significantly reduce CO_2 release in the production of aluminum.

Pulp and Paper

While pulp and paper products are quite energy-intensive, much of the energy used in their production is obtained from biomass. By using biomass waste, such as hog fuel and black liquor, some types of pulp mills (and associated paper plants) are energy self-sufficient. These plants could be considered carbon neutral because the capture of carbon as forests grow is assumed to offset the CO_2 released from such activities.[9] However, fuel handling difficulties and air quality concerns (especially from particulates) can arise from the use of biomass as a fuel depending on the location.

Cement, Lime, and Other Nonmetallic Minerals

Cement and lime production requires the calcination of limestone, which releases CO_2. This process emission is releases about 0.78 Mt CO_2 per metric ton of lime calcined.

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

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 during the calcining process.

The production of soda ash (sodium carbonate) from sodium bicarbonate in the Solvay Process releases CO_2 in its manufacture and, in some cases such as glass production, in its utilization. Soda ash is used in the production of pulp and paper to manufacture detergents and soften water.

$2NaHCO_3$	$\rightarrow$	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 the pure metal. In such operations, a reductant, a substance that can carry away the oxygen from the metal, is required. Typically, the reductant is carbon, usually in the form of coke. The coke is added to the hot metal oxide, as in the case of iron, zinc, or magnesium, to generate the reduced metal and CO_2. Such reduction processes

[9] Based on guidelines from the United Nations Framework Convention on Climate Change, biomass-based industries such as pulp and paper are deemed, in effect, to be carbon neutral in so far as biomass is concerned (UNFCCC, IPCC guidelines).

generate relatively pure streams of CO_2 (with some CO), which improves the potential for capture and storage.

In electric arc furnaces, carbon anodes decompose to CO_2 as they melt the scrap iron and steel feed in steel mini-mills. In a Hall-Heroult cell in the aluminium industry, a carbon anode oxidizes when an electric current forces oxygen from aluminium oxide (alumina) in the production of aluminium, with CO_2 as a by-product.

Metal and Nonmetal Mining

Mining involves the extraction of ore and its transformation into a more concentrated form. This involves milling (grinding) the ore after it has been transported from the mine site and removing mineral-bearing material from the ground rock. Much of the process involves grinding and separating, most of which is done through the action of devices driven by electric motors. Thus, a large proportion of the activity in mining operations requires electricity rather than fossil fuels directly—although fossil fuels may have produced the electricity. Some processes, like the sintering or agglomeration of iron ore and the liquid extraction of potash, use a considerable amount of fossil fuels directly. And, of course, much of the movement of the ores from mine to mill is accomplished by diesel-driven motorized vehicles.

Chemical Products

This diverse group of industries includes energy-intensive electrolytic processes as well as the consumption of large quantities of natural gas and natural gas liquids (hydrocarbon liquids found with natural gas) as a feedstock to produce commodities like ammonia, methanol, and hydrogen from natural gas and monomers such as ethylene and propylene from natural gas liquids. These products provide the feedstock for many synthetic resins and plastics. Some chemical processes, such as the production of ammonia, generate fairly pure streams of CO_2 suitable for capture and sequestration.

Forest Products

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

Other Manufacturing

Most of the remaining industries, while economically important, each play a relatively minor role in the carbon cycle because they are not energy intensive and use little biomass—the exceptions being the food industry, the beverage industry, and some textile industries. Industries in this group include the

automotive industry, electronic products, leather and allied products, fabricated metals, furniture and related products, and plastics and rubber products. In aggregate, however, these various industries contribute significantly to total industrial CO_2 emissions.

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 industries are further disaggregated into energy-intensive industries, growing at 1.5% per year, and non-energy intensive industries, growing at 2.9% per year. The slower growth in the energy-intensive industries is reflected by an expected decline of 1.6% per year in the energy intensity of United States industrial output over the forecast (EIA forecast 2005).

The International Energy Agency reviewed energy consumption and emissions during the last 30 years to identify and project underlying trends in carbon intensity.[10] 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 fossil fuels. The shift from coal and refined petroleum products to natural gas and electricity[11] 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.

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

[11] Emissions associated with electricity are considered "indirect" to industry and are allocated to the electricity supply sector. Thus, a shift to electricity is like a shift from coal to natural gas, moving from a more CO_2 intense energy supply to a less intense one (in this case, to 0 CO_2/unit). However, one shifts the allocation of associated CO_2 to another sector as well; there is no net reduction in CO_2 emitted, unless the supply sector chooses to generate electricity from a less CO_2 intense source.

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 reduces energy consumption per unit of output by 26 to 95% (see Table 8-1). Further work on materials substitution also holds promise for reduced energy consumption and 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.

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, both generic and industry-specific. These include efficient Hall-Heroult cell retrofits in aluminium production, black liquor gasification in kraft pulp production, and shape casting in iron and steel industries. Worrel *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 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), as shown in Table 8-2. Of the 25 Mt generated in Canada, the contribution from each of these sources is about the same (Statistics Canada, 2004). In Mexico, as much as 20% of wastes are not systematically collected, and no disaggregated data are available (EPA, 2005).

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

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, a slightly lower percentage in Canada. Incineration can reduce the waste stream in a given location by up to 80%, but this ensures that more of the carbon reaches the atmosphere as opposed to being buried in solid form (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 for electricity generation and heat production.

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[12] depending on the conditions of the landfill site, as well as a trace amount of carbon monoxide (which soon becomes CO_2 in the atmosphere) 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,[13] a relatively small amount compared to total other (sub)sectors in this chapter. One should consider this derived estimate highly uncertain and not of the same calibre as other emissions data provided here. Also recall that, in the context of IPCC assessment guidelines, CO_2 emissions from biological sources are considered GHG-neutral and that these emissions are from biomass.

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). However, the complexity of this assessment and the data required to support it from the multiple sources prevented any further assessment from taking place for this report.

Fugitive methane gases are the result of anaerobic digestion and can be captured and, like incineration, used to generate power and steam. 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

[12] When based on gas volumes, this would mean that roughly equivalent amounts of carbon are released to the atmosphere in CO_2 as in CH_4.

[13] 14 Mt of CH_4 (see Table 8-3) are equivalent, volume wise at standard temperature and pressure, to 38 Mt of CO_2.

released from such combustion is considered biological in origin (i.e., the methane used arose from biological material). Thus, only methane emissions, at 21 times the CO_2 global warming potential, are included as part of GHG inventories.[14] Their combustion greatly alleviates the net contribution to GHG emissions and provides power or steam that might prevent the combustion of fossil fuels elsewhere for these purposes.

COSTS RELATED TO CONTROLLING ANTHROPOGENIC IMPACTS ON THE CARBON CYCLE

The subject of defining costs associated with reducing anthropogenic impacts on the carbon cycle is one of the most contentious of issues in any carbon-focussed analysis. Different modelling approaches to cost assessments (top-down, bottom-up, applicable discount rates, social costing, cost effectiveness, no regrets, etc.), different understandings of what costs actually include (risk, option values, welfare, intangibles, etc.), different values associated with energy demand in different countries (accessibility, availability, infrastructure, resource type and size), the number of possible actions and technologies included in the analysis, and the perspective on technology development all have an impact on how one evaluates costs. Should analysts consider only historical responses to energy prices, production and demand elasticities, income changes and the like? Does one consider only technology options and their strict financial costs? Should one review producers' or consumers' welfare issues associated with new technologies? Are there local, national, international issues to be broached?

How might one reduce emissions in industrial and waste sectors? Methods of reduction can be classified as:

- reducing process/fugitive emissions or converting currently released emissions (e.g., reduce process emissions from cement, lime production, capture or prevent fugitive emissions leaks from pipelines or combustion of emissions such as methane from landfills, cogeneration using landfill offgases);
- energy efficiency, including combined heat and power;
- process change (materials efficiency, recycling, substitution between materials or between materials and energy);
- fuel substitution; and
- carbon capture and storage.

Variation within industries is significant, but some simple allocation of a broad range of costs can be attributed to potential reductions over a set time period. We suggest the cost categories ("A" through "D")

[14]Theoretically, one should assume a factor of 20 because, were the methane released as CO_2, it would be considered to have no net GHG effect.

shown in Table 8-3. The table contains estimates of the percentage reduction at the grouped cost levels. The costs represented here are not drawn from a single source but, rather, are the authors' estimates based on a long history of interaction with cost reported in various documents.

Table 8-3. Approximate costs and reductions potential

When looking at cost numbers like this, one should remember that, for each $10 cost increment per Mt CO_2 (or $2.73 per Mt C), gasoline prices would increase about 2.4¢/L (9¢/U.S. gal). Diesel fuel cost would be slightly higher, at nearly 2.7¢/L (10¢/U.S. gal). At this rate, costs per GJ (slightly smaller than one million BTU) vary by fuel: coal would rise about 90¢/GJ, depending on type, HFO by 73¢, and natural gas by 50¢. Were one to use these fuels to generate electricity at a 35% efficiency rate, the cost increase in coal-fired electricity generation would be about 0.8¢/kWh, about 0.65¢/kWh for HFO fired electricity, and about 0.45¢/kWh if natural gas was used.

Of course, as the cost of carbon increases one can always obtain greater reductions, but the return on these expenditures becomes marginal or insignificant and so are not included in the cells of Table 8-3. If two cost categories are shown in a cell (e.g., A/B) and the quantity reduced ($\%Q_{red}$) as 15/20 in the neighbouring cell, the value associated with the second portrays the marginal addition that may be made at that increased expenditure level. In this example, spending up to $25/t CO_2 may reduce emissions by 15% and with a further expenditure of up to $50/t CO_2 would add a further 20% for a total of 35% were all expenditures to reduce emissions made (see "Metal Smelt" in Table 8-3).

Because not all actions are applicable to all industries, as one aggregates to an "all industry" level (top line in the table), the total overall emissions reduction level may be less than any of the individual industries sited. We provide an approximation of each industry, but if potentials for a certain option are not available in that industry (e.g., process change), this lowers the average for the aggregate category.

Some Explanatory Notes

The five categories are not independent, and thus, reductions are not additive across categories. We have tried to isolate somewhat what reductions might be like were one to focus only on that particular category. Data come from a variety of sources and often focus on more than one of the following aspects (Hertzog, 1999; Martin *et al.*, 2001; Jaccard *et al.*, 2002; Jaccard *et al.*, 2003; Jaccard, Nyboer, *et al.*, 2003; Worrel *et al.*, 2004; DOE, 2006).

Process and Fugitives: Process and fugitive reductions are only available in certain industries. For example, cement and lime calcination, ammonia production, and others (see above) have process emissions that one may be able to control or manipulate. Because wood products industries burn a lot of

wood waste, fugitives (methane and VOCs) are higher than in other industries and reduction potentials exist. In this particular example, fugitive emission and reduction potential are small compared to those possible in petroleum refining and upstream gas and oil.

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. In an EPA study (EPA, 2003a), estimates of between 40% and 60% of methane available for capture may generate net economic benefits.

Energy Efficiency: While efficiency is important for more than just CO_2 reduction, depending on how one views the advent and penetration of new technologies, potentials for reduction are limited if one does not consider changing processes or switching fuels; that is, the potential for emissions reductions from efficiency improvements is strongly linked with these other two avenues. For example, using DRI processes in iron smelting, moving to Cermet anodes in electric arc furnaces in iron and steel and aluminium smelting industries or shifting to hydrometallurgic processes from pyrometallurgic ones in nonferrous metal smelting can significantly improve efficiencies and lower both combustion and process GHG emissions; we include them here as an efficiency improvement even though they may be considered a process change and fall under the next column in Table 8-3.

Because so much emphasis is placed on this particular avenue to reductions, we define it here as a separate category even though it is difficult to disaggregate from fuel switching and process change. Modeling from a more technical, strict end-use approach using technology possibility curves or similar factors for efficiency improvement over time tends to show higher potentials than when one uses hybrid approaches that try to assess the impacts of costs on technology choice (and thus energy demand); we have portrayed the outcome of the latter and provide 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; Worrel *et al.*, 2004).

Process Change: Process change in its broader sense is difficult to estimate; it 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 be different than before the change was made. In pulp production, for example, one could move away from kraft pulp and increase production ratios (the kraft process only converts one-half the tree into pulp), but will market acceptability for the end product be unaffected? Reducing the actual clinker content of ground cement can radically alter emissions levels. Numerous substitution possibilities exist in the rather diverse Other Manufacturing section (carpet recycling, alternative uses for plastics, etc.).

Fuel Substitution: As mentioned, it is difficult to isolate fuel substitution and efficiency improvement because fuel types do contain inherent qualities that affect efficiency. While fuel

substitution is an important method of reducing carbon, this is beneficial only if options to move to less carbon-intense fuels exist. In pulp and paper, one can move to biomass, but the industry already depends on at least one-half of its energy from biomass. Some operating pulp and paper plants are totally self-sufficient. Even so, further potential exists especially in combination with energy efficiency improvement such as cogeneration. Most of the cement and lime, in Canada at least, is produced using coal or coke, allowing for reductions were they to move to biomass, waste fuels, natural gas, or even oil. In some industries, like mining, the bulk of the energy used is electricity, and direct reduction opportunities are small.

Carbon Capture and Storage (CC&S): In one sense, all industries and landfills could invoke CC&S but the methods to accomplish this are not well understood and/or the costs are very high. For example, one could introduce an oxygen stream into all combustion devices such that the exhaust steam is CO_2 rich, suitable for capture and storage. Some industries, like cement production (nonmetal minerals), are reasonable candidates for capture, but transport of the CO_2 for storage may prohibit implementation (see particularly Hertzog, 1999; DOE, 2006).

REFERENCES

Barlaz, Morton A., and Robert K. Ham. 1990 "The Use of Mass Balances for Calculation of the Methane Potential of Fresh and Anaerobically Decomposed Refuse," in *Proceedings from the GRCDA 13th Annual International Landfill Gas Symposium, March 27–29, 1990* (Silver Spring, MD: GRCDA—The Association of Solid Waste Management Professionals) 1990, p. 235.

Barlaz, M. 1994 *Measurement of the Methane Potential of the Paper, Yard Waste, and Food Waste Components of Municipal Solid Waste*. Unpublished paper, Department of Civil Engineering, North Carolina State University, 1994.

Bogner, J., and K. Spokas. 1993. *Landfill CH_4: Rates, Fates, and Role in the Global Carbon Cycle.* Chemosphere, Vol. 26, Nos. 1–4, pp. 369–386.

California Environmental Protection Agency. 2003. *Environmental Technologies and Service Opportunities in the Baja California Peninsula*. International Affairs Unit.

Canadian Industrial Energy End-Use Data and Analysis Centre. 2005. *Development of Energy Intensity Indicators for Canadian Industry: 1990–2004*, Simon Fraser University, Vancouver.

Energy Information Administration. 2005. International Energy Outlook, 2005.

EPIC (Environment and Plastics Industry Council). 2002. Opportunities for Reducing Greenhouse Gas Emissions through Residential Waste Management. Prepared by Environment and Plastics Industry Council.

Environmental Protection Agency. 2003a. *International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21*.

Environmental Protection Agency. 2003b. *Municipal Solid Waste in the United States: 2003 Facts and Figures*.

Environmental Protection Agency. 2005. Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990–2003.

Hershkowitz, Allen. 1997. *Too Good to Throw Away: Recycling's Proven Record.* National Resources Defense Council. February 1997.

Herzog, H. 1999. "The Economics of CO_2 Capture," P Reimer, B Eliasson, A Wokaum, eds., *Greenhouse Gas Control Technologies*, Oxford: Elsevier Science Ltd., pp. 101–106 (1999).

International Energy Agency. 2004. *30 Years of Energy Use in IEA Countries.*

IPCC (Intergovernmental Panel on Climate Change). 2001. *Third Assessment Report, Volume 3 Mitigation*, Chapter 3.

Jaccard, M., J. Nyboer, and B. Sadownik. 2002. *The Cost of Climate Policy*. Vancouver, UBC Press.

Jaccard, M., J. Nyboer, C. Bataille, and B. Sadownik. 2003. *Modeling the Cost of Climate Policy: Distinguishing Between Alternative Cost Definitions and Long-Run Cost Dynamics.* The Energy Journal 24(1): 49–73.

Jaccard, M., R. Loulou, A. Kanudia, J. Nyboer, A. Bailie, and M. Labriet. 2003. *Methodological contrasts in costing GHG abatement policies: Optimization and simulation modeling of micro-economic effects in Canada.* European Journal of Operations Research 145 (1): 148–164.

Martin, N., E. Worrell, M. Ruth, L. Price, R. N. Elliott, A. M. Shipley, and J. Thorne. 2001. *Emerging Energy-Efficient Industrial Technologies: New York State Edition.* LBNL Report Number 46990, published by American Council for an Energy-Efficient Economy (ACEEE).

Mohareb, A. K., M. Warith, and R. M. Narbaitz. 2003. Strategies for the municipal solid waste sector to assist Canada in meeting its Kyoto Protocol commitments. Environmental Review 12: 71–95.

Statistics Canada. 2004. *Human Activity and the Environment*. Statistics Canada, Cat no.16-201-XIE.

DOE. 2006. www.fossil.energy.gov/programs/sequestration/overview.html Accessed on March 27, 2006. U.S. Department of Energy.

Worrell, Ernst, Lynn K. Price, and Christina Galitsky. 2004. *Emerging energy-efficient technologies in industry: Case studies of selected technologies.* Environmental Technologies Division, Lawrence Berkeley Laboratory, University of California at Berkeley.

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 recycled	47.3	4.3	–
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	–

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		$MtCO_2$	%
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		$MtCO_2$	%
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		$MtCO_2$	%
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		$MtCO_2$	%
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		$MtCO_2$	%
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		$MtCO_2$	%
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		$MtCO_2$	%
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		$MtCO_2$	%
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		$MtCO_2$	%
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		$MtCO_2$	%
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).

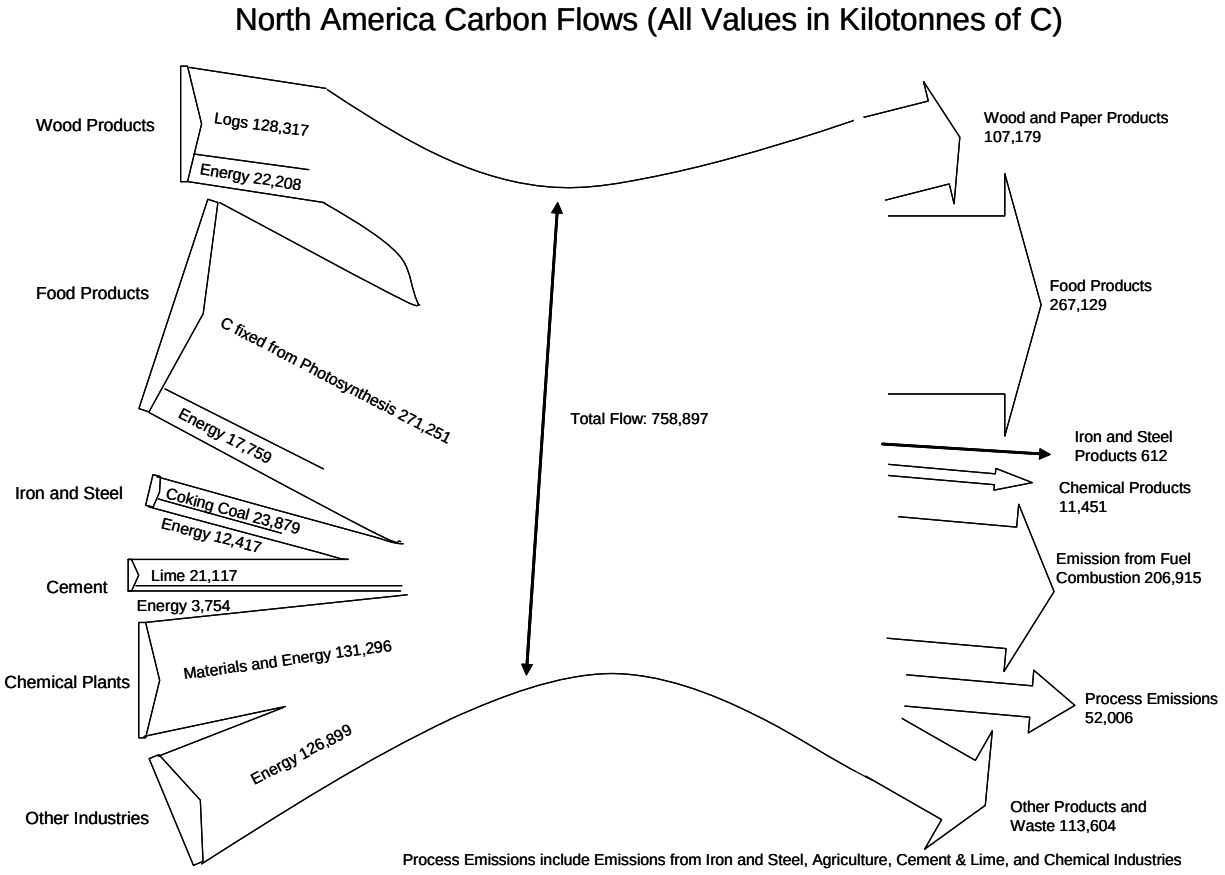


Fig. 8-2. Carbon flows for Canada, the United States and Mexico combined. Values in kilotons carbon can be converted to kilotons CO_2 equivalents by multiplying by 44/12, the ratio of carbon dioxide mass to carbon mass. Comparable diagrams for the individual countries are in Appendix 8A**.** *Source*: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

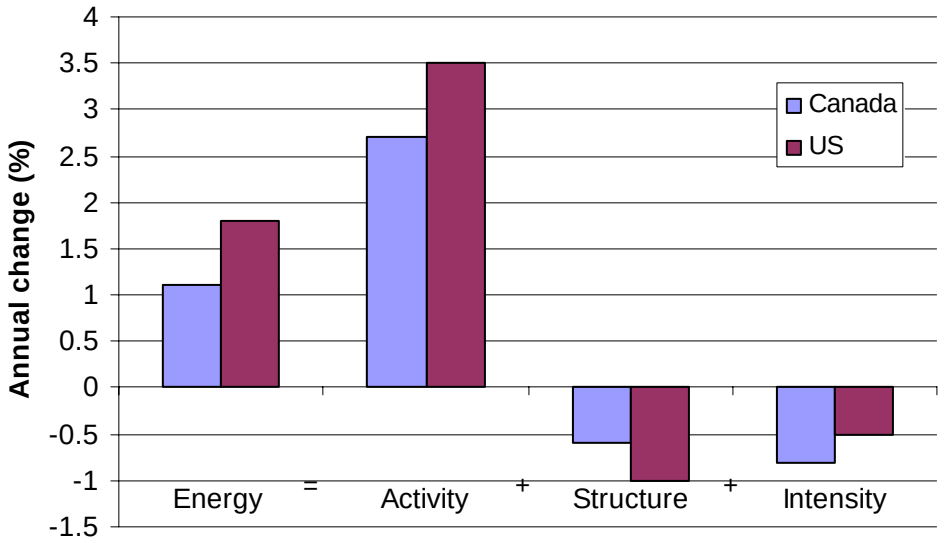


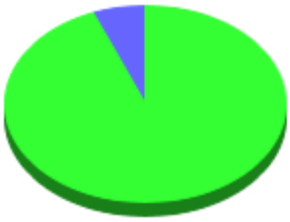
Fig. 8-3. Decomposition of energy use, manufacturing sector, 1990–1998. *Source*: IEA, 2004.

World

Gas	$MtCO_2$	%
CH_4	1,386.4	93.5
N_2O	97.2	6.5
Total	**1,483.6**	

North America (w/ Mexico)

Gas	$MtCO_2$	%
CH_4	281.8	93.9
N_2O	18.2	6.1
Total	**300.0**	

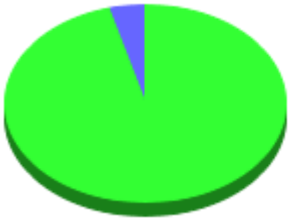


United States of America

Gas	$MtCO_2$	%
CH_4	227.7	93.6
N_2O	15.6	6.4
Total	**243.3**	

Canada

Gas	$MtCO_2$	%
CH_4	23.2	95.8
N_2O	1.0	4.2
Total	**24.2**	



Mexico

Gas	$MtCO_2$	%
CH_4	31.0	95.2
N_2O	1.6	4.8
Total	**32.5**	

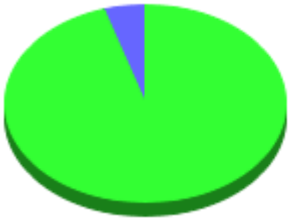


Fig. 8-4. GHG emissions by gas from waste in 2000. *Source*: Climate Analysis Indicators Tool (CAIT) Version 3.0 (Washington, D.C.: World Resources Institute, 2005).

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.

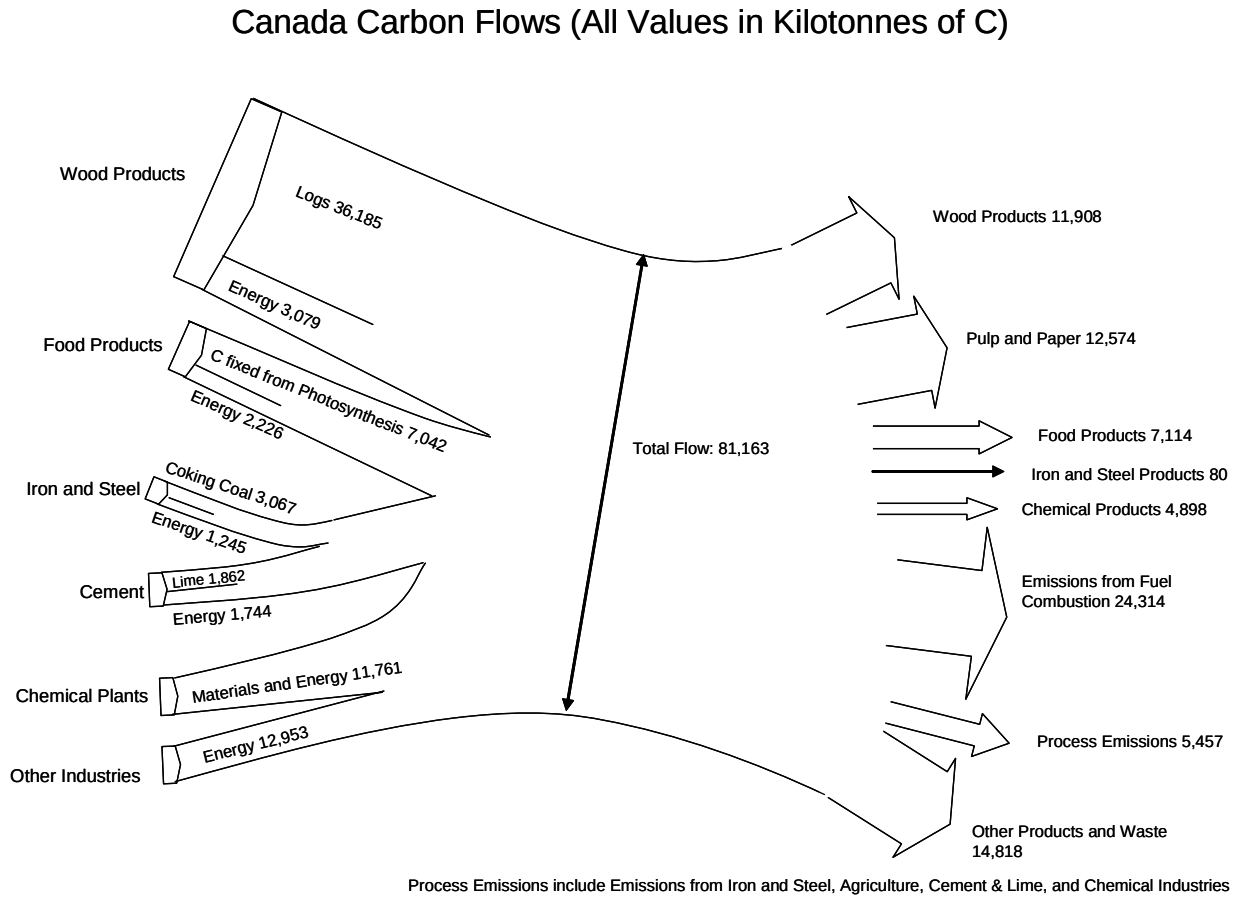


Fig. 8A-1. Carbon flows, Canada. *Source*: Energy data from Statistics Canada Industrial Consumption of Energy survey, conversion coefficients and process emissions from Environment Canada, *Canada GHG Inventory, 2002.* Production data from Statistics Canada, CANSIM Table 002-0010, Tables 303-0010, -0014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

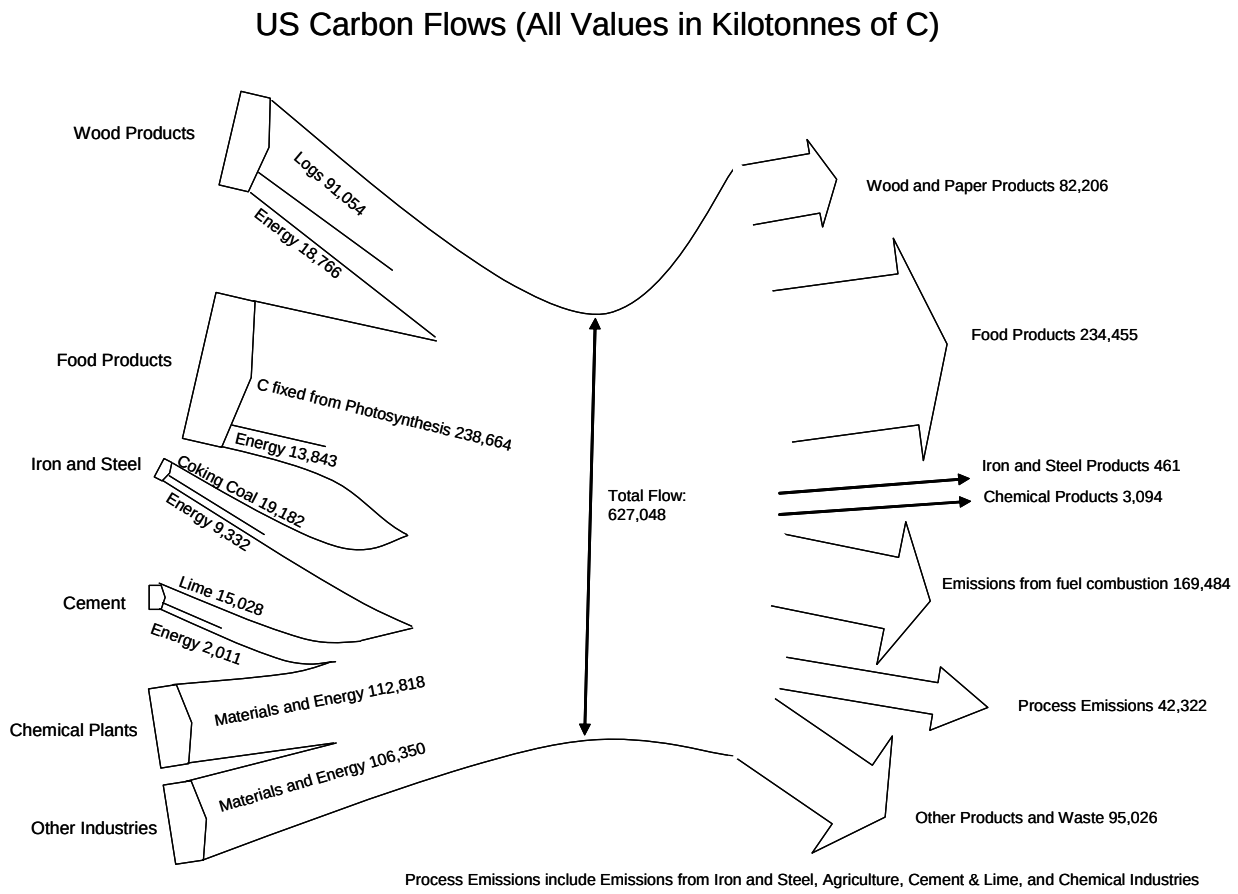


Fig. 8A-2. Carbon flows, United States. *Source*: Energy data from IEA Oil Information 2004, IEA Coal Information 2005, IEA Natural Gas Information 2004. Process emissions: EPA, U.S. Emissions Inventory. Production of forestry products: USDA Database; FO-2471000 and -2472010, U.S. Timber Production,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

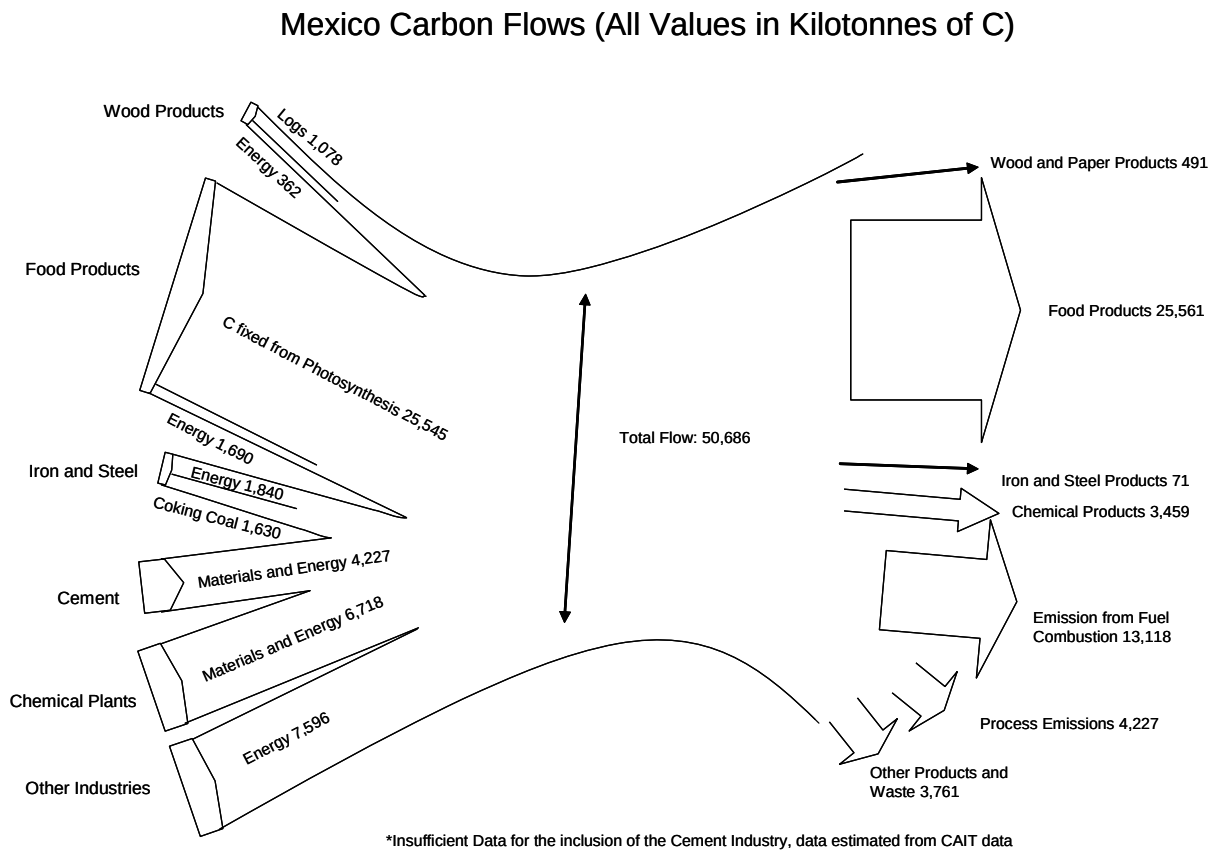


Fig. 8A-3. Carbon flows, Mexico. *Source*: Energy data from IEA Oil Information 2004, IEA Coal Information 2005, IEA Natural Gas Information 2004. Process emissions: EPA, U.S. Emissions Inventory. Production of forestry products: USDA Database; FO-2471000, -2472010, -2482000, -2483040, -6342000, -6342040. 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 the annual emission of 2,712 Mt CO_2 in 2003, which is 36% of total North American CO_2 emissions and 9% of global emissions. U.S. buildings alone are responsible for more CO_2 emissions than total CO_2 emissions of any country in the world, except China.
- Carbon dioxide missions from energy use in buildings in the United States and Canada has increased by 30% since 1990, 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, with the amount of living area per capita increasing in all three countries of North America.
- 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 30% 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.

Buildings are responsible for 36% of carbon emissions in North America (2712 Mt CO_2 in 2003) (Natural Resources Canada, 2005; SENER México, 2005; U.S. DOE-EIA, 2005a[1]) and 9% in the world (U.S. DOE-EERE, 2005[2]). U.S. buildings alone are responsible for more CO_2 emissions than total CO_2 emissions of any 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 (U.S. DOE-EERE, 2005.[3]). The discussions in this chapter include an accounting of CO_2 emissions from electricity consumed in the buildings sector; however, this accounting 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, such as 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 by at least 60% for offices[4] and 30% for homes.[5] Residential and commercial buildings in the United States and Canada contain 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). 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. Primary energy inputs from the source of production are tracked, their emissions rates are known, and the total end user consumption data are gathered and reported by energy utilities, typically monthly. The quantity of energy consumed by each 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.

[1] U.S. Sector Emissions from Table 18 in U.S. DOE-EIA (2005a).
[2] See Table 3.1.1 in U.S. DOE-EERE (2005).
[3] See Tables 1.1.6 and 1.1.7 in U.S. DOE-EERE (2005).
[4] Leadership in Energy and Environment Design (LEED) Gold Certification.
[5] U.S. DOE Building America Program.

Currently, the influence of secondary fluxes due to use of materials and consumption of water is more uncertain.

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 10.7 metric tons [6] of carbon dioxide per year in the United States, 6.5 metric tons [7] per year in Canada, and 5.0 metric tons [8] in Mexico (U.S. DOE-EIA, 2005a; Natural Resources Canada, 2005; SENER México, 2005). Energy consumption in a 500-m^2 commercial, government, or public-use building in the United States produces 7.1 metric tons of CO_2 (U.S. DOE-EIA, 2005a).[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 660 g of CO_2 to the atmosphere in 2003 (U.S. DOE-EIA, 2005a).[10] The equivalent amount of energy from natural gas or other fuels contributed about 190 g of CO_2 (U.S. DOE-EIA, 2005a).[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 (U.S. DOE-EERE, 2005).[12]

Buildings sector carbon dioxide 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, 9%; and electronics (including televisions, computers, and office equipment), 7.7% (U.S. 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 (U.S. 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.

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

[6] U.S. residential sector emissions of 1213 Mt CO_2 divided by 114 million households in 2004.
[7] Canada residential sector emissions of 45.2Mt CO_2 divided by 12.2 million households in 2003.
[8] Mexico residential sector emissions of 85.2 Mt CO_2 divided by 167 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 U.S. 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; available on-line at http://buildingsdatabook.eere.energy.gov (2003 data).

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 in Mexico, sales of this equipment are now growing significantly, 14% per year over the past 10 years.[15] 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, major appliances are common in middle- and upper-income households, and even the poorest electrified households own a television, a refrigerator, and small appliances.

Many end uses—such as water heating and heating, cooling, and ventilation—occur in most commercial sector buildings. Factors such as climate and building construction influence the carbon emissions from 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 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

[15] *Air conditioner sales 1995–2004 from* Asociacion Nacional de Fabricantes de Aparatos Domesticos (ANFAD).

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.

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-ft^2 (2200-ft^2) house requires about 20 Mt of wood and creates 2 to 7 Mt of construction waste (U.S. DOE-EERE, 2005).[16] Building lifetimes are many decades and, especially for commercial buildings, may include several cycles of remodeling and renovation. Water consumption in buildings also impacts the carbon cycle because water supply, treatment, and waste disposal require energy. In California, for example, total water use accounts for 19% of statewide electricity (CEC, 2005). In the United States as a whole, water supplied to residential and commercial customers accounts for about 6% of total national freshwater consumption.

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. In general, the trend over the last decade has been toward emissions growth, with emissions from energy use in buildings in the United States and Canada increasing 30% since 1990 (U.S. DOE-EERE, 2005; Natural Resources Canada, 2005),[17] 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 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.[18] On the other hand, a shift from large, extended-family households to nuclear-family and single-occupant households means an increase in

[16] Table 2.1.7. Wood content estimated from lumber content. Construction waste from Table 3.4.1.
[17] U.S.DOE-EERE, 2005 Table 3.1.1.
[18] *Source:* UN Department of Economic and Social Affairs.

the number of households per unit population—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.[19] Per capita energy consumption generally grows with economic development because wealthier people live in larger households and have more appliances. 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 fraction of electricity to total household primary energy has increased. This is significant 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 floorspace 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 for a house built in 1980 to 216 m^2 in 2003. In the same time, commercial floor space per capita has increased from 20 m^2 to 22.6 m^2 (U.S. DOE-EERE, 2005).[20] Certain end uses once considered luxuries have now become commonplace. Only 56% of U.S. homes in 1978 used mechanical space-cooling equipment (U.S. DOE-EIA, 2005b). 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

Although the general trend has been toward growth in per capita emissions, emissions per unit of GDP has 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. Efficiency increases 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.

[19] For example, whether biomass, natural gas or electricity is used for space heating and cooking.
[20] See Table 2.1.6 and 2.2.1 in U.S. DOE-EERE (2005). Residential data are from 1981.

[SIDEBAR 1 TEXT BOX HERE]

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 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 (S. Wiel and J. E. 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 one or more of these options in a policy portfolio that takes advantage of synergies, avoids unduly burdening certain sectors, and is cost-effective. Major participants include federal agencies, state and local governments, energy and water utilities, private research and development firms, equipment manufacturers and importers, energy services companies (ESCOs), 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 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.

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.

[SIDEBAR 2 TEXT BOX HERE]

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 nongovernment, nonprofit organization. In existence for five years, the LEED program has certified 36 million m^2 of commercial and public-sector buildings and has recently implemented a certification system for homes. The LEED program includes a graduated rating system. Typical energy savings achieved by LEED Gold-rated buildings are 50–60% (U.S. GBC, 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. 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 non-carbon-emitting equipment and building systems (including energy demand and supply) 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 roadmap will need to be updated at regular intervals to account for changes in technologies, production practices, and market acceptance of competing solutions.

REFERENCES

CEC (2005). *California's Water Energy Relationship*. Staff Final Report, California Energy Commission. Sacramento, 2005.

Interlaboratory Working Group, 2000. *Scenarios for a Clean Energy Future* (Oak Ridge, TN; Oak Ridge National Laboratory and Berkeley, CA; Lawrence Berkeley National Laboratory), ORNL/CON-476 and LBNL-44029, November.

Kinsey *et al.* (2002). *The Federal Buildings Research and Development Program: A sharp Tool for Climate Policy*. ACEEE Buildings Summer Study 2002, Pacific Grove.

Natural Resources Canada (2005). *Office of Energy Efficiency National Energy Use Database 2005*. Ottawa http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/data_e/database_e.cfm

SENER México (2005). Secretaria de Energia—Sistema de Información Energética. México D.F. http://sie.energia.gob.mx/sie/bdiController

U.S. DOE-EERE (2005). *2005 Buildings Energy Data Book*. Office of Energy Efficiency and Renewable Energy. Washington, 2005.

U.S. DOE-EIA (2005a). *Annual Energy Outlook 2005*. EIA-0383(2005). Energy Information Administration. Washington, 2005a.

USDOE-EIA (2005b). *Changes in Energy Usage in Residential Housing Units*. Washington http://www.eia.doe.gov/emeu/recs/recs2001/hc_pdf/ac/hc4-11a_so_region2001.pdf.

USGBC (2005). *LEED for New Construction—Rating System 2.2*, LEED (NC) 2.2, U.S. Green Building Council. Washington, 2005.

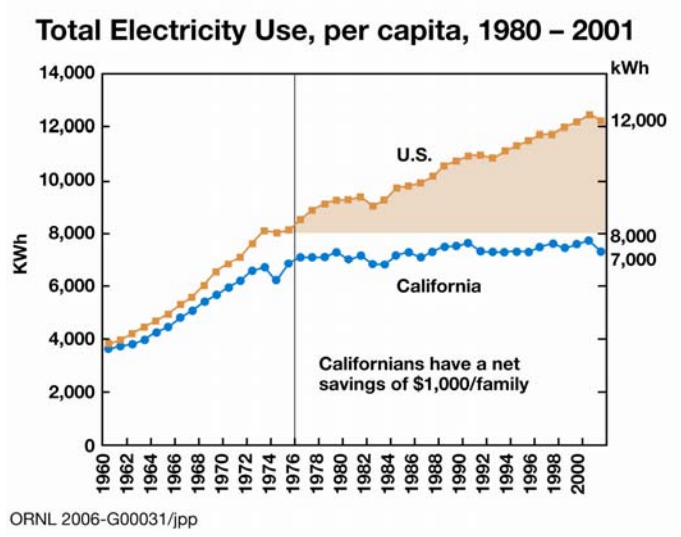
Wiel, S., and J.E. McMahon (2005). *Energy-Efficiency Labels and Standards: A Guidebook for Appliances, Equipment, and Lighting, 2nd Edition*. Washington, Collaborative Labeling and Standards Program.

[BEGIN SIDEBAR 1]

Since the mid-1970s, the state of California has pursued an aggressive set of efficiency regulations. As a result, per capita electricity consumption has stabilized in that state even 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

Per capita electricity consumption in the U.S. and California



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

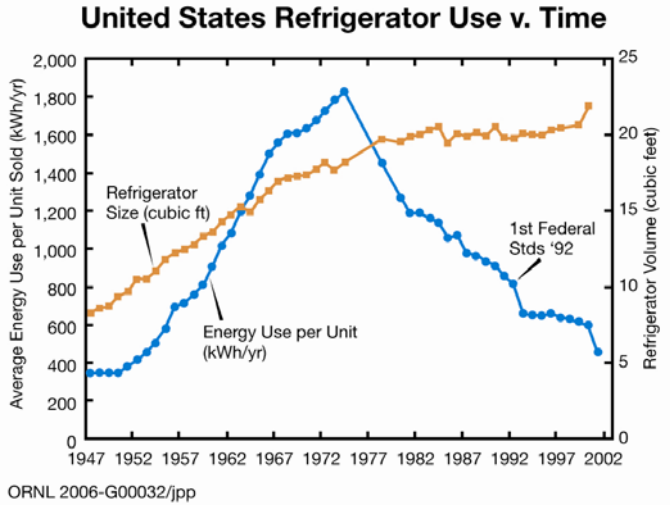
[END SIDEDBAR 1]

[BEGIN SIDEBAR 2]

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 minimum efficiency standards for more than 30 residential and commercial product types. Canada and Mexico also have many product efficiency standards, and a program is under way to harmonize standards throughout North America in connection with North American Free Trade Agreement.

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

Impact of efficiency improvements



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[END SIDEBAR 2]

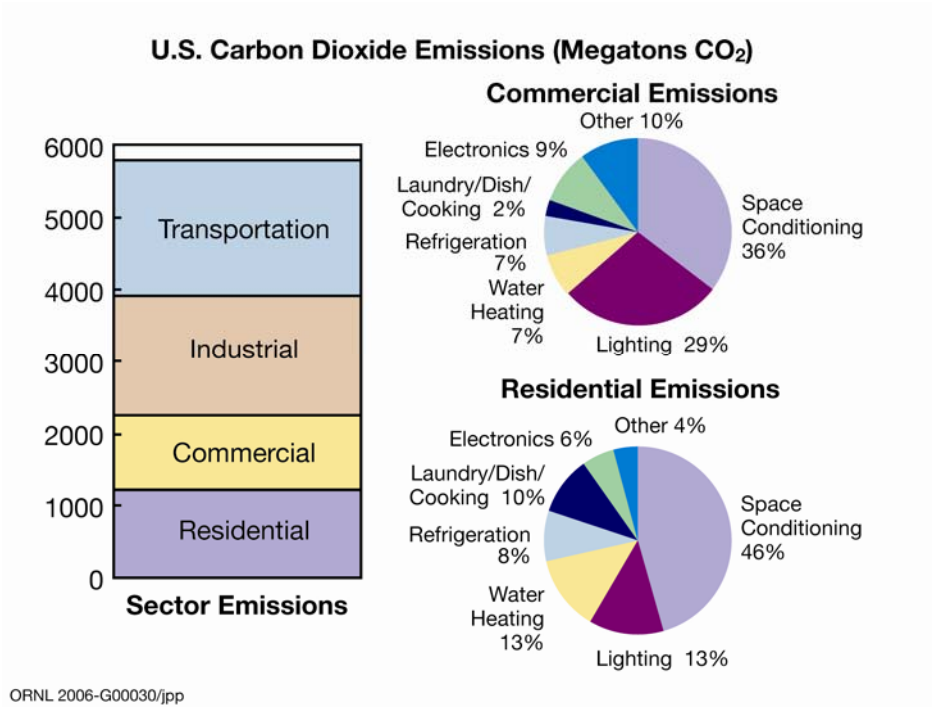

Fig. 9-1. U.S. carbon emissions by sector and—for commercial and residential buildings—by end use.

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

	Greenhouse emission (megatons) CO_2				
	Electricity	Natural gas	Other fuels	Wood	Total
United States	**1609.1**	**434.6**	**166.3**	**0.0**	**2210.0**
Residential	823.7	265.9	105.1	0.0	1194.7
Commercial	785.4	168.7	61.2	0.0	1015.4
Canada	**61.6**	**58.5**	**22.0**	**1.9**	**143.9**
Residential	31.4	32.3	9.1	1.9	74.7
Commercial	30.2	26.2	12.9	0.0	69.3
Mexico	**52.7**	**1.7**	**16.2**	**2.1**	**72.7**
Residential	40.2	1.3	15.8	2.1	59.4
Commercial	12.5	0.4	0.4	0.0	13.3
Total	**1723.4**	**494.8**	**204.5**	**4.0**	**2426.6**

Table 9-2. Principal drivers of buildings emissions trends

Drivers	United States		Canada		Mexico	
	Total 2000	Growth rate 1990–2000	Total 2000	Growth rate 1990–2000	Total 2000	Growth rate 1990–2000
Population (millions)	288	1.1%	31.0	1.0%	100	1.7%
Household size (persons/HH)	2.5	–0.6%	2.6	–0.9%	5.3	–0.1%
GDP/Cap (thousand $U.S. 1995)	31.7	2.0%	23.0	1.8%	3.8	1.8%
Res. floorspace (billion m^2)	15.7	0.0%	1.5	2.4%	NA	NA
Comm. floorspace (million m^2)	6.4	0.6%	0.5	1.6%	NA	NA
Building energy emissions/GDP (g CO_2/$U.S.)	256	–0.5%	217	–0.9%	NA	NA