

## 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 225 million metric tons of carbon (826 million tons of carbon dioxide), 16% of the world's carbon dioxide emissions to the atmosphere from industry. Waste treatment plants and landfill sites in North America accounted for 13.4 million tons of methane (282 million tons of carbon dioxide equivalent; 10 million tons of carbon), roughly 20% of global totals.
- Industrial carbon dioxide emissions from North America decreased nearly 11% between 1990 and 2002, while energy consumption in the United States and Canada increased 8% to 10% during that period. In both countries, a shift in production activity toward less energy-intensive industries and dissemination of more energy efficient equipment kept the rate of energy demand growth lower than industrial gross domestic product growth.
- Changes in industrial carbon dioxide emissions are a consequence of changes in industrial energy demand and changes in the mix of fossil fuels used by industry to supply that demand. Changes in industrial energy demand are themselves a consequence of changes in total industrial output, shifts in the relative shares of industrial sectors, and increases in energy efficiency. Shifts from coal and refined petroleum products to natural gas and electricity contributed to a decline in total industrial carbon dioxide emissions since 1997 in both Canada and the United States.
- An increase in carbon dioxide emissions from North American industry is likely to accompany the forecasted increase in industrial activity (2.3% per year until 2025 for the United States).
- Emissions per unit of industrial activity will likely decline as non-energy intensive industries grow faster than energy intensive industries and with increased penetration of energy efficient equipment. However, continuation of the trend toward less carbon-intensive fuels is uncertain given the rise in natural gas prices relative to coal in recent years.
- Options for reducing carbon dioxide emissions from North American industry can be broadly classified as methods to: (1) reduce process/fugitive emissions or convert currently released emissions; (2) increase energy efficiency, including combined heat and power management; (3) change industrial processes (materials efficiency, recycling, substitution between materials or between materials and energy, and nanotechnology); (4) substitute less carbon intense fuels; and (5) capture and store carbon dioxide.
- Further work on materials substitution holds promise for industrial emissions reduction, such as the replacement of petrochemical feedstocks by feedstocks derived from vegetative matter (biomass), of steel by aluminum in the transport sector, and of concrete by wood in the buildings sector. The prospects for greater usage of energy efficiency technologies are equally substantial.



### 8.1 INTRODUCTION

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

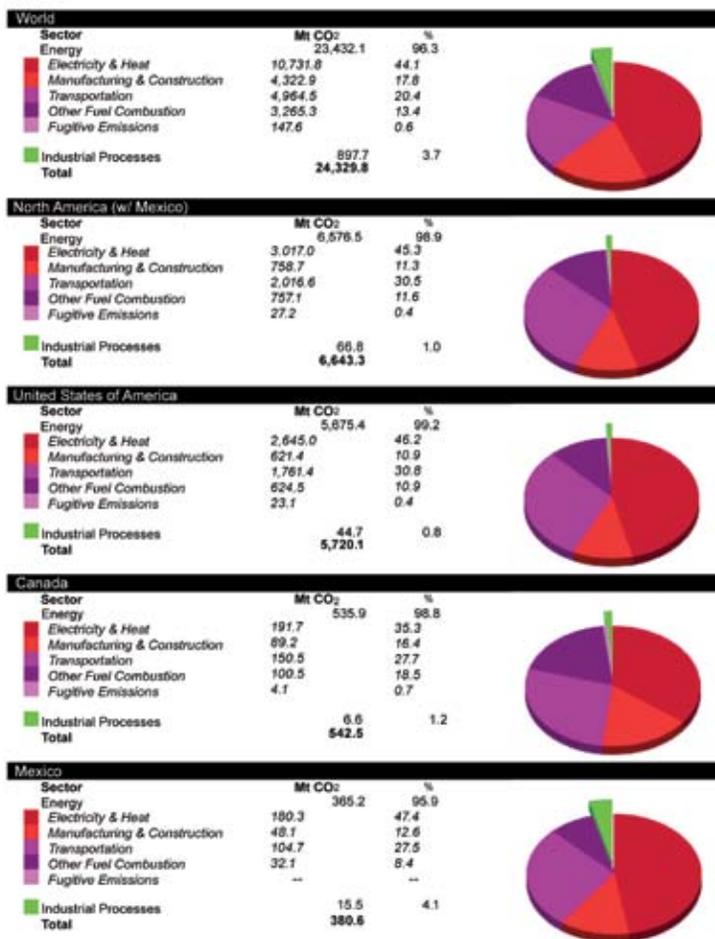
In 2002, industry was responsible for 21% of human-caused (anthropogenic) emissions to the atmosphere.

In 2002, industry was responsible for 1423.8 million metric tons of carbon (Mt C) (5220.6 million tons of carbon dioxide [Mt CO<sub>2</sub>]), which is 21% of human-caused (anthropogenic) emissions to the atmosphere (244.8 Mt C [4322.9 Mt CO<sub>2</sub>] from fuel combustion and 1179.0 Mt C [897.7 Mt CO<sub>2</sub>] from industrial processes).

North America's industry contributed 206.9 Mt C (758.7 Mt CO<sub>2</sub>) of combustion-sourced emissions and 18.2 Mt C (66.8 Mt CO<sub>2</sub>) of process emissions for a total of 225 Mt C (826 Mt CO<sub>2</sub>) or 16% of global totals (WRI, 2005; see Figure 8.1A)<sup>2</sup>. The manufacturing industry contributed 12% of total North American greenhouse gas (GHG) emissions, lower than in many other parts of the world. However, with North America's population at 6.8% of the world's total, industry contributed a proportionally larger share of total industrial emissions *per capita* than the rest of the world<sup>3</sup>.

Industrial CO<sub>2</sub> emissions decreased nearly 11% between 1990 and 2002 while energy consumption in the United States and Canada increased 8% to 10% (EIA, 2005; CIEED-AC, 2005). In both countries, a shift in production activity toward less energy-intensive industries and dissemination of more energy efficient equipment kept the rate of growth in energy demand lower than industrial gross domestic product (GDP) growth (IEA, 2004)<sup>4</sup>. This slower demand growth, in concert with a shift toward less carbon-intensive fuels, explains the decrease in industrial CO<sub>2</sub> emissions.

The municipal waste stream excludes agricultural and forestry wastes but includes wastewater. Carbon dioxide,



**Figure 8.1A** Carbon dioxide emissions by sector in 2002. Source: WRI (World Resources Institute)(2005). The magnitude and/or range of uncertainty for the given numerical values is not provided in the reference. To convert from Mt CO<sub>2</sub> to MtC, multiply the Mt CO<sub>2</sub> value by 12/44.

generated from aerobic metabolism in waste removal and storage processes, arises from biological material and is considered GHG neutral. Methane (CH<sub>4</sub>) released from anaerobic activity at waste treatment plants and landfill sites, forms a substantial portion of carbon emissions to the atmosphere. Given its high global warming potential (GWP) (*i.e.*, the GWP for CH<sub>4</sub> is 21 times that of CO<sub>2</sub>), CH<sub>4</sub> plays an important role in the evaluation of possible climate change impacts (WRI, 2005; see Figure 8.1B)<sup>5</sup>. Globally, CH<sub>4</sub> emissions from waste amount to 66 Mt, or 378 Mt C equivalent (1386 Mt CO<sub>2</sub> equivalent). North American activity accounts for 13.4 Mt of CH<sub>4</sub> (77 Mt C equivalent [282 Mt CO<sub>2</sub> equivalent]) or roughly 20% of global totals.

Substantial sequestration of carbon occurs in landfills<sup>6</sup>. Data on carbon buried there are poor. The Environmental Protection Agency (EPA), using data from Barlaz and Ham (1990) and Barlaz (1994), estimated that 30% of carbon in

<sup>1</sup> This includes direct flows only. Indirect carbon flows (*e.g.*, due to electricity generation) are associated with power generation.

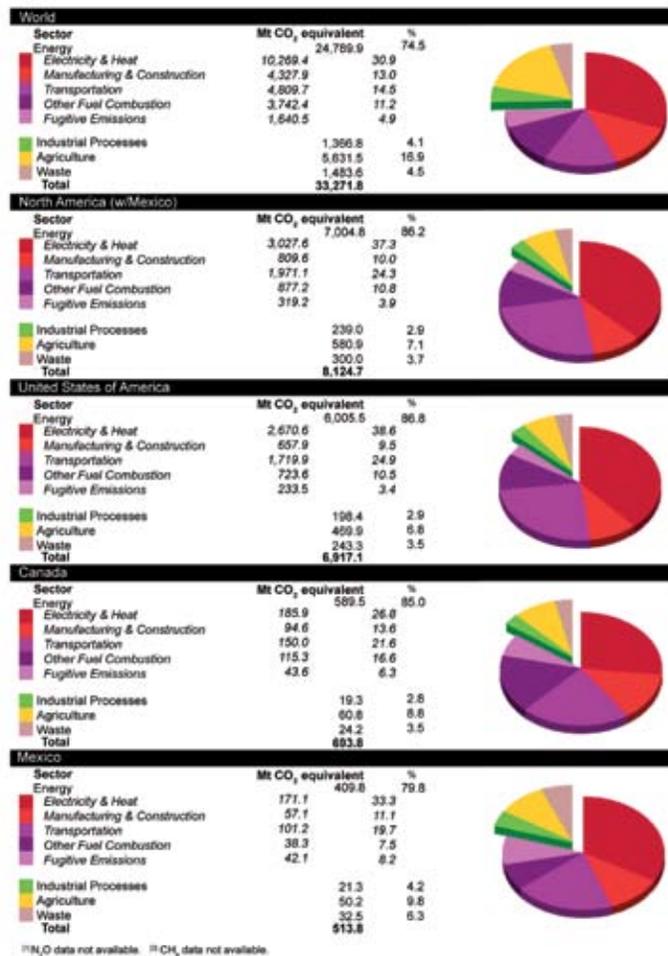
<sup>2</sup> A dagger symbol indicates that the magnitude and/or range of uncertainty for the given numerical value(s) is not provided in the references cited.

<sup>3</sup> North America, including Mexico, was responsible for about 27% of global CO<sub>2</sub> emissions in 2002.

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

<sup>5</sup> While not carbon-based, N<sub>2</sub>O from sewage treatment is included in Figure 8.4, below, to show its relative GHG importance.

<sup>6</sup> IPCC guidelines currently do not address landfill sequestration. Such guidelines will be in the 2006 publication.



**Figure 8.1B** Greenhouse gas emissions by sector in 2000, CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, PFCs, HFCs, and SF<sub>6</sub>. Source: WRI (World Resources Institute)(2005). The magnitude and or range of uncertainty for the given numerical values is not provided in the reference. To convert from MtCO<sub>2</sub> equivalent to MtC equivalent, multiply the Mt CO<sub>2</sub> value by 12/44.

food waste and up to 80% of carbon in newsprint, leaves, and branches remain in the landfill<sup>†</sup>. Plastics show no deterioration. In all, 80% of the carbon entering a landfill site may be sequestered, depending on moisture, aeration, and site conditions. Bogner and Spokas (1993) estimate that “more than 75% of the carbon deposited in landfills remains in sedimentary storage.”

## 8.2 INDUSTRY CARBON CYCLE

Carbon may enter industry as a fuel or as a feedstock where the carbon becomes entrained in the industry’s final product. Carbon in the waste stream can be distinguished as atmospheric and non-atmospheric, the former being comprised of process and combustion-related emissions. Process CO<sub>2</sub> emissions, a non-combustive source, are the result of the transformation of the material inputs to the production process. For example, cement production involves the calcination of lime, which chemically alters limestone to

form calcium oxide and releases CO<sub>2</sub>. Of course, combustion-related CO<sub>2</sub> emissions occur when carbon-based fuels provide thermal energy to drive industrial processes.

### 8.2.1 Overview of Carbon Inputs and Outputs

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

#### 8.2.1.1 CARBON IN

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

While the bulk of the input carbon leaves the industrial site as a product, some leaves as process CO<sub>2</sub> and some is converted to combustible fuel. Waste wood (or hog fuel) and black liquor, generated in the production of chemical pulps, are burned to provide process heat or steam for digesting wood chips or for drying paper or wood products, in some cases providing electricity through cogeneration. Chemical processes utilizing natural gas often generate off-gases that, mixed with conventional fuels, provide process heat. Finally, some of the carbon that enters as a feedstock leaves as solid or liquid waste.

In some industries, carbon is used to remove oxygen from other input materials through “reduction.” In most of the literature, such carbon is considered an input to the process and is released as “process” CO<sub>2</sub>, even though it acts as a fuel (*i.e.*, it unites with oxygen to form CO<sub>2</sub> and releases heat). For example, in metal smelting and refining processes, a carbon-based reductant separates oxygen from the metal atoms. Coke, from the destructive distillation of coal, enters a blast furnace with iron ore to strip off the oxygen associated with the iron. Carbon anodes in electric arc furnaces in steel mills and specialized electrolytic “Hall-Heroult” cells oxidize to CO<sub>2</sub> as they melt recycled steel or reduce alumina to aluminum.

#### 8.2.1.2 CARBON OUT

Carbon leaves industry as part of the intended commodity or product, as a waste product or as a gas, usually CO<sub>2</sub>.



Process emissions are CO<sub>2</sub> emissions that occur as a result of the process itself—the calcining of limestone releases about 0.5 tons CO<sub>2</sub> per ton of clinker (unground cement) or about 0.8 tons per ton of lime<sup>7,8</sup>. The oxidation of carbon anodes generates about 1.5 tons CO<sub>2</sub> to produce a ton of aluminum. Stripping hydrogen from CH<sub>4</sub> to make ammonia releases about 1.6 tons CO<sub>2</sub> per ton of ammonia.

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

Combustion of carbon-based fuels results in the emission of CO<sub>2</sub>. In many cases, the combustion process is not complete and other carbon-based compounds may

be released (carbon monoxide, CH<sub>4</sub>, volatile organic compounds). These often decompose into CO<sub>2</sub>, but their life spans in the atmosphere vary.

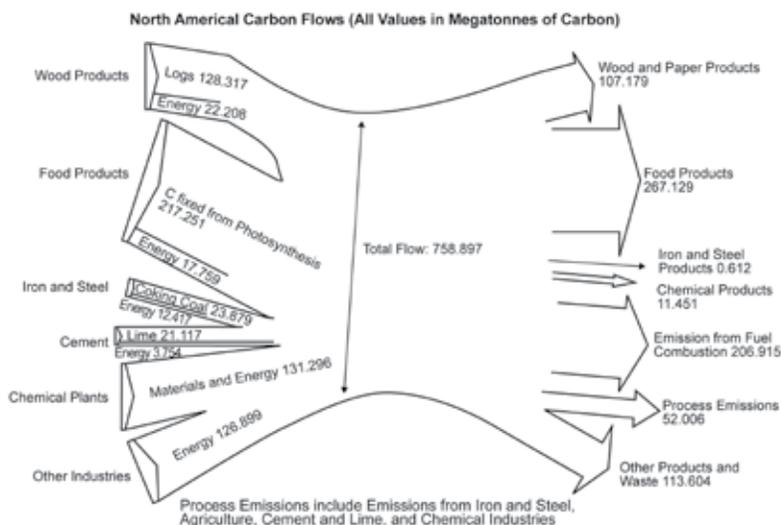
### 8.2.1.3 CARBON FLOW

Figure 8.2 illustrates the flows of carbon in and out of industries in North America.

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

## 8.2.2 Sectoral Trends in the Industrial Carbon Cycle

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



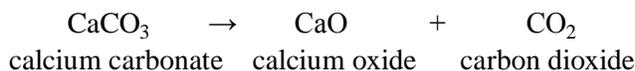
**Figure 8.2** Carbon flows for Canada, the United States, and Mexico combined. Values in megatons carbon can be converted to megatons CO<sub>2</sub> equivalents by multiplying by 44/12; the ratio of CO<sub>2</sub> mass to carbon mass. Comparable diagrams for the individual countries are in Appendix C. *Source:* Energy data from Statistics Canada Industrial Consumption of Energy survey, Conversion coefficients, IEA Oil Information (2004), IEA Coal Information (2005), IEA Natural Gas Information (2004). Process emissions from Environment Canada, Canada GHG Inventory (2002), EPA, U.S. Emissions Inventory. Production data from Statistics Canada, CANSIM Table 002-0010, Tables 303-0010, -0014 to -0021, -0024, -0060, Pub. Cat. Nos.: 21-020, 26-002, 45-002, Canadian Pulp and Paper Association on forestry products. Production of forestry products: USDA Database; FO-2471000, -2472010, -2482000, -2483040, -6342000, -6342040, U.S. Timber Production, Trade, Consumption, and Price Statistics 1965-2005. Production of organic products (e.g., food): USDA PS&D Official Statistical Results. Steel: International Iron and Steel Institute, World steel in figures (2003). Minerals production: USGS mineral publications.

### 8.2.2.1 PULP AND PAPER

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

### 8.2.2.2 CEMENT, LIME, AND OTHER NONMETALLIC MINERALS

Cement and lime production require the calcination of limestone, which releases CO<sub>2</sub>; about 0.78 tons of CO<sub>2</sub> per ton of lime calcined.



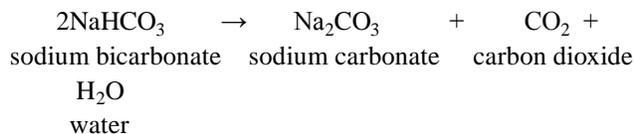
<sup>7</sup> In these industries, more CO<sub>2</sub> is generated from processing limestone than from the fossil fuels combusted.

<sup>8</sup> The calcination of limestone also takes place in steel, pulp and paper, glass, and sugar industries.

<sup>9</sup> This is also reflected in the United Nations Framework Convention on Climate Change (UNFCCC) IPCC guidelines to estimate CO<sub>2</sub> emissions.

Outside of the combustion of fossil fuels, lime calcining is the single largest human-caused source of CO<sub>2</sub> 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<sub>2</sub> generated.

The production of soda ash (sodium carbonate) from sodium bicarbonate in the Solvay process releases CO<sub>2</sub>, as in glass production, in its utilization. Soda ash is used to produce pulp and paper, detergents, and soft water.



### 8.2.2.3 NONFERROUS METAL SMELTING AND IRON AND STEEL SMELTING

Often metal smelting requires the reduction of metal oxides to obtain pure metal through use of a “reductant”, usually coke. Because reduction processes generate relatively pure streams of CO<sub>2</sub>, the potential for capture and storage is good.

In electric arc furnaces, carbon anodes decompose to CO<sub>2</sub> as they melt the scrap iron and steel feed in “mini-mills”. In Hall-Heroult cells, a carbon anode oxidizes when an electric current forces oxygen from aluminum oxide (alumina) in the production of aluminum<sup>10</sup>.

### 8.2.2.4 METAL AND NONMETAL MINING

Mining involves the extraction of ore and its transformation into a concentrated form. This involves transportation from mine site, milling, and separating mineral-bearing material from the ore. Some transportation depends on truck activity, but the grinding process is driven by electric motors (*i.e.*, indirect release of CO<sub>2</sub>). Some processes, like the sintering or agglomeration of iron ore and the liquid extraction of potash, use a considerable amount of fossil fuels directly.

### 8.2.2.5 CHEMICAL PRODUCTS

This diverse group of industries includes energy-intensive electrolytic processes as well as the consumption of large quantities of natural gas as a feedstock to produce commodities like ammonia, methanol, and hydrogen. Ethylene and propylene monomers from natural gas liquids are used in plastics production. Some chemical processes generate fairly pure streams of CO<sub>2</sub> suitable for capture and storage.

### 8.2.2.6 FOREST PRODUCTS

This industry uses biomass waste to dry commercial prod-



ucts such as lumber, plywood, and other products. The industry also includes silviculture, the practice of replanting and managing forests.

### 8.2.2.7 OTHER MANUFACTURING

Most of the remaining industries, while economically important, individually play a relatively minor role in the carbon cycle because they are not energy intensive and use little biomass<sup>11</sup>. In aggregate, however, these various industries contribute significantly to total industrial CO<sub>2</sub> emissions. Industries in this group include the automotive industry, electronic products, leather and allied products, fabricated metals, furniture and related products, and plastics and rubber products.

## 8.2.3 Changing Role of Industry in the Carbon Cycle

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

The National Energy Modeling System operated by the United States’ Energy Information Administration applies growth forecasts from the Global Insight macro-economic model. While the United States economy is forecast to grow at an average rate of 3.1% per year to 2025, industrial growth is forecast at 2.3% per year—an amalgam of manufacturing growth of 2.6% per year and non-manufacturing of 1.5% per year. Manufacturing is further disaggregated

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The shift from coal and refined petroleum products to natural gas and electricity contributed to a decline in total industrial CO<sub>2</sub> emissions since 1997 in both Canada and the United States.

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<sup>10</sup> Ceramic anodes may soon be available to aluminum producers and significantly reduce process CO<sub>2</sub> emissions.

<sup>11</sup> Except, of course, the food, beverage, and some textile industries.

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

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

Changes in carbon emissions result from these three factors, but also from changes in fuel shares—substitution away from or toward more carbon-intensive fuels. The shift from coal and refined petroleum products to natural gas and electricity<sup>13</sup> contributed to a decline in total industrial CO<sub>2</sub> 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.

### 8.2.4 Actions and Policies for Carbon Management in Industry

Industry managers can reduce carbon flows through industry by altering the material or energy intensity and character of production (IPCC, 2001). Greater materials efficiency

**Table 8.1 Energy reductions in recycling.**

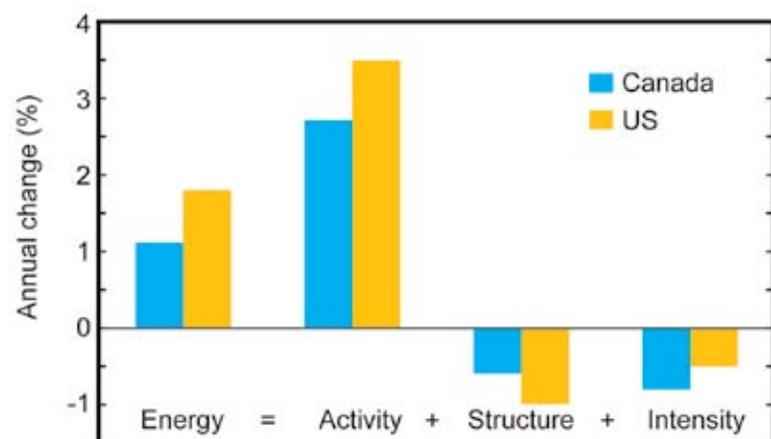
Recycled material	Energy saved	Recycled material	Energy saved
Aluminum	95%	Glass	31%
Tissue paper	54%	Newsprint	45%
Printing/writing paper	35%	Corrugated cardboard	26%
Plastics	57%–75%	Steel	61%

Source: Hershkowitz (1997)

typically reduces energy demands in processing because of reduced materials handling. For example, recycling materials often reduces energy consumption per unit of output by 26 to 95% (Table 8.1). Further work on materials substitution also holds promise for reduced energy consumption and emissions reduction<sup>14</sup>.

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

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



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

<sup>12</sup> Most of the information in this section is obtained from IEA (2004).

<sup>13</sup> As noted earlier, emissions associated with electricity are allocated to the electricity supply sector. Thus a shift to electricity reduces the GHG intensity of the industry using it. If electricity is made in coal-fired plants, however, total CO<sub>2</sub> emissions may actually increase.

## 8.3 WASTE MANAGEMENT CARBON CYCLE

The carbon cycle associated with human wastes includes industrial, commercial, construction, demolition, and residential waste. Municipal solid waste contains significant amounts of carbon. Paper, plastics, yard trimmings, food scraps, wood, rubber, and textiles made up more than 80% of the 236 Mt of municipal solid waste generated in the United States in 2003 (EPA, 2005) and the 25

<sup>14</sup> For example, substitute petrochemical feedstocks by biomass or concrete by wood in home foundations.

Mt generated in Canada (Statistics Canada, 2004), as shown in Table 8.2. In Mexico, as much as 20% of wastes are not systematically collected; no disaggregated data are available (EPA, 2005).

A portion of municipal solid waste is recycled: 31% in the United States (EPA, 2003b)<sup>†</sup> and 27% in Canada (Statistics Canada, 2004).<sup>‡</sup> Up to 14% of the remaining waste is incinerated in the United States, slightly less in Canada. Incineration can reduce the waste stream by up to 80%, but this ensures that more of the carbon reaches the atmosphere as opposed to being sequestered (or subsequently released as CH<sub>4</sub>) in a landfill. Incineration, however, can be used to cogenerate electricity and useful heat, which may reduce carbon emissions from stand-alone facilities.

Once in a landfill, carbon in wastes may be acted upon biologically, releasing roughly equal amounts of CO<sub>2</sub> and CH<sub>4</sub> by volume<sup>15</sup> depending on ambient conditions, as well as a trace amount of carbon monoxide and volatile organic compounds. While no direct data on the quantity of CO<sub>2</sub> released from landfills exists, one can estimate the CO<sub>2</sub> released by using this ratio; the estimated amount of CO<sub>2</sub> released from landfills in Canada and the United States (no data from Mexico) would be approximately 38 Mt<sup>16</sup>, a relatively small amount compared to the total of other subsectors in this chapter. Also, recall that these emissions are from biomass and, in the context of IPCC assessment guidelines, are considered GHG-neutral.

Depending on the degree to which aerobic or anaerobic metabolism takes place, a considerable amount of carbon remains unaltered and more or less permanently stored in the landfill (75%-80%; see Barlaz and Ham, 1990; Barlaz, 1994; and Bogner and Spokas, 1993). Because data on the proportions of carboniferous material entering landfills can be estimated, approximate carbon contents of these materials can be determined and the degree to which these materials can decompose, it would be possible to estimate the amount of carbon sequestered in a landfill site (see EPIC,

<sup>15</sup> Based on gas volumes, this means that roughly equivalent amounts of carbon are released as CO<sub>2</sub> as CH<sub>4</sub>.

<sup>16</sup> 14 Mt of CH<sub>4</sub> (see Table 8.3) are equivalent, volume wise at standard temperature and pressure, to 38 Mt of CO<sub>2</sub>. This derived estimate is highly uncertain and not of the same caliber as other emissions data provided here.

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

	United States	Canada	Mexico
Total waste (Mt per year)	236.0	24.8	29.2
Recycled	72.0	6.6	–
Carbon-based waste	197.1	19.6	–
Carbon-based waste recycled	47.3 <sup>a</sup>	4.3	–
Carbon sequestered (CO <sub>2</sub> equivalents)	10.1	–	–
Methane (kt per year)			
Generated	12,486	1,452	–
Captured, oxidized	6,239	336	–
Emitted	6,247	1,117	–
Emitted (CO <sub>2</sub> equivalents)	131,187	23,453	–

<sup>a</sup> Calculated estimate

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

2002; Mohareb *et al.*, 2004; EPA, 2003b; EPA, 2005). While EPA (2005) provides an estimate of carbon sequestered in US landfills (see Table 8.2), no data are available for other regions.

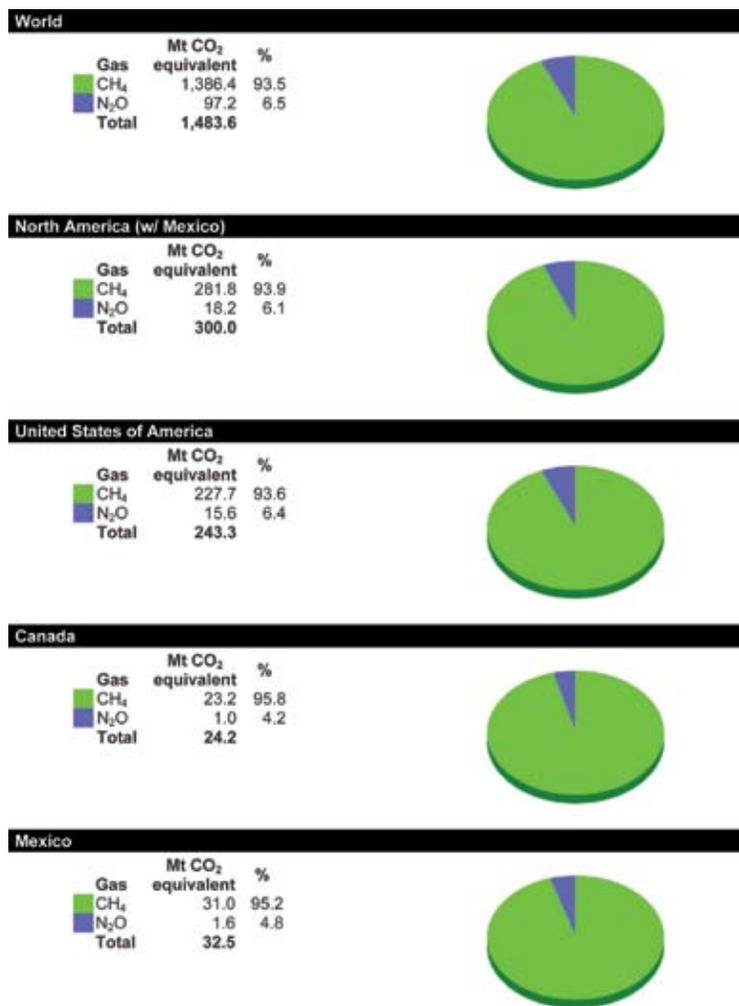
Municipal solid waste contains significant amounts of carbon.

Anaerobic digestion generates CH<sub>4</sub> gases that can be captured and used in cogenerators. Many of the 1800 municipal solid waste sites in 2003 in the United States captured and combusted landfill-generated CH<sub>4</sub>; about half of all the CH<sub>4</sub> produced was combusted or oxidized in some way (EPA, 2005). In Canada, about 23% of the CH<sub>4</sub> emissions were captured and utilized to make energy in 2002 (Mohareb *et al.*, 2004). The resultant CO<sub>2</sub> released from such combustion is considered biological in origin. Thus only CH<sub>4</sub> emissions, at 21 times the CO<sub>2</sub> warming potential, are included as part of GHG inventories. Their combustion greatly alleviates the net contribution to GHG emissions and, if used in cogeneration, may offset the combustion of fossil fuels elsewhere. Figure 8.4 provides an estimate of CH<sub>4</sub> (and nitrous oxide [N<sub>2</sub>O]) as the other GHG for comparison) released from landfills and waste treatment facilities.

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

Defining costs associated with reducing human-caused (anthropogenic) impacts on the carbon cycle is a highly contentious issue. Different approaches to cost assessments (top-down, bottom-up, applicable discount rates, social costing, cost effectiveness, no regrets), different understandings of what costs include (risk, welfare, intangibles, capital investment cycles), different values associated with energy demand in different countries (accessibility, availability, infrastructure, resource type and size), actions and technologies included in the analysis, and the perspective





**Figure 8.4** Greenhouse gas emissions by gas from waste in 2000. Source: WRI (World Resources Institute) (2005). The magnitude and/or range of uncertainty for the given numerical values is not provided in the reference. To convert from Mt CO<sub>2</sub> equivalent to Mt C equivalent, multiply the Mt CO<sub>2</sub> value by 12/44.

on technology development all have an impact on evaluating costs. Should analysts consider only historical responses to energy prices, production and demand elasticities, or income changes? Does one consider only technology options and their strict financial costs or see historic technology investments as sunk costs? Should one include producers' or consumers' welfare? Are there local, national, international issues?

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

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

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

When looking at cost numbers like this, one should remember that, for each \$10 cost increment per t CO<sub>2</sub> (or about \$37 per t C), gasoline prices would increase about 2.4¢/L (9¢/U.S. gallon). Diesel fuel cost would be nearly 2.7¢/L (10¢/U.S. gallon). Costs per Gigajoule (GJ)<sup>18</sup> vary by fuel: coal rises about 90¢/GJ, depending on type, heavy fuel oil (HFO) by 73¢, and natural gas by 50¢. At 35% efficiency, coal-fired electricity generation would be about 0.8¢/kWh higher, about 0.65¢/kWh for HFO, and about 0.45¢/kWh for natural gas.

Of course, as the cost of carbon increases, one moves up the carbon supply curve for industrial sectors. However, reductions become marginal or insignificant and so are not included in Table 8.3.

If a cell in Table 8.3 shows two cost categories (e.g., A/B) and two reduction levels (%Q<sub>red</sub> is 15/20), the value associated with the second portrays the additional reduction at that increased expenditure level. Thus spending up to \$50/t CO<sub>2</sub> to improving efficiency in metal smelting implies a potential reduction of 35% (see Table 8.3). Reductions in each category are not additive for an industry type because categories are not independent.

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

<sup>17</sup> Studies vary widely in how they define system boundaries, baseline, and time periods, which sectors or subsectors are included, economic assumptions, and many other factors. See *Some Explanatory Notes* in Section 8.4.1 for a list.

<sup>18</sup> A Gigajoule (GJ), or one billion joules, is slightly smaller than 1 MMBtu (1 GJ = 0.948 MMBtu).

**Table 8.3 Approximate costs and reductions potential.**

Sector	Reduction of fugitives		Energy efficiency		Process change		Fuel substitution		Carbon Capture and Storage	
	Cost category	%Q <sub>red</sub>	Cost category <sup>a</sup>	%Q <sub>red</sub> <sup>a</sup>	Cost category	%Q <sub>red</sub>	Cost category	%Q <sub>red</sub>	Cost category <sup>a</sup>	%Q <sub>red</sub> <sup>a</sup>
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

<sup>a</sup> 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<sub>2</sub>-Based: A: \$0–\$25/t CO<sub>2</sub>; B: \$25–\$50/t CO<sub>2</sub>; C: \$50–\$100/t CO<sub>2</sub>; D: >\$100/t CO<sub>2</sub>

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

### 8.4.1 Some Explanatory Notes

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

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

#### 8.4.1.1 PROCESS AND FUGITIVES

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

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

<sup>20</sup> John Weyant of Stanford University is currently editing another analysis similar to this listed publication to be released in the near future.

In the waste sector, the reductions potentials are very large; we have simply estimated possible reductions if we were to trap and burn all landfill CH<sub>4</sub>. The costs for this are quite low. EPA (2003a) estimates of between 40% and 60% of CH<sub>4</sub> available for capture may generate net economic benefits.

#### 8.4.1.2 ENERGY EFFICIENCY

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

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

#### 8.4.1.3 PROCESS CHANGE

Reductions from process change requires not only an understanding of the industry and its potential for change but also an understanding of the market demand for industry products that may change over time. In pulp production, for example, one could move from higher quality kraft pulp to mechanical pulp and increase production ratios (the



kraft process only converts one-half the input wood into pulp), but will market acceptability for the end product be unaffected? Numerous substitution possibilities exist in the rather diverse *Other Manufacturing* industries (carpet recycling, alternative uses for plastics, *etc.*).

#### 8.4.1.4 FUEL SUBSTITUTION

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

#### 8.4.1.5 CARBON CAPTURE AND STORAGE (CC&S)

In one sense, all industries and landfills could reduce emissions through CC&S but the range of appropriate technologies has not been fully defined and/or the costs are very high. For example, one could combust fuels in a pure oxygen environment such that the exhaust steam is CO<sub>2</sub>-rich and suitable for capture and storage. Even so, some industries, like cement production, are reasonable candidates for capture, but cost of transport of the CO<sub>2</sub> to storage may prohibit implementation (see particularly Herzog, 1999; DOE, 2006).



## 8.5 RESEARCH AND DEVELOPMENT NEEDS

If we assume that carbon management will play a significant role in the future and that fossil fuels are likely to remain an economical energy supply for industries, research and development (R&D) will focus on the control of carbon emissions related to the extraction of this energy. Typical combustion technologies extract and transform fossil fuels' chemical energy relatively efficiently but, outside of further improvements in efficiency, they generally do little to manage the emissions generated. More recently, advanced technologies remove particularly onerous airborne emissions, such as compounds of sulphur and nitrogen, particulates, volatile organic compounds, and other criteria air contaminants. However, emissions of CO<sub>2</sub> remain relatively unaltered. In the light of changing views on the impacts of CO<sub>2</sub> released to the atmosphere, R&D will likely focus on the extraction of the energy while preventing CO<sub>2</sub> release. Fossil fuels might well remain economically competitive and socially

desirable as a source of energy in some circumstances, even when one includes the extra cost of capturing the CO<sub>2</sub> and preventing its atmospheric release when converting these fuels into non-carbon secondary forms of energy like electricity, hydrogen, or heat.

Some carbon capture and storage processes currently exist; indeed, oil companies have long "sequestered" CO<sub>2</sub> to enhance oil recovery from underground wells simply by injecting it into the oil reservoir. Many newer processes to accomplish CO<sub>2</sub> capture are being investigated, primarily in two categories: pre-combustion and post-combustion processes. Pre-combustion alternatives include gasification processes where, for example, coal's energy is entrapped in hydrogen and the CO<sub>2</sub> stream is subsequently sequestered. Post-combustion alternatives include carbon combustion in pure oxygen atmospheres and then trapping the resultant CO<sub>2</sub> for sequestration, and flue stack devices designed to extract the CO<sub>2</sub> from the flue gases for delivery to sequestration systems. Research has also been conducted on devices that can extract CO<sub>2</sub> directly from the atmosphere (Keith *et al.*, 2003).

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