Chapter 8. Industry and Waste Management

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KEY FINDINGS

- In 2002, North America's industry (not including fossil fuel mining and processing or electricity generation) contributed 826 Mt CO_2, 16% of the world's CO_2 emissions to the atmosphere from industry. Waste treatment plants and landfill sites in North America accounted for 13.4 Mt of CH_4 (282 Mt CO_2e), roughly 20% of global totals.
- Industrial CO_2 emissions from North America decreased nearly 11% between 1990 and 2002, while energy consumption in the United States and Canada increased 8% to 10% during that period. In both countries, a shift in production activity toward less energy-intensive industries and dissemination of more energy efficient equipment kept the rate of energy demand growth lower than industrial GDP growth.
- Changes in industrial CO_2 emissions are a consequence of changes in industrial energy demand and changes in the mix of fossil fuels used by industry to supply that demand. Changes in industrial energy demand are themselves a consequence of changes in total industrial output, shifts in the relative shares of industrial sectors, and increases in energy efficiency. Shifts from coal and refined petroleum products to natural gas and electricity contributed to a decline in total industrial CO_2 emissions since 1997 in both Canada and the United States.
- An increase in CO_2 emissions from North American industry is likely to accompany the forecasted increase in industrial activity (2.3% yr^{-1} until 2025 for the United States). Emissions per unit of industrial activity will likely decline as non-energy intensive industries grow faster than energy intensive industries and with increased penetration of energy efficient equipment. However, continuation of the trend toward less carbon-intensive fuels is uncertain given the rise in natural gas prices relative to coal in recent years.
- Options and measures for reducing CO_2 emissions from North American industry can be broadly classified as methods to: (1) reduce process/fugitive emissions or converting currently released emissions; (2) increase energy efficiency, including combined heat and power; (3) change industrial processes (materials efficiency, recycling, substitution between materials or between materials and energy); (4) substitute less carbon intense fuels; and (5) capture and store carbon dioxide.

- Further work on materials substitution holds promise for industrial emissions reduction, such as the replacement of petrochemical feedstocks by biomass feedstocks, of steel by aluminium in the transport sector, and of concrete by wood in the buildings sector. The prospects for greater energy efficiency technologies, including efficient Hall-Heroult cell retrofits in aluminium production, black liquor gasification in kraft pulp production, and shape casting in iron and steel industries are equally substantial.

INTRODUCTION

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

In 2002, industry was responsible for 5220.6 Mt of CO_2, 21% of anthropogenic CO_2 emissions to the atmosphere (4322.9 Mt from fuel combustion and 897.7 Mt from industrial processes). North America's industry contributed 758.7 Mt of combustion-sourced emissions and 66.8 Mt of process emissions for a total of 826 Mt, 16% of global totals. The manufacturing industry contributed 12% of total North American greenhouse gas (GHG) emissions, lower than in many other parts of the world. But with North America's population at 6.8% of the world's total, industry contributed a proportionally larger share of total industrial emissions per capita than the rest of the world (see Fig. 8-1A).[2]

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

Industrial CO_2 emissions decreased nearly 11% between 1990 and 2002 while energy consumption in the United States and Canada increased 8% to 10% (EIA, 2005; CIEEDAC, 2005). In both countries, a shift in production activity toward less energy-intensive industries and dissemination of more energy efficient equipment kept the rate of growth in energy demand lower than industrial GDP growth (IEA, 2004).[3] This slower demand growth, in concert with a shift toward less carbon-intensive fuels, explains the decrease in industrial CO_2 emissions.

The municipal waste stream excludes agricultural and forestry wastes but includes wastewater. CO_2, generated from aerobic metabolism in waste removal and storage processes, arises from biological material and is considered GHG neutral. Methane (CH_4), released from anaerobic activity at waste

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

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

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

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

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

Substantial sequestration of carbon occurs in landfills.[5] Data on carbon buried there are poor. The Environmental Protection Agency (EPA), using data from Barlaz (1990, 1994), estimated that 30% of carbon in food waste and up to 80% of carbon in newsprint, leaves, and branches remain in the landfill. Plastics show no deterioration. In all, 80% of the carbon entering a landfill site may be sequestered, depending on moisture, aeration, and site conditions. Bogner and Spokas (1993) estimate that "more than 75% of the carbon deposited in landfills remains in sedimentary storage."

INDUSTRY CARBON CYCLE

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

Overview of Carbon Inputs and Outputs

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

Carbon In

Carbon-based raw materials typically enter industrial sites as biomass (primarily wood), limestone, soda ash, oil products, coal/coke, natural gas and natural gas liquids. These inputs are converted to

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

dimension lumber and other wood products, paper and paperboard, cement and lime, glass, and a host of chemical products, plastics, and fertilizers.

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

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

Carbon Out

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

Process emissions are CO_2 emissions that occur as a result of the process itself—the calcining of limestone releases about 0.5 tons CO_2 per ton of clinker (unground cement) or about 0.8 tons per ton of lime.[6,7] The oxidation of carbon anodes generates about 1.5 tons CO_2 to produce a ton of aluminum. Striping hydrogen from methane to make ammonia releases about 1.6 tons CO_2 per ton of ammonia.

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

Carbon Flow

Figure 8-2 illustrates the flows of carbon in and out of industries in North America. Comparable diagrams for individual countries are presented in Appendix 8A. On the left side of Fig. 8-2, all carbon-

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

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

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

Sectoral Trends in the Industrial Carbon Cycle

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

Pulp and Paper

While pulp and paper products are quite energy-intensive, much of the energy is obtained from biomass. By using hog fuel and black liquor, some types of pulp mills are energy self-sufficient. Biomass fuels are considered carbon neutral because return of the biomass carbon to the atmosphere completes a cycle that began with carbon uptake from the atmosphere by vegetation.[8] Fuel handling difficulties and air quality concerns can arise from the use of biomass as a fuel.

Cement, Lime, and Other Nonmetallic Minerals

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

$CaCO_3$	$\rightarrow$	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.

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

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

$$2NaHCO_3 \rightarrow Na_2CO_3 + CO_2 + H_2O$$

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

In electric arc furnaces, carbon anodes decompose to CO_2 as they melt the scrap iron and steel feed in "mini-mills". In Hall-Heroult cells, a carbon anode oxidizes when an electric current forces oxygen from aluminium oxide (alumina) in the production of aluminum.[9]

Metal and Nonmetal Mining

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

Chemical Products

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

Forest Products

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

Other Manufacturing

Most of the remaining industries, while economically important, individually play a relatively minor role in the carbon cycle because they are not energy intensive and use little biomass.[10] In aggregate, however, these various industries contribute significantly to total industrial CO_2 emissions. Industries in

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

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

Changing Role of Industry in the Carbon Cycle

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

The National Energy Modelling System operated by the United States' Energy Information Administration applies growth forecasts from the Global Insight macroeconomic model. While the United States economy is forecast to grow at an average rate of 3.1% per year to 2025, industrial growth is forecast at 2.3% per year—an amalgam of manufacturing growth of 2.6% per year and non-manufacturing of 1.5% per year. Manufacturing is further disaggregated into energy-intensive industries, growing at 1.5% per year, and non-energy intensive industries at 2.9% per year. The slower growth in the energy-intensive industries is reflected in the expected decline in industrial energy intensity of 1.6% per year over the EIA (2005) forecast.

The International Energy Agency reviewed energy consumption and emissions during the last 30 years to identify and project underlying trends in carbon intensity.[11] The review's decomposition analysis (Fig. 8-3) attributes changes in industrial energy demand to changes in total industrial output (activity), shifts in the relative shares of industrial sectors (structure), and increases in energy efficiency (intensity).

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

Changes in carbon emissions result from these three factors, but also from changes in fuel shares—substitution away from or toward more carbon-intensive fuels. The shift from coal and refined petroleum products to natural gas and electricity[12] contributed to a decline in total industrial CO_2 emissions since 1997 in both Canada and the United States. The continuation of this trend is uncertain given the rise in natural gas prices relative to coal in recent years.

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

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

Actions and Policies for Carbon Management in Industry

Industry managers can reduce carbon flows through industry by altering the material or energy intensity and character of production (IPCC, 2001). Greater materials efficiency typically reduces energy demands in processing because of reduced materials handling. For example, recycling materials often reduces energy consumption per unit of output by 26 to 95% (Table 8-1). Further work on materials substitution also holds promise for reduced energy consumption and emissions reduction.[13]

Table 8-1. Energy reductions in recycling

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

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

WASTE MANAGEMENT CARBON CYCLE

The carbon cycle associated with human wastes includes industrial, commercial, construction, demolition, and residential waste. Municipal solid waste contains significant amounts of carbon. Paper, plastics, yard trimmings, food scraps, wood, rubber, and textiles made up more than 80% of the 236 Mt of municipal solid waste generated in the United States in 2003 (EPA, 2005) and the 25 Mt generated in Canada (Statistics Canada, 2004), as shown in Table 8-2. In Mexico, as much as 20% of wastes are not systematically collected; no disaggregated data are available (EPA, 2005).

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

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

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

Once in a landfill, carbon in wastes may be acted upon biologically, releasing roughly equal amounts of CO_2 and methane (CH_4) by volume[14] depending on ambient conditions, as well as a trace amount of carbon monoxide and volatile organic compounds. While no direct data on the quantity of CO_2 released from landfills exists, one can estimate the CO_2 released by using this ratio; the estimated amount of CO_2 released from landfills in Canada and the United States (no data from Mexico) would be approximately 38 Mt,[15] a relatively small amount compared to total other (sub)sectors in this chapter. Also recall that these emissions are from biomass and, in the context of IPCC assessment guidelines, are considered GHG-neutral.

Depending on the degree to which aerobic or anaerobic metabolism takes place, a considerable amount of carbon remains unaltered and more or less permanently stored in the landfill (75%–80%; see Barlaz, 1990, 1994; and Bogner and Spokas, 1993). Because data on the proportions of carboniferous material entering landfills can be estimated, approximate carbon contents of these materials can be determined and the degree to which these materials can decompose, it would be possible to estimate the amount of carbon sequestered in a landfill site (see EPIC, 2001; Mohareb *et al.*, 2003; EPA, 2003; EPA, 2005). While EPA (2005) provides an estimate of carbon sequestered in US landfills (see Table 8-2), no data are available for other regions.

Anaerobic digestion generates methane gases that can be captured and used in cogenerators. Many of the 1,800 municipal solid waste sites in 2003 in the United States captured and combusted landfill-generated methane; about half of all the methane produced was combusted or oxidized in some way (EPA, 2005). In Canada, about 23% of the methane emissions were captured and utilized to make energy in 2002 (Mohareb *et al.*, 2003). The resultant CO_2 released from such combustion is considered biological in origin. Thus, only methane emissions, at 21 times the CO_2 warming potential, are included as part of GHG inventories. Their combustion greatly alleviates the net contribution to GHG emissions and, if used in cogeneration, may offset the combustion of fossil fuels elsewhere.

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

[15]14 Mt of CH_4 (see Table 8-3) are equivalent, volume wise at standard temperature and pressure, to 38 Mt of CO_2. This derived estimate is highly uncertain and not of the same caliber as other emissions data provided here.

COSTS RELATED TO CONTROLLING ANTHROPOGENIC IMPACTS ON THE CARBON CYCLE

Defining costs associated with reducing anthropogenic impacts on the carbon cycle is a highly contentious issue. Different approaches to cost assessments (top-down, bottom-up, applicable discount rates, social costing, cost effectiveness, no regrets), different understandings of what costs include (risk, welfare, intangibles, capital investment cycles), different values associated with energy demand in different countries (accessibility, availability, infrastructure, resource type and size), actions and technologies included in the analysis, and the perspective on technology development all have an impact on evaluating costs. Should analysts consider only historical responses to energy prices, production and demand elasticities or income changes? Does one consider only technology options and their strict financial costs or see historic technology investments as sunk costs? Should one include producers' or consumers' welfare? Are there local, national, international issues?

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

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

One can attribute potential reductions over a set time period under a range of costs. We suggest the cost-range categories ("A" through "D") shown in Table 8-3. The table contains estimates of the percentage reduction by industry under these cost categories. Costs are not drawn from a single source but are the authors' estimates based on a long history of costs reported in various documents.[16] Some studies focus on technical potential and don't provide the cost of achieving the reductions. As such, achievable reductions are likely overestimated. Others describe optimization models that provide normative costs and likely overestimate potentials and underestimate costs. Still others use top-down approaches where historic data sets are used to determine relationships between emissions and factors of production; costs are often high and emissions reductions underestimated.

Table 8-3. Approximate costs and reductions potential

[16] Studies vary widely in how they define system boundaries, baseline and time periods, which sectors or subsectors are included, economic assumptions, and many other factors. See *Some Explanatory Notes* below Table 8-3 for a list.

When looking at cost numbers like this, one should remember that, for each \$10 cost increment per t CO_2 (or about \$37 per t C), gasoline prices would increase about 2.4¢/L (9¢/U.S. gal). Diesel fuel cost would be nearly 2.7¢/L (10¢/U.S. gal). Costs per GJ[17] vary by fuel: coal rises about 90¢/GJ, depending on type, HFO by 73¢, and natural gas by 50¢. At 35% efficiency, coal-fired electricity generation would be about 0.8¢/kWh higher, about 0.65¢/kWh for HFO, and about 0.45¢/kWh for natural gas.

Of course, as the cost of carbon increases, one moves up the carbon supply curve for industrial sectors. But reductions become marginal or insignificant and so are not included in Table 8-3. If a cell in Table 8-3 shows two cost categories (e.g., A/B) and two reduction levels ($\%Q_{red}$ is 15/20), the value associated with the second portrays the *additional* reduction at that increased expenditure level. Thus, spending up to \$50/t CO_2 to improving efficiency in metal smelting implies a potential reduction of 35% (see Table 8-3). Reductions in each category are *not* additive for an industry type because categories are not independent.

Because not all reduction methods are applicable to all industries, as one aggregates to an "all industry" level (top line, Table 8-3), the total overall emissions reduction level may be less than any of the individual industries sited.

Some Explanatory Notes

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

- *General overviews*: Grubb *et al*., 1993; Weyant *et al*., 1999;[19] Grubb *et al*., 2002; Löschel, 2002.
- *Top-down analyses*: McKitrick, 1996; Herzog, 1999; Sands, 2002; McFarland *et al*., 2004; Schäfer and Jacoby, 2005; Matysek, *et al*., 2006.
- *Bottom up analyses*: Martin *et al.*, 2001; Humphreys and Mahasenan, 2002; Worrell *et al.*, 2004; Kim and Worrell, 2002; Morris *et al.*, 2002; Jaccard *et al.*, 2003; DOE, 2006; IEA, 2006.
- *Hybrid model analyses*: Böhringer, 1998; Jacobsen, 1998; Edmonds *et al.*, 2000; Koopmans and te Velde, 2001; Jaccard, 2002; Frei *et al.*, 2003; Jaccard *et al.*, 2003; Jaccard, Nyboer, *et al.*, 2003; Edenhofer *et al.*, 2006.
- *Others*: Newell *et al.*, 1999; Sutherland, 2000; Jaffe *et al.*, 2002.

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

[18] Two authors are currently involved with IPCC's upcoming fourth assessment report where estimated costs of reduction are provided. Preliminary reviews of the cost data presented there do not differ substantially from those in table 8-3.

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

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

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

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

A "bottom up" technical analyses tends to show higher potentials and lower costs than when one uses a hybrid or a "top-down" approach to assess reduction potentials due to efficiency improvements; Table 8-3 portrays the outcome of the more conservative hybrid (mix of top-down and bottom-up) approach and provides what some may consider conservative estimates of reduction potential (see particularly Martin *et al.*, 2001; Jaccard *et al.*, 2002; Jaccard *et al.*, 2003; Jaccard, Nyboer, *et al.*, 2003; Worrell *et al.*, 2004).

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

Fuel Substitution: It is difficult to isolate fuel substitution and efficiency improvement because fuels display inherent qualities that affect efficiency. Fuel substitution can reduce carbon flow but efficiency may become worse. In wood products industries, shifts to biomass reduces emissions but increases energy use. In terms of higher heating values, shifts from coal or oil to natural gas may worsen efficiencies while reducing emissions.[20]

Carbon Capture and Storage (CC&S): In one sense, all industries and landfills could reduce emissions through CC&S but the range of appropriate technologies has not been fully defined and/or the costs are very high. For example, one could combust fuels in a pure oxygen environment such that the exhaust steam is CO_2-rich and suitable for capture and storage. Even so, some industries, like cement

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

production, are reasonable candidates for capture, but cost of transport of the CO_2 to storage may prohibit implementation (see particularly Herzog, 1999; DOE, 2006).

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Table 8-1. Energy reductions in recycling

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

Source: Hershkowitz, 1997.

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

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

* Calculated estimate

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

Table 8-3. Approximate costs and reductions potential

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

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

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

The "Cost Categories" are as follows:

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

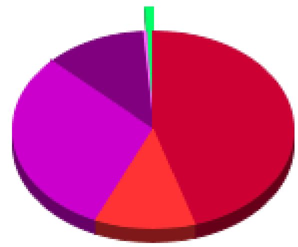
Carbon-Based: **A:** \$0–\$92/t C; **B:** \$92–\$180/t C; **C:** \$180–\$367/t C; **D:** >\$367/t C

World

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

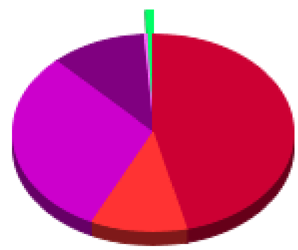
North America (w/ Mexico)

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



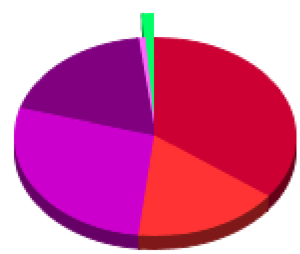
United States of America

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



Canada

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



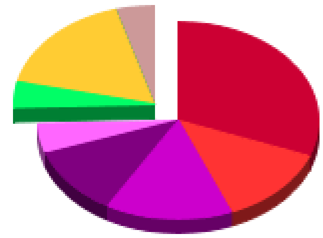
Mexico

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

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

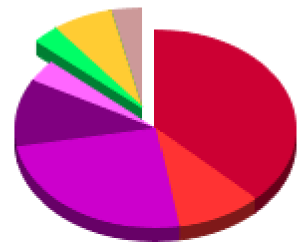
World

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



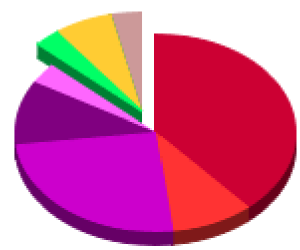
North America (w/ Mexico)

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



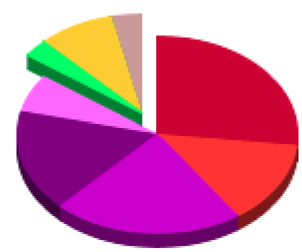
United States of America

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



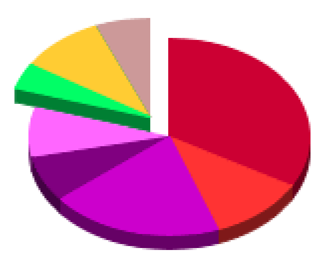
Canada

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



Mexico

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



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

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

1

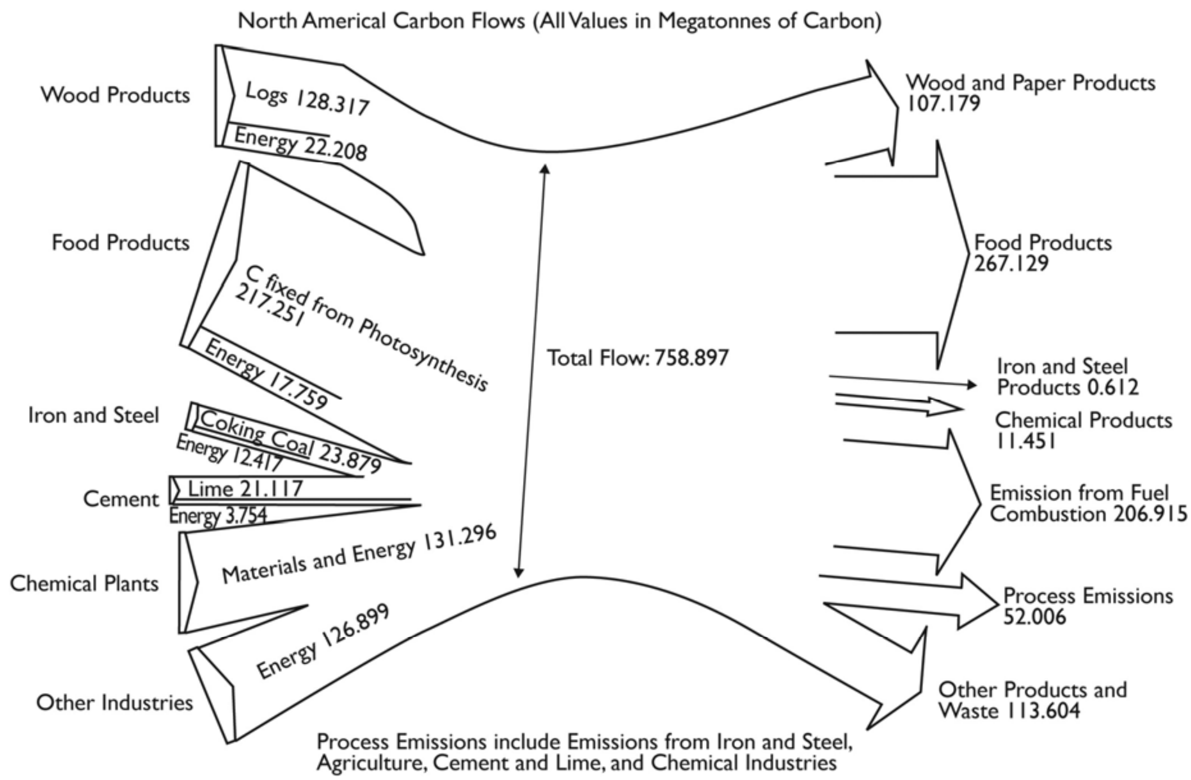


Fig. 8-2. Carbon flows for Canada, the United States and Mexico combined. Values in kilotons carbon can be converted to kilotons CO_2 equivalents by multiplying by 44/12, the ratio of carbon dioxide mass to carbon mass. Comparable diagrams for the individual countries are in Appendix 8A**.** *Source*: Energy data from Statistics Canada Industrial Consumption of Energy survey, Conversion coefficients, IEA Oil Information 2004, IEA Coal Information 2005, IEA Natural Gas Information 2004. Process emissions from Environment Canada, *Canada GHG Inventory, 2002,* EPA, U.S. Emissions Inventory. Production data from Statistics Canada, CANSIM Table 002-0010, Tables 303-0010, -0014 to -0021, -0024, -0060, Pub. Cat. Nos.: 21-020, 26-002, 45-002, Canadian Pulp and Paper Association on forestry products. Production of forestry products: USDA Database; FO-2471000, -2472010, -2482000, -2483040, -6342000, -6342040, U.S. Timber Production, Trade, Consumption, and Price Statistics 1965–2005. Production of organic products (e.g., food): USDA PS&D Official Statistical Results. Steel: International Iron and Steel institute, World steel in figures 2003. Minerals production: USGS mineral publications.

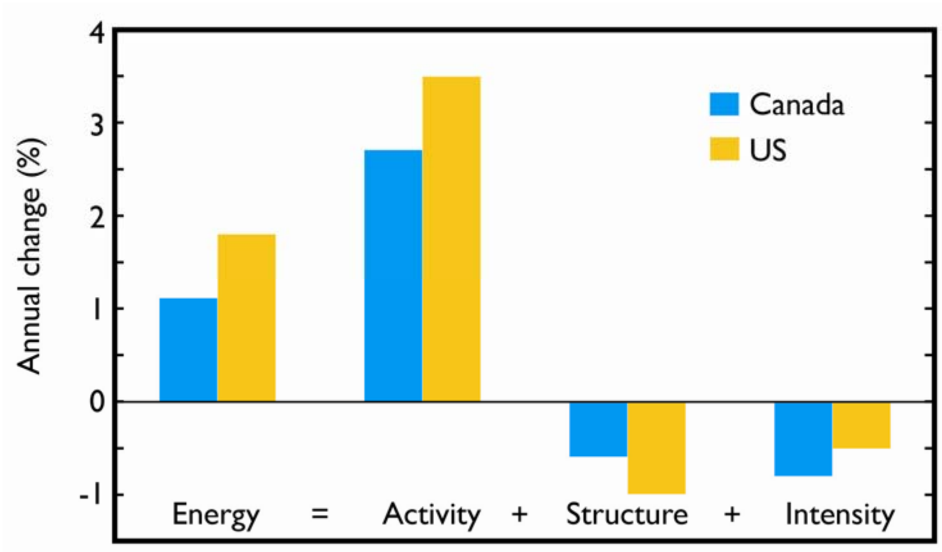
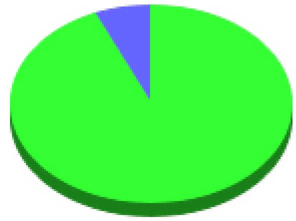


Fig. 8-3. Decomposition of energy use, manufacturing sector, 1990–1998. *Source*: IEA, 2004.

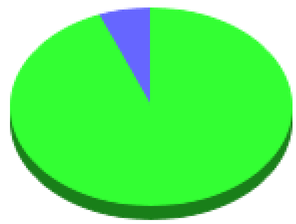
World

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



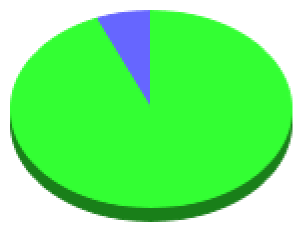
North America (w/ Mexico)

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



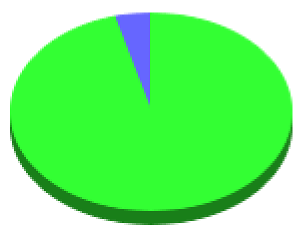
United States of America

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



Canada

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



Mexico

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

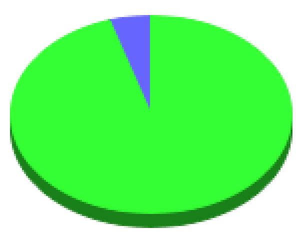


Fig. 8-4. GHG emissions by gas from waste in 2000. *Source*: Climate Analysis Indicators Tool (CAIT) Version 3.0 (Washington, D.C.: World Resources Institute, 2005).

Appendix 8A

Industry and Waste Management – Supplemental Material

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

Figure 8A-1. Carbon flows, Canada.

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

Figure 8A-3. Carbon flows, Mexico.

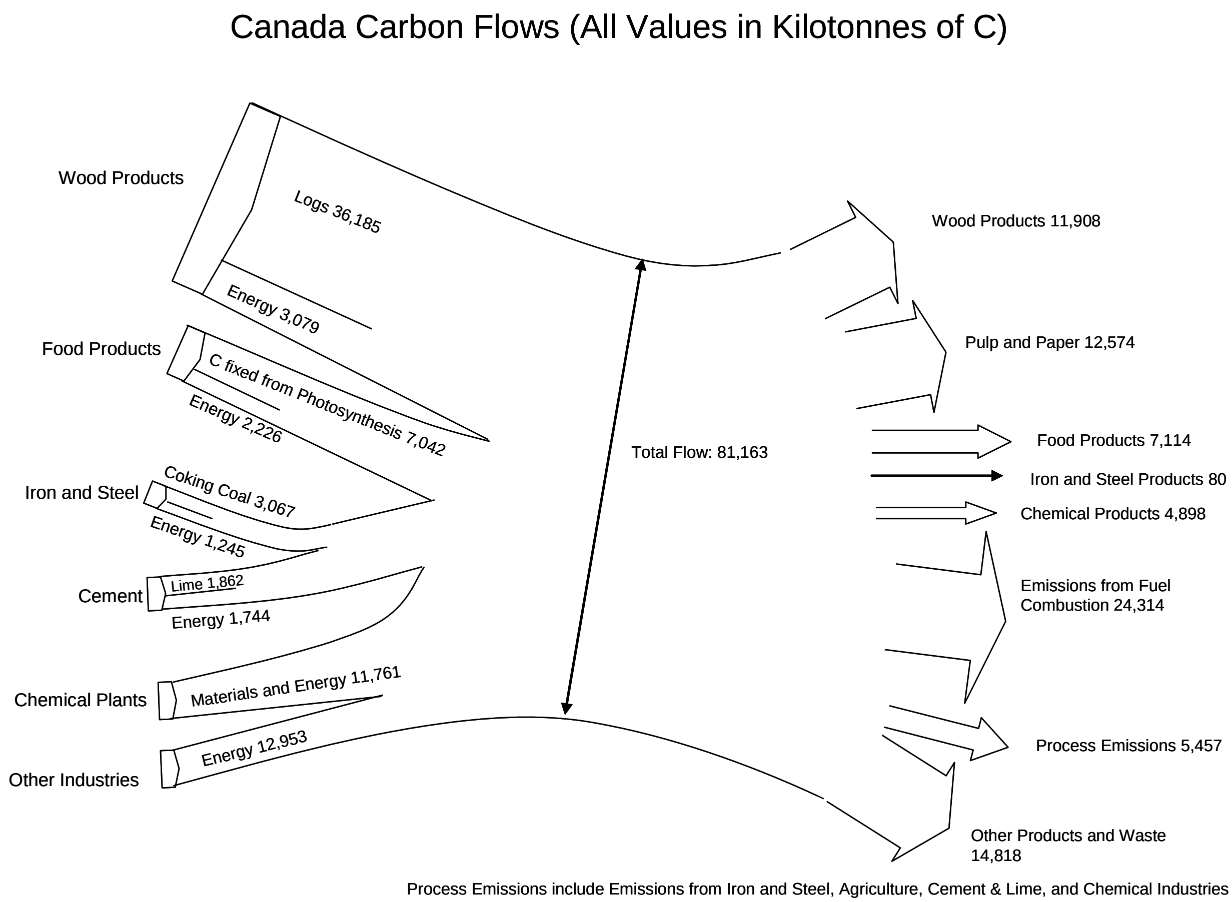


Fig. 8A-1. Carbon flows, Canada. *Source*: Energy data from Statistics Canada Industrial Consumption of Energy survey, conversion coefficients and process emissions from Environment Canada, *Canada GHG Inventory, 2002*. Production data from Statistics Canada, CANSIM Table 002-0010, Tables 303-0010, -0014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

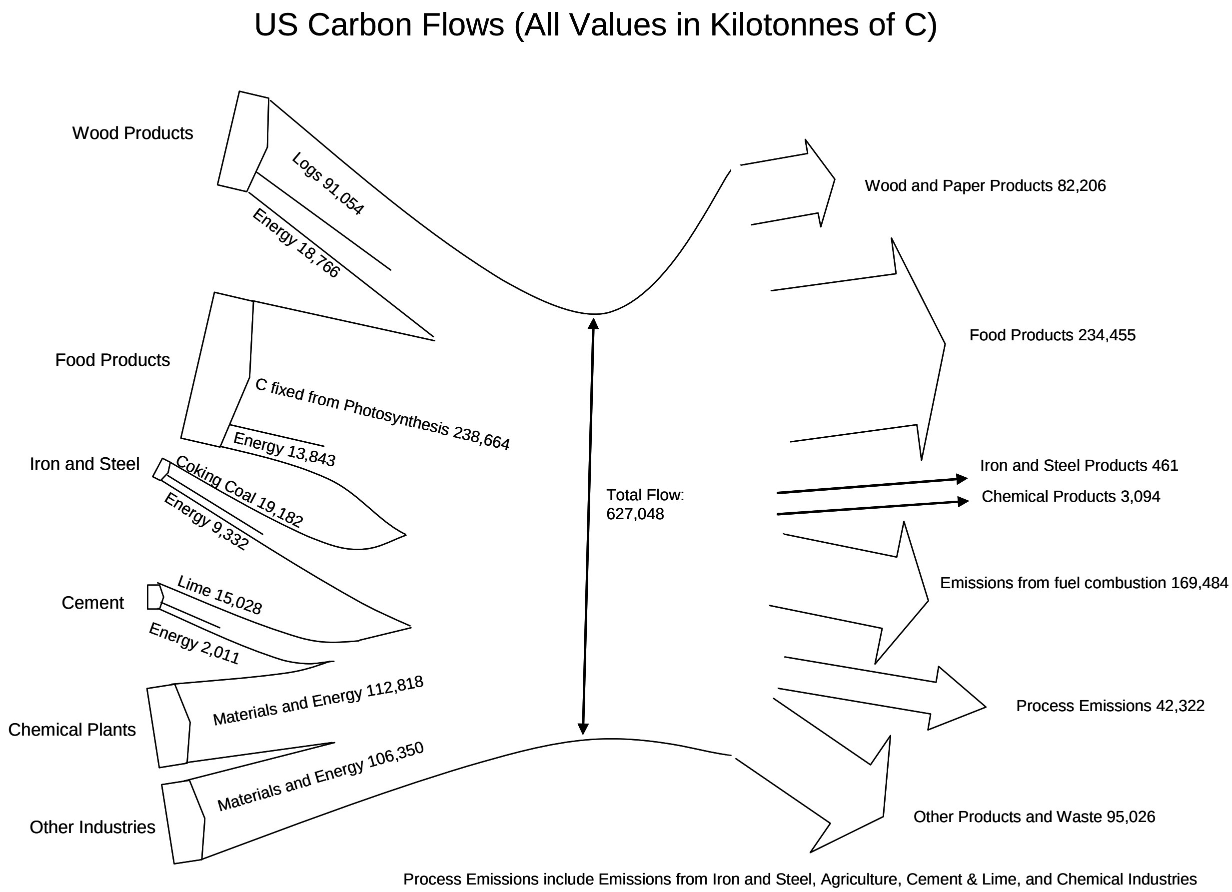


Fig. 8A-2. Carbon flows, United States. *Source*: Energy data from IEA Oil Information 2004, IEA Coal Information 2005, IEA Natural Gas Information 2004. Process emissions: EPA, U.S. Emissions Inventory. Production of forestry products: USDA Database; FO-2471000 and -2472010, U.S. Timber Production, Trade, Consumption, and Price Statistics 1965–2005, Production of organic products (e.g., food): USDA PS&D Official Statistical Results, Steel: International Iron and Steel institute, World steel in figures 2003, Minerals production: USGS mineral publications.

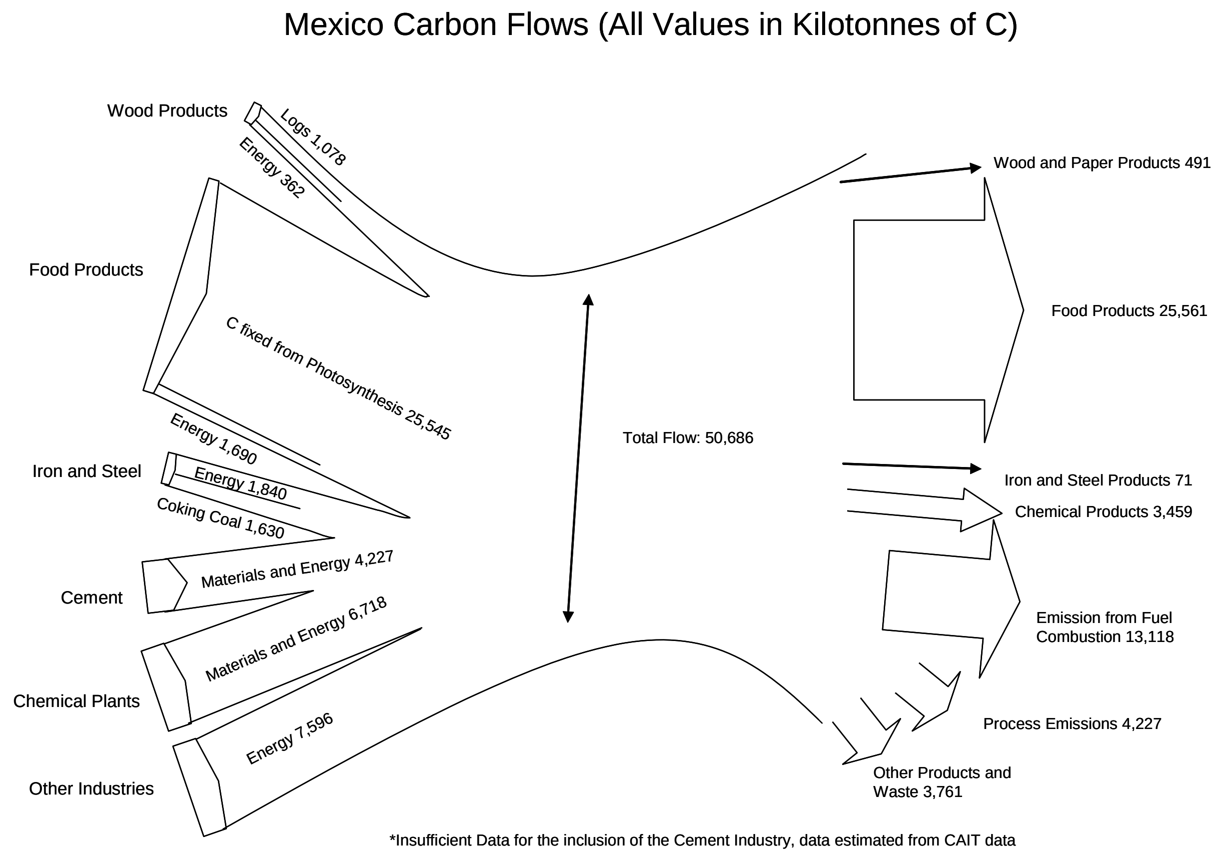


Fig. 8A-3. Carbon flows, Mexico. *Source*: Energy data from IEA Oil Information 2004, IEA Coal Information 2005, IEA Natural Gas Information 2004. Process emissions: EPA, U.S. Emissions Inventory. Production of forestry products: USDA Database; FO-2471000, -2472010, -2482000, -2483040, -6342000, -6342040.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