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Chapter 7 Industry

EXECUTIVE SUMMARY

Historically the industrial sector has reduced its emissions intensity through the adoption of energy-efficient technologies, but *the industrial sector is a major emitter of GHGs* (*much evidence/high agreement*). Industry emits carbon dioxide (CO_2) from energy use, from non-energy uses of fossil fuels, and from non-fossil fuel sources (e.g. cement manufacture). Energy-related CO_2 emissions from the industrial sector grew from 5.9 $GtCO_2$ in 1971 to 8.5 $GtCO_2$ in 2002. However, since energy use in other sectors grew faster, the industrial sector's share of global primary energy use declined from 40% in 1971 to 36% in 2002. Developed nations accounted for 51% of the 2002 total; transition economies, 12%; and developing nations, 37%. CO_2 emissions from non-energy uses of fossil fuels and from non-fossil fuel sources were estimated at 1.7 Gt in 2000.

About 85% of the industrial sector's energy use in 2003 was from energy-intensive industries: iron and steel, non-ferrous metals, chemicals and fertilizers, petroleum refining, cement, and forest products, and much of that energy-intensive industry is now located in developing countries. In 2003, developing countries accounted for 42% of iron and steel production, 57% of nitrogen fertilizer production, 78% of cement manufacture, and about 50% of primary aluminium production. Many industrial facilities in developing nations are new and include the latest technology with lowest specific energy use. However, as in industrialized countries, many older, inefficient facilities still remain. This creates a huge demand for technology transfer to developing countries to achieve energy efficiency and emissions reductions (*much evidence/high agreement*).

Industrial processes also emit other GHGs, including: HFCs from chemical processes, PFCs from aluminium smelting and semiconductor processing, SF_6 from use in electrical switchgear and magnesium processing, and CH_4 and N_2O from chemical industry sources and food industry waste streams. As a result of mitigation actions, total emissions from these sources decreased from 470 $MtCO_2$-eq (130 MtC-eq) in 1990 to be 430 $MtCO_2$-eq (120 MtC-eq) in 2000. This total did not include emissions from the food processing industry or from caprolactam manufacture, which are believed to be small compared to the total. With no further action, these emissions are projected to grow to 860 $MtCO_2$-eq (230 MtC-eq) in 2020 (*medium evidence/medium agreement*). However, many programs are underway to control non-CO_2 emissions from the industrial sector, and their total is expected to be lower than the no-action projection (*much evidence/high agreement*).

Many options exist for mitigating GHG emissions from the industrial sector (*much evidence/high agreement*). These options can be divided into three categories:

- Sector-wide options, e.g., more efficient electric motor driven systems; fuel switching, including the use of waste materials; and recycling.
- Process-specific options, e.g., the use of the bio-energy contained in food and forest products industry wastes, turbines to recover the energy contained in pressurized blast furnace gas, and control strategies to minimize PFC emissions from aluminium manufacture.
- Operating procedures, e.g., control of steam and compressed air leaks, reduction of air leaks into furnaces, optimum use of insulation, and optimization of equipment size to ensure high capacity utilization.

While existing technologies can significantly reduce industrial GHG emissions, *new and lower cost technologies will be needed to meet long term mitigation objectives* (*medium evidence/medium agreement*). Examples include: development of an inert electrode to eliminate process emissions from aluminium manufacture, use of carbon capture and storage in ammonia manufacture, and use of hydrogen to reduce iron and non-ferrous metal ores.

Mitigation potential and cost in 2030 have been estimated by an industry-by-industry assessment and also by two recent global studies. The industry-by-industry approach yields mitigation potentials of 3.6 -6.9 $GtCO_2$-eq (0.98-1.9 GtC-eq) in 2030 under the A1B scenario, and 2.6-5.5 $GtCO_2$-eq (0.71 -1.5 GtC-eq) under the B2 scenario[1]. This approach shows that most of the mitigation potential is located in the steel, cement, and petroleum refining industries, and in the control of non-CO_2 gases, and that much of the potential is available at $ <20/tCO_2-eq (<$73.4/tC-eq) (*low evidence/low agreement*). The global studies indicate mitigation potential at 2.5-3.0 $GtCO_2$-eq/yr (0.7-0.8 GtC-eq/yr) in 2030. One of the studies indicates costs of ≤ $25/$tCO_2$ (≤ $92/tC)(2004$).

Full use of available mitigation options is not being made in either industrialized or developing nations (*much evidence/high agreement*). In many areas of the world, GHG mitigation is not demanded by either the market or government regulation. In these areas, companies can afford to invest in GHG mitigation only to the extent that these investments are compensated by lowered energy or raw material costs, or some similar benefit. Slow rate of capital stock turnover is also a barrier in many industries, as is the lack of the financial and technical resources needed to implement mitigation options, and limitations in the ability of industrial firms to access and absorb information about available options.

Industry GHG investment decisions, many of which have long-term consequences, will continue to be driven by consumer preferences, costs, competitiveness, and government regulation. A policy environment that encourages the implementation of existing and new mitigation technologies would lead to lower GHG emissions. Policy portfolios that reduce the barriers to the adoption of cost-effective, low-GHG emission technology can be effective (*medium evidence/high agreement*).

In addition to implementing the mitigation options discussed above, achieving sustainable development will require restructuring through the adoption of industrial development pathways that minimize the need for future mitigation (*much evidence/high agreement*). Large companies

[1] A1B and B2 refer to scenarios described in the IPCC Special Report on Emission Scenarios (IPCC, 2000b).The A1 family of scenarios describe a future with very rapid economic growth, low population growth, and rapid introduction of new and more efficient technologies. B2 describes a world "in which emphasis is on local solutions to economic, social, and environmental sustainability." It features moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than the A1B scenario.

have greater resources, and usually more incentives, to factor environmental and social considerations into their operations than small and medium enterprises (SMEs), but SMEs provide the bulk of employment and manufacturing capacity in many countries. Integrating SME development strategy into the broader national strategies for development, is consistent with sustainable development objectives.

Industry is vulnerable to the impacts of climate change, particularly to the impacts of extreme weather (*much evidence/high agreement*). Companies can adapt to these potential impacts by designing facilities that are resistant to projected changes in weather and climate, relocating plants to less vulnerable locations, and diversifying raw material sources, especially agricultural inputs. Industry is also vulnerable to the impacts of changes in consumer preference and government regulation in response to the threat of climate change. Companies can respond to these by mitigating their own emissions and developing lower-emission products.

Both the public and the private sectors play important roles to play in the development of low GHG emission technologies that will be needed to meet long-term mitigation objectives (*much evidence/high agreement*). Governments are often more willing than companies to fund the higher risk, earlier stages of the R&D process, while companies should assume the risks associated with actual commercialisation. The Kyoto Protocol's Clean Development Mechanism (CDM) and Joint Implementation (JI), and a variety of bi-lateral and multi-lateral programs, have the deployment, transfer, and diffusion of mitigation technology as one of their goals.

7.1 Introduction

This chapter addresses actions taken to date or that can be taken in the short (to 2010)- and medium (to 2030)-term to mitigate GHG emissions from the manufacturing and process industries[2]. The range and diversity of these actions very large; we can present only a small sampling. As in all IPCC reports, we are constrained to examples that are well-described in the literature.

Globally, and in most countries, CO_2 accounts for more than 90% of CO_2-eq. GHG emissions from the industrial sector (Price, *et al.*, 2006; USEPA, 2006c). These CO_2 emissions arise from three sources: (1) the use of fossil fuels for energy, either directly by industry for heat and power generation or indirectly in the generation of purchased electricity and steam; (2) non-energy uses of fossil fuels in chemical processing and metal smelting; and (3) non-fossil-fuel sources, e.g. cement and lime manufacture. Industrial processes also emit other GHGs, e.g.:

- nitrous oxide (N_2O) is emitted as a by-product of adipic acid, nitric acid, and caprolactam production;
- hydrofluorocarbons (HFCs) are emitted as by-products of HCFC-22 production, a refrigerant also used in foam-blowing;
- perfluorocarbons (PFCs) are emitted as by-products of aluminium smelting and in semiconductor manufacture;
- sulphur hexafluoride (SF_6) is emitted in the manufacture, use and, decommissioning of gas insulated electrical switchgear, and used in magnesium processing;
- methane (CH_4) is emitted as a by product of some chemical processes; and
- CH_4 and N_2O can be emitted by food industry waste streams.

[2] For purposes of this chapter, industry includes the food processing and forest products industries, but the growing of food crops and trees are covered in Chapters 8 and 9 respectively. Also, the production of biofuels are covered in Chapter 4, and off-site management of industrial wastes is covered in Chapter 10. Petroleum refining is discussed in section 7.4.4, and emissions from coke production are included in the totals given in section 7.4.1.

Many GHG emission mitigation options have been developed for the industrial sector. They fall into three categories: operating procedures, sector-wide technologies, and process-specific technologies. Section 7.2 summarizes mitigation options in matrix form, section 7.3 discusses operating procedures and technologies that are applicable across the industrial sector, and section 7.4 discusses process-specific technologies. The short- and medium-term potential for and cost of all classes of options are discussed in section 7.5, barriers to the application of these options are addressed in section 7.6, and the implication of industrial mitigation for sustainable development is discussed in section 7.7.

Section 7.8 discusses the sector's vulnerability and options for adaptation to climate change. A number of policies have been designed either to encourage voluntary GHG emission reductions from the industrial sector or to mandate such reductions. Section 7.9 describes these policies and the experience gained to date. Co-benefits of the reduction GHG emissions from the industrial sector are discussed in section 7.10. As with other sectors, development of new technology is key to the cost-effective control of industrial GHG emissions. Section 7.11 provides a summary of the technology process in the industrial sector. Finally, section 7.12 examines the long-term (post-2030) outlook for GHG emissions reduction from the industrial sector.

7.1.1 Status of the Sector

The chapter's focus will be on the mitigation of GHGs from energy-intensive industries: iron and steel, non-ferrous metals, chemicals and fertilizer, petroleum refining, cement, and forest products, which account for more than half of the sector's energy consumption in most countries (Dasgupta and Roy, 2000; IEA, 2003a; IEA, 2003b; Sinton and Fridley, 2000). The food processing industry is also important because it represents a large share of industrial energy consumption in many non-industrialized countries. Each of these industries is discussed in detail in section 7.4.

Though large scale production dominates these sectors in developing countries, small and medium-sized enterprises (SMEs) are structurally important. For example, in India, SMEs have a significant share in the metals, chemicals, food, and forest products sectors. (GOI, 2005). There are 39.8 million SMEs in China, accounting for 99% of the country's enterprises, 50% of asset value, 60% of turnover, 60% of exports, and 75% of employment (APEC, 2002). While regulations are moving large industrial enterprises towards the use of environmentally sound technology, SMEs typically do not always have the economic or technical capacity to install the necessary control equipment (Chaudhuri and Gupta, 2003; Gupta, 2002) or are slower in innovation (Swamidass, 2003). These SME limitations create special challenges for efforts to regulate GHG emissions. However, some innovative R&D is taking place for this sector is also taking place (See section 7.7.).

7.1.2 Development Trends

As shown in Figure 7.1, the production of energy-intensive industrial goods grew dramatically during the 20th century. This growth is expected to continue as population and GDP increase.

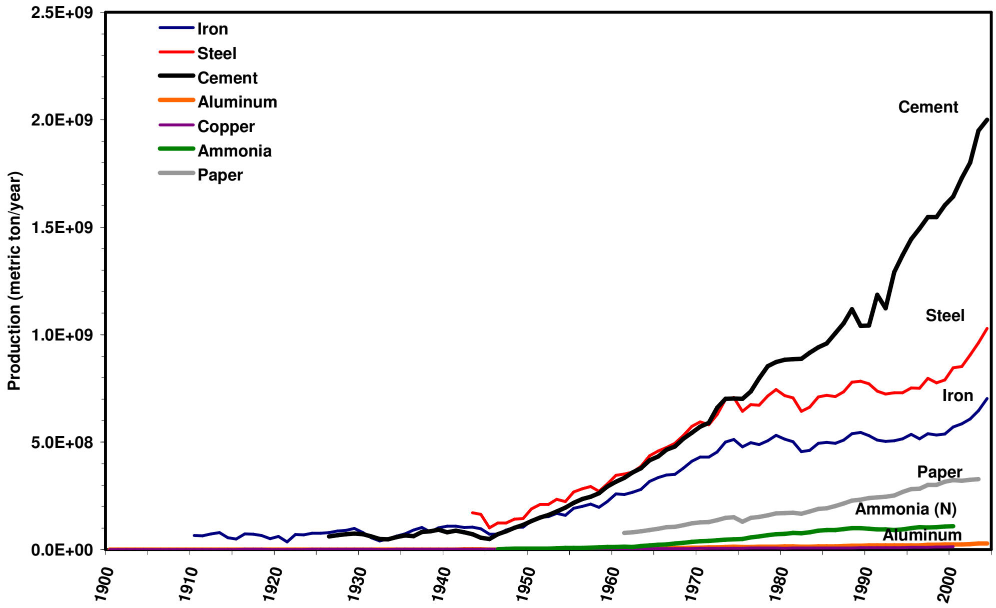


Figure 7.1: *Annual production of major GHG-intensive industrial products (in tonnes/year). Statistics on the aluminum, cement iron, and steel are provided by the USGS2004, Ammonia by the IFA, 2005 and FAO, 2005*

Much of the world's energy-intensive industry is now located in developing nations. China is now the world's largest producer of steel (IISI, 2005), aluminium (USGS 2004), and cement (USGS, 2004). In 2003, developing countries accounted for 42% of iron and steel production (IISI, 2005), 57% of nitrogen fertilizer production (IFA, 2004), 78% of cement manufacture (USGS, 2004), and about 50% of primary aluminium production (USGS, 2004). Since many facilities in developing nations are new, they sometimes include the latest technology and have the lowest specific emissions rates. This has been demonstrated in the aluminium (Navarro *et al*., 2003), cement (BEE, 2003), and fertilizer industries (Swaminathan and Sukalac, 2004). However, due to the need to upgrade existing facilities, there continues to be a huge demand for technology transfer to developing nations to achieve energy efficiency and emissions reduction in their industrial sectors.

New rules introduced both domestically and through the multilateral trade system, foreign buyers, insurance companies and banks require SMEs to comply with higher technical (e.g. technical barriers to trade), environmental (e.g. ISO14000) and labour standards (ENDS-Directory, 2006). These efforts can be in conflict with pressures for economic growth. IEA (2006) reports:

For energy efficiency and environmental reasons, the Chinese government has been trying to ban the use of small-scale coke-producing facilities, but the rapid economic expansion and a resulting scarcity of materials has countered this effort.

Multinational enterprises seeking out new markets and investments offer capable SMEs the opportunity to insert themselves into global value chains through subcontracting linkages, while those that are unable to do so increasingly face the danger of losing their existing markets. Competition within the developing world for export markets, foreign investment and resources is also intensifying. Against this backdrop of increased global competition, SMEs, SME associations, support institutions, and governments in transition and developing countries face the challenge of adopting new approaches and fostering SME competitiveness. Integration of SME development strategy in the broader national strategies for sustainable development and/or poverty reduction and growth is under consideration in transition and developing countries (GOI, 2004).

7.1.3 Development Trends

Global and sectoral data on primary energy use[3], final energy use, and energy-related CO_2 emissions for 1971-2002 (Price, et al., 2006) are shown in Table 7.1. In 1971, the industrial sector used 89 EJ of primary energy, 40% of the global total of 222 EJ. By 2002, industry's share of global primary energy use had declined to 36%. The developing nations' share of industrial CO_2 emissions from energy use grew from 18% in 1971 to 37% in 2002. In 2002, energy use by the industrial sector resulted in emissions of 8.5 $GtCO_2$, 36% of global CO_2 emissions from energy use. In 2000, CO_2 emissions from non-energy uses of fossil fuels (e.g. production of petrochemicals) and from non-fossil fuel sources (e.g. cement manufacture) were estimated to be 1.7 $GtCO_2$ (Olivier, 2005).

Table 7.1: *Industrial Sector Final Energy, Primary Energy, and Energy-Related Carbon Dioxide Emissions, 10 World Regions, 1971-2002. Source: Price, et al., 2006*

	Final Energy (EJ)			**Primary Energy (EJ)**			**Energy-Related Carbon Dioxide ($MtCO_2$)**		
	1971	**1990**	**2002**	**1971**	**1990**	**2002**	**1971**	**1990**	**2002**
Pacific OECD	6.02	7.44	10.08	8.40	10.57	14.03	529.3	639.1	790
North America	20.21	19.18	22.05	25.90	26.17	29.06	1,532.5	1,492.9	1,536
Western Europe	14.78	14.89	16.07	19.71	19.61	20.95	1,404.0	1,176.1	1,104
Central and E. Europe	3.78	4.62	2.62	5.29	6.72	3.67	397.5	484.8	241
Former Soviet Union	11.22	18.59	9.36	13.87	22.98	13.16	962.6	1,464.7	822
Centrally Planned Asia	5.12	14.17	16.93	6.58	18.86	27.39	572.2	1,559.2	2,197
Other Asia	2.21	5.48	9.24	2.74	7.52	13.64	138.1	448.0	823
Latin America	2.78	5.94	7.45	3.43	7.43	9.64	170.2	325.8	424
Sub Saharan Africa	1.25	2.13	2.40	1.86	2.95	3.40	117.7	179.7	200
Middle East and N. Africa	0.83	3.60	5.66	1.05	4.31	7.31	62.7	237.6	393
World	68.20	96.04	101.87	88.83	127.12	142.25	5,886.7	8,007.8	8,530

Note: Biomass included

Table 7.2 shows the results for the industrial sector of the disaggregation of two of the emissions scenarios, A1B and B2, produced for the IPCC Special Report on Emissions Scenarios (SRES) (IPCC, 2000b) into four subsectors and ten world regions (Price et al., 2006). These projections show a range of energy-related industrial CO_2 emissions from 14 to 20 Gt CO_2 in 2030 for the B2

[3] Primary energy associated with electricity and heat consumption was calculate by multiplying the amount of electricity and heat consumed by each end-use sector by electricity and heat primary factors. Primary factors were derived as the ratio of fuel inputs at power plants to electricity or heat delivered. Fuel inputs for electricity production were separated from inputs to heat production, with fuel inputs in combined heat and power plants are separated into fuel inputs for electricity and heat production according to the shares of electricity and heat produced in these plants. In order to calculate primary energy for non fossil fuel (hydro, nuclear, renewables), we followed the direct equivalent method (SRES method): the primary energy of the non fossil fuel energy is accounted for at the level of secondary energy, that is, the first usable energy form or "currency" available to the energy system (IPCC, 2000b, p 221).

and A1B scenarios, respectively. In both scenarios the developing countries in Latin America, Sub-Saharan Africa, Other Asia, and the Middle East and North Africa have the highest average annual growth rates. Growth in industrial sector CO_2 emissions in the regions of Central and Eastern Europe, Former Soviet Union, and Centrally Planned Asia are envisioned to slow to an average annual rate of 0.3 to 1.5% in the B2 scenario, and 0.5 to 2.3% in the A1 scenario for the period 2000-2030. CO_2 emissions are expected to decline in the Pacific OECD, North America, and Western Europe regions on both scenarios.

Table 7.2: *Projected Industrial Sector Final Energy and Energy-Related Carbon Dioxide Emissions, Based on SRES Scenarios, 2000-2030. Source: Price, et al., 2005a*

A1B Scenario

	Final Energy (EJ)			Primary Energy (EJ)			Energy-Related Carbon Dioxide ($MtCO_2$)		
	2000	**2010**	**2030**	**2000**	**2010**	**2030**	**2000**	**2010**	**2030**
Pacific OECD	9.95	8.50	8.10	13.72	11.50	11.39	774.3	896.5	681.1
North America	23.09	26.18	29.55	31.36	32.43	33.76	1661.0	1,819.4	1,585.4
Western Europe	16.21	17.62	21.25	21.03	24.31	29.94	1107.7	1,322.7	1,216.9
Central and E. Europe	2.76	6.68	8.76	3.83	8.28	11.75	256.4	532.3	553.9
Former Soviet Union	9.41	23.82	31.24	13.03	29.68	42.12	800.5	1,820.0	1,893.7
Centrally Planned Asia	15.67	28.60	46.32	24.57	37.14	63.88	2012.2	3,321.7	4,483.3
Other Asia	8.66	16.27	36.26	12.75	21.95	45.67	765.5	1,755.9	3,274.3
Latin America	7.54	19.98	35.57	9.72	25.69	42.86	429.3	1,505.0	2,326.1
Sub Saharan Africa	2.28	6.85	13.62	3.26	10.71	21.15	194.6	750.8	1,296.3
Middle East and N. Africa	5.38	16.17	32.17	6.79	22.78	44.97	364.1	1,421.2	2,454.0
World	100.96	170.67	262.83	140.06	224.47	347.50	8365.7	15,145.7	19,764.9

Note: Biomass included

B2 Scenario

	Final Energy (EJ)			Primary Energy (EJ)			Energy-Related Carbon Dioxide ($MtCO_2$)		
	2000	**2010**	**2030**	**2000**	**2010**	**2030**	**2000**	**2010**	**2030**
Pacific OECD	9.95	9.00	8.17	13.72	12.89	10.97	774.3	926.5	650.4
North America	23.09	19.54	21.06	31.36	27.46	27.01	1,661.0	1,836.1	1,652.8
Western Europe	16.21	13.98	13.39	21.03	18.35	16.54	1,107.7	1,248.6	1,066.0
Central and E. Europe	2.76	3.06	4.48	3.83	4.00	5.59	256.4	294.2	382.1
Former Soviet Union	9.41	11.49	15.41	13.03	14.18	18.97	800.5	985.3	1,088.7
Centrally Planned Asia	15.67	25.55	37.81	24.57	31.50	47.58	2,012.2	2,549.2	3,301.7
Other Asia	8.66	12.91	26.01	12.75	16.77	32.43	765.5	1,135.0	1,862.9
Latin America	7.54	10.45	16.62	9.72	13.93	22.14	429.3	839.8	1,107.8
Sub Saharan Africa	2.28	2.54	9.25	3.26	3.75	12.21	194.6	243.5	622.3
Middle East and N. Africa	5.38	7.66	11.77	6.79	11.13	16.80	364.1	714.0	975.1
World	100.96	116.18	163.96	140.06	153.96	210.25	8,365.7	10,772.2	12,709.9

Note: Biomass included

Table 7.3A shows projections of non-CO_2 GHG emissions from the industrial sector to 2020 (US EPA, 2006b; 2006c). Globally, if no further action is taken to control non-CO_2 emissions, these emissions are projected to increase by a factor of 1.8, from 470 $MtCO_2$-eq. (130 MtC-eq.) in 1990 to 860 $MtCO_2$-eq (230 MtC-eq.) in 2020. However, as a result of mitigation actions, non-CO_2 GHG emissions decreased from 1990 to 2000, and there are many programs underway to further reduce these emissions (See sections 7.4.2 and 7.4.8.). Table 7.3B shows these emissions by industrial process. Both tables include HFC emissions from refrigeration equipment used in industrial processes, but not HFC emissions from other refrigeration and air conditioning applications. US EPA (2006b, 2006c) includes these other refrigeration and air conditioning applications in the industrial sector, but in this report they are discussed in Chapters 5 (Transport) and 6 (Buildings). Neither table includes emissions from caprolactam manufacture or the food processing industry. Global totals for these sources are not available, but they are believed to be small compared with the total presented in the tables.

Table 7.3A: *Projected Industrial Sector Emissions of Non-CO_2 GHGs, $MtCO_2$-eq./yr.*
Source: US EPA, 2006c.

	1990	2000	2010	2020
Region*				
Pacific OECD	38	53	62	87
North America	147	117	160	204
Western Europe	157	95	103	118
Central and Eastern Europe	30	18	20	22
Former Soviet Union	38	22	28	31
Centrally Planned Asia	28	77	146	209
Other Asia	7	18	50	121
Latin America	17	17	25	32
Sub Saharan Africa	4	7	8	11
Middle East and North Africa	4	5	16	27
World**	469	429	619	860

* Emissions from refrigeration equipment used in industrial processes included; emissions from all other refrigeration and air conditioning applications excluded.
** Columns may not sum to total because of independent rounding.

Table 7.3.B: *Projected Baseline Industrial Sector Emissions of Non-CO_2 GHGs*
Source: US EPA, 2006b; 2006c

Industrial Sector	Emissions, $MtCO_2$ eq/yr			
	1990	2000	2010	2020
N_2O Emissions from Adipic/Nitric Acid Production	223	154	165	177
HFC/PFC Emissions from Substitutes for Ozone-Depleting Substances *	0	52	96	146
HFC-23 Emissions from HFC-22 Production	77	96	118	138
SF_6 Emission from Electrical Equipment	42	27	52	66
PFC Emission from Aluminium Production	98	58	70	77
PFC and SF_6 Emissions from Semiconductor Manufacture	10	27	99	232
SF_6 Emissions from Magnesium Production	12	9	12	18
CH_4 and N_2O Emissions from Other Industrial Processes	7	7	7	7
Total**	469	429	619	860

* Emissions from refrigeration equipment used in industrial processes included; emissions from all other refrigeration and air conditioning applications excluded.
** Columns may not sum to total because of independent rounding.

7.2 Industrial Mitigation Matrix

A wide range of measures and technologies have the potential to reduce industrial GHG emissions. These technologies can be grouped into categories of energy efficiency, fuel switching, power recovery, etc. Within each category, some technologies, such as the use of more efficient electric motors, are broadly applicable across all industries; while others, such as top-gas pressure recovery in blast furnaces, are process-specific. Table 7.4 presents examples of both classes of technologies for a number of industries. The table is not comprehensive, since it does not cover all industries or GHG mitigation technologies.

Table 7.4: *Selected Examples of Industrial Technology for Reducing Greenhouse Gas Emissions (not comprehensive). Technologies in italics are under demonstration or development*

Sector	Energy Efficiency	Fuel Switching	Power Recovery	Renewables	Feedstock Change	Product Change	Material Efficiency	Non-CO_2 GHG	CO_2 Sequestration
Sector wide	Energy management systems and practices, Motor systems, Efficient boilers and burners, Heat recovery, Efficient lighting & HVAC	Coal to natural gas	Cogeneration	Biomass, Biogas (anaerobic digestion, gasification), PV wind turbines	Recycled inputs				Oxy-fuel combustion
Iron & Steel	Smelt reduction, Near net shape casting, Scrap preheating, Efficient furnace, Dry coke quenching	Natural gas, oil or plastic injection BF	Top-gas pressure recovery, By-product gas combined cycle	Charcoal	Scrap	High strength steel	Recycling, High strength steel, Reduction process losses	n/a	Hydrogen reduction, Oxygen use in blast furnace
Non-Ferrous Metals	Inert anode, Efficient cell designs				Scrap		Recycling, thinner film and coating	PFC-controls	
Chemicals	Efficient furnaces, Process integration, Membranes, Reactive distillation	Natural gas	Pre-coupled gas turbine, Pressure recovery turbine, hydrogen recovery		Recycled plastics, bio-feedstock	LLDPE, high-performance plastics	Recycling, Thinner film and coating, Reduction process losses	Control technology for N_2O, PFC, CFC and HCFC	Ammonia, Ethylene oxide
Cement	Precalciner kiln, Roller mill, fluidized bed kiln	Waste fuels, Biogas, Biomass	Drying with gas turbine, power recovery	Biomass fuels, Biogas	Slags, pozzolanes	Blended cement Geo-polymers		n/a	O_2 combustion in kiln
Glass	Cullet preheating Oxyfuel furnace	Natural gas	Air Bottoming Cycle	n/a	Increased cullet use	High-strength thin containers	Re-usable containers	n/a	O_2 combustion
Forest Products	Efficient pulping, Efficient drying, Shoe press, Condebelt drying	Biomass, Landfill gas	Black liquor gasification combined cycle	Biomass fuels (bark, black liquor)	Recycling, Non-wood fibres	Fiber orientation, Thinner paper	Reduction cutting and process losses	n/a	O_2 combustion in lime kiln
Electronics	Continuous melt silicon growth		RTO-power recovery	n/a				PFC, SF_6 controls	
Food	Efficient drying, Membranes		Anaerobic digestion, Gasification	Biomass, By-products, Solar drying			Reduction process losses, Closed water use		

7.3 Industrial Sector-wide Operating Procedures and Technologies

7.3.1 Management Practices, Including Benchmarking

A variety of management tools are available to reduce GHG emissions, often without capital investment or increased operating costs. Staff training in both skills and the company's general approach to energy efficiency for use in their day-to-day practices has been shown to be beneficial (Caffal, 1995). Programs with regular feedback on staff behaviour, such as reward systems, have had good results.

Even when energy is a significant cost for an industry, opportunities for improvement may be missed because of organizational barriers. Energy audit and management programs create a foundation for improvement and provide guidance for managing energy throughout an organization. Several countries have instituted voluntary corporate energy management standards, e.g. Denmark (Danish Standard for Energy Management) and the U.S. (ANSI, 2005). Others, e.g. India (BEE, n.d.), promote energy audits. Integration of energy management systems into broader industrial management systems (e.g. ISO 9000/14000, Six-Sigma), allowing energy use to be managed for continuous improvement, in the same manner as labour, waste, and other inputs are managed, is highly beneficial (McKane, et al., 2005). Documentation (work instructions) for existing practices and planned improvements is essential to achieving a transition from energy efficiency programs and projects dependent on individuals to processes and practices that are part of the corporate culture.

Energy Audits and Management Systems. Companies of all sizes use energy audits to identify opportunities for reducing energy use, which in turn reduces GHG emissions. In 2000, ExxonMobil implemented a system known as GEMS (Global Energy Management System) with the goal of achieving a 15% reduction in energy use in its refineries and chemical plants (Eidt, 2004). For SMEs in Germany, Schleich (2004) reports that energy audits help overcome several barriers to energy efficiency, including missing information about energy consumption patterns and energy saving measures. Schleich also found that energy audits conducted by engineering firms were more effective than those conducted by utilities or trade associations.

GHG Inventory and Reporting Systems. Understanding the sources and magnitudes of its GHG emissions gives industry the capability to develop business strategies to adapt to government and consumer requirements as they develop. Various protocols for inventory development and reporting have been developed; the Greenhouse Gas Protocol developed by the World Resources Institute and World Business Council for Sustainable Development (WRI/WBCSD, 2004) is the most broadly used. The Protocol defines an accounting and reporting standard that companies can use to ensure that their measurements are accurate and complete. Several industries (e.g. aluminium, cement, chemical, and forest products) have developed specific calculation tools to implement the Protocol. Other calculation tools have been developed to estimate GHG emissions from office-based business operations and to quantify the uncertainty in GHG measurement and estimation (WRI/WBCSD, 2005). Within the European Union, GHG reporting guidelines have been developed for companies participating in the EU Emission Trading System.

GHG Management Systems. Quality management systems were first promoted by Edward Deming in the 1950s (Deming, 1986), and codified in 1978 in the ISO 9000 standards, which were updated as ISO 9000:2000 (ISO, 2000). This approach was extended to environmental issues in 1996 in the ISO 14001 standard (ISO, 1996). Many companies are following this approach, though not necessarily the ISO standards, to build capacity for GHG emission reduction. For example, the U.S.

petroleum industry developed their own standard based on systems developed by various companies (API, 2005). The GHG emissions reduction opportunities identified by these management systems are evaluated using normal business criteria, and those meeting the current business or regulatory requirements are adopted. Those not adopted represent additional capacity that could be used should business, government, or consumer requirements change.

Benchmarking. Companies can use benchmarking to compare their operations with those of others to determine whether they have opportunities to improve energy efficiency or reduce GHG emissions. Benchmarking is widely used in industry, but benchmarking programs must be carefully designed to comply with laws ensuring fair competition, and companies must develop their own procedures for using the information generated through these programs. The petroleum industry has the longest experience with energy efficiency benchmarking through the use of an industry-accepted index developed by a private company (Barats, 2005). Many benchmarking programs are developed through trade associations or ad hoc consortia of companies, and their details are often proprietary. However, 10 Canadian potash operations published the details of their benchmarking exercise (CFI, 2003), which showed that increased employee awareness and training was the most frequently identified opportunity for improved energy performance.

Several governments have supported the development of benchmarking programs in various forms, e.g. Canada, Flanders, Netherlands, Norway, and the United States. As part of its energy and climate policy the Dutch government has reached an agreement with the Dutch energy-intensive industry that is explicitly based on industry's relative energy efficiency performance. The energy efficiency of the Dutch industry is benchmarked against that of comparable industries in countries worldwide. In the agreement, industry is required to belong to the top-of-the-world in terms of energy efficiency. In return, the government refrains from implementing additional climate policies. By 2002, this program involved companies using 94% of the energy consumed by industry in The Netherlands. Most of the companies involved in the program were already in the top 10% of energy efficiency world-wide, but 100% participation in the covenant would result in cumulative emissions reductions of 5.7 $MtCO_2$ (1.6 MtC) through 2012 (Government of The Netherlands, 2002). Phylipsen, et al. (2002) critiqued The Netherlands' benchmarking agreement, and conclude that it would avoid emissions of 4-9 $MtCO_2$ (1.1-2.5 MtC) in 2012 compared with a business-as-usual scenario. While these emission reductions are larger than projected by the government, Phylipsen, et al. (2002) conclude that they were smaller than those that would be achieved by a continuation of the Long-Term Agreements with industry (which ended in 2000) that called for a 2%/year improvement in energy efficiency. The Flemish covenant, agreed in 2002, uses a similar approach. As of 1 January 2005, 177 companies had joined the covenant, which projects cumulative emissions saving of 2.45 $MtCO_2$ (0.67 MtC) in 2012 (Government of Flanders, 2005).

In the United States, the Energy Star program has developed a benchmarking system for selected industries (e.g. breweries, automotive assembly plants, cement and wet corn milling) to help companies improve their energy management systems (Boyd, 2005). The system is used by participants in the program to evaluate the performance of individual plants against a distribution of the energy performance of peers. Other benchmarking programs compare individual facilities to world best practice (Galitsky, et al., 2004).

7.3.2 Energy Efficiency

IEA (2006) reports:

The energy intensity of most industrial processes is at least 50% higher than the theoretical minimum determined by the laws of thermodynamics. Many processes have very low energy efficiency and average energy use is much higher than the best available technology would permit.

This provides a significant opportunity to reduce energy use and its associated CO_2 emissions.

The energy efficiency of industrial plants depends on three factors: choice and optimization of technology, operating procedures and maintenance, and capacity utilization, i.e., the fraction of maximum capacity at which the process is operating. Many studies (e.g. US DOE, 2004; IGEN/BEE; n.d.) have shown that large amounts of energy can be saved and CO_2 emissions avoided by strict adherence to carefully designed operating and maintenance procedures. Steam and compressed air leaks, poorly maintained insulation, air leaks into boilers furnaces, and similar problems all contribute to excess energy use. Quantification of the amount of CO_2 emission that could be avoided is difficult, because, while it is well known that these problems exist, the information on their extent is case-specific. Low capacity utilization is associated with more frequent shut-downs and poorer thermal integration, both of which lower energy efficiency and raise CO_2 emissions.

In view of the low energy efficiency of industries in many developing counties, in particular Africa (UNIDO, 2001), application of industry-wide technologies and measures can yield technical and economic benefits, while at the same time enhance environmental integrity. Application of housekeeping and general maintenance can yield energy savings of 10-20%; low cost/minor capital measures (combustion efficiency optimisation, recovery and use of exhaust gases, use of high efficiency electric motors and insulation, etc.) show energy savings of 20-30%; and high capital expenditure measures (automatic combustion control, improved design features for optimisation of piping sizing, and air intake sizing, and use of variable speed drive motors, automatic load control systems, and process residuals) can result in energy savings of 40-50% (UNIDO, 2001, Bakaya-Kyahurwa, 2004).

Electric motor driven systems provide a large potential for improvement of industry-wide energy efficiency. De Keulenaer et al., (2004) report that motor-driven systems account for approximately 65% of the electricity consumed by EU-25 industry. Xenergy (1998) gave similar figures for the U.S., where motor-driven systems account for 63% of industrial electricity use. The efficiency of motor driven systems can be increased by improving the efficiency of the electric motor through reducing losses in the motor windings, using better magnetic steel, improving the aerodynamics of the motor, and improving manufacturing tolerances. However, the motor is only one part of the system, and maximizing efficiency requires properly sizing all components, improving the efficiency of the end-use devices (pumps, fans, etc.), reducing electrical and mechanical transmission losses, and use of proper operation and maintenance procedures. Implementing high-efficiency motor driven systems, or improving existing ones, in the EU-25 could save about 30% of the energy consumption, up to 202 TWh per year, and avoid emissions of up to 100 $MtCO_2$ (27.2 MtC) per year (De Keulenaer et al., 2004). In the U.S. use of more efficient electric motor systems could save over 100 TWh per year by 2010, and avoid emissions of 90 $MtCO_2$ (24.5 MtC) per year (Xenergy, 1998). A study (CEEEZ, 2003) of the use of variable speed drives in selected African food processing, petroleum refineries, and municipal utility companies with a total motor capacity of 70,000 kW resulted in a potential saving of 100 $ktCO_2$ eq. (27 ktC)/yr, or between 30-40%, at an economically attractive IRR of 40%.

IEA (2006) estimates that steam generation consumes about 15% of global final industrial energy use. While the efficiency of steam boilers can be as high as 85%, average efficiencies are often much lower. Efficiency measures exist for both boilers and distribution systems. Besides general maintenance, these include improved insulation, combustion controls and leak repair in the boiler, improved steam traps, and condensate recovery. Boiler systems can also be upgraded to cogeneration systems. Studies in the U.S. identified energy-efficiency opportunities with economically attractive potentials up to 18-20% (Einstein *et al.*, 2001; US DOE, 2002). Efficient high-pressure boilers using process residual like bagasse are now available (Cornland *et al*., 2001), and can be used to replace traditional boilers (15-25 bars) in the sugar industry. The high-pressure steam is used to generate electricity for own use with a surplus available for export to the grid (see also 7.3.4). For example, a boiler with a 60 MW steam turbine system in a 400 t/hr sugar factory could provide a surplus of 40 MW of zero-carbon electricity 400 ktCO_2/year (Yamba and Matsika, 2003). Similar technology installed at an Indian sugar mill increased the crushing period from 150 to 180 days, and exported an average of 10 MW of zero carbon electricity to the grid (Sobhanbabu, 2003).

7.3.3 Fuel Switching, Including the Use of Waste Materials

While some industrial processes require specific fuels (e.g. metallurgical coke for iron ore reduction)[4], many industries use fuel for steam generation and/or process heat, with the choice of fuel being determined by cost, fuel availability, and environmental regulations. The TAR (IPCC, 2001a) limited its consideration of industrial fuel switching to switches within fossil fuels (replacing coal with oil or natural gas), and concluded, based on a comparison of average and lowest carbon intensities for 8 industries, that such switches could reduce CO_2 emissions by 10-20%. These values are still applicable. A variety of industries are using methane from landfills as a boiler fuel (US EPA, 2005). While there are no technical barriers to broader use of biomass, for most industrial applications biomass is high cost, and its greater use is likely to be limited in the short- or medium-term.

Waste materials (tyres, plastics, used oils and solvents, sewerage sludge) are being used by a number of industries. The steel industry has developed technology to use wastes such as plastics (Ziebek and Stanek, 2001) as alternative fuel and raw materials. Pre-treated plastic wastes have been recycled in coke ovens and blast furnaces (Okuwaki, 2004), reducing CO_2 emissions by reducing both emissions from incineration and the demand for fossil fuels. In Japan, annual use of plastics wastes in steel has resulted in a net emissions reduction of 0.6 MtCO_2 eq. (Okazaki et al., 2004). Incineration of wastes (e.g. tyres, municipal and hazardous waste) in cement kilns is one of the most efficient methods to dispose of these materials (Cordi and Lombardi, 2004; Houillon and Jolliet, 2005). Heidelberg Cement (2006) reported using 78% waste materials (tyres, animal meal and grease, and sewerage sludge) as fuel for one of its cement kilns. The cement industry, particularly in Japan, is investing to allow use of waste as fuel. Cement companies in India are using non-fossil fuels, including agricultural wastes, sewage, domestic refuse and used tyres, as well as wide range of waste solvents and other organic liquids; coupled with improved burners and burning systems (Jain, 2005).

Humphreys and Mahasenan (2002) estimate that global CO_2 emissions could be reduced by 12% through increased use of waste fuels. However, IEA (2006) notes that use of waste materials is limited by their availability, Also, use of these materials for fuel must address their variable composition, and comply with all applicable environmental regulations, including control of air toxics.

7.3.4 Heat and Power Recovery

[4] Options for fuel switching in those processes are discussed in Section 7.4.

Energy recovery provides major energy efficiency and mitigation opportunities in virtual all industries. Energy recovery is an old technique, but large potentials still exist (Bergmeier, 2003). Energy recovery can take different forms, e.g. heat, power, and fuel recovery. Fuel recovery options are discussed in the specific industry sectors in section 7.4. While water (steam) is the most used energy recovery medium, the use of chemical heat sinks, e.g. such as used in heat pumps, organic Rankine cycles, and chemical recuperative gas turbines, allows heat recovery at lower temperatures. Energy-efficient process designs are often based on increased internal energy recovery, making it hard to define the technology or determine the mitigation potential.

Heat is used and generated at specific temperature and pressures and discarded afterwards. The discarded heat can be re-used in other processes onsite, or used to preheat incoming water and combustion air. Heat is recovered through the use of heat exchangers. New, more efficient heat exchangers or more robust (e.g. low corrosion) heat exchangers are developed continuously, improving the profitability of enhanced heat recovery. In industrial sites the use of low-temperature waste heat is often limited, except for preheating boiler feed water. Using heat pumps allows recovery of the low-temperature heat for the production of higher temperature steam.

While there is a significant potential for heat recovery in most industrial facilities, it is important to design a heat recovery system that is energy-efficient and cost-effective (i.e. process integration). The energy savings potential of process integration exceeds that from well-known conventional heat recovery techniques, estimated at 5-10% (Einstein *et al.*, 2001; US DOE, 2002). Even in new designs, process integration finds additional opportunities for energy efficiency improvement. Typically, cost-effective energy savings of 5-40% are found in process integration analyses in almost all industries (Martin *et al.*, 2000; IEA-PI, n.d.). The wide variation makes it hard to estimate the overall potential for energy-efficiency improvement and GHG mitigation. However, Martin *et al.* (2000) estimated the potential fuel savings from process integration in U.S. industry to be 10% above the gain for conventional heat recovery systems.

Power can be recovered from processes operating at elevated pressures using even small pressure differences to produce electricity through pressure recovery turbines. Examples of pressure recovery opportunities are blast furnaces, fluid catalytic crackers, and natural gas grids (at sites where pressure is reduced before distribution and use). Power recovery may also include the use of pressure recovery turbines instead of pressure relief valves in steam networks and organic Rankine cycles from low-temperature waste streams. A recent study in the United States of power recovery technologies (Bailey and Worrell, 2005) found a combined potential of 1-2% of all power produced in the United States, mitigating 21 Mt CO_2 (5.7 MtC).

Cogeneration (Combined Heat and Power) involves using energy losses in power production to generate heat for industrial processes and district heating, providing significantly higher system efficiencies. Cogeneration technology is discussed in section 4.4.1.3. Industrial cogeneration is an important part of power generation in countries like Germany and The Netherlands, and is the majority of installed cogeneration capacity in many countries. Laurin, et al. (2004) estimated that currently installed cogeneration capacity in Canada provided a net emission reduction of almost 30 $MtCO_2$/year. Cogeneration is also well established in the paper, sugar and chemical industries in India, but not in the cement industry due to lack of indigenously proven technology suitable for high dust loads. The Indian government is recommending adoption of technology already in use in China, Japan and Southeast Asian countries (Raina, 2002).

There is still a large potential for cogeneration. Different studies use different definitions and methods to determine the potential; hence estimates may not be comparable. However, mitigation potential for industrial cogeneration is estimated at almost 150 Mt CO_2 for the U.S. (Lemar, 2001), and 334 Mt CO_2 for Europe (De Beer et al., 2001). Studies also have been performed for specific countries, e.g. Brazil (Szklo et al., 2004), although the CO_2 emissions mitigation impact is not always specified.

7.3.5 Renewable Energy

The use of biomass is well established in some industries. The forest products industry uses biomass for much of its energy needs (See section 7.4.6.). In many developing countries, the sugar industry uses bagasse and edible oils industry uses byproduct wastes to generate steam and/or electricity (See section 7.4.7.). The use of bagasse for energy is likely to grow as more becomes available as a by-product of sugar-based ethanol production (Kaltner, et al, 2005). The food and jute industries also makes use of solar energy for drying in appropriate climates (Das and Roy, 1994). The African Rural Energy Enterprise Development initiative is promoting the use of solar food driers in Mali and Tanzania to preserve fresh produce for local use and for the commercial market (AREED, 2000). When economically attractive, other industries use biomass fuels, e.g. charcoal in blast furnaces in Brazil (Kim and Worrell, 2002a). These applications will reduce CO_2 emissions, but will achieve zero CO_2 emissions only if the biomass is grown sustainably. The cost of collection of biomass remains a major barrier to its broader industrial use. While biomass is expected to be the major source of renewable energy for the next few decades, industrial use of biomass is not projected to grow significantly during that time. Industry also can use solar or wind generated electricity, if it is available. The potential for this technology is discussed in section 4.3.3.

7.3.6 Materials Efficiency and Recycling

Materials efficiency refers to the reduction of energy use by appropriate choice of materials and recycling. Many of these technologies are applicable to the transport and building sectors and are discussed in Chapters 5 and 6. Recycling is the best-documented material efficiency option for the industrial sector. Recycling of steel in electric arc furnaces accounts about a third of world production. This process typically uses 60-70% less energy and with CO_2 emission reductions being a function of the source of electricity (De Beer, et al., 1998). This technology, and options for further energy savings, are discussed in section 7.4.1. Recycling aluminium requires only 5% of the energy of primary aluminium production. Recycled aluminium from used products and sources outside the aluminium industry is now constitutes 33% of world supply and is projected to rise to 40% by 2025 (IAI, 2006, Martcheck, 2006). Recycling is also an important energy saving factor in other non-ferrous metal industries, as well as the glass and plastics industries (GOI, various issues). Recycling occurs both internally within plants and externally in the waste management sector (See Section 10.4.5).

Materials substitution, e.g. use of blend cement and geo-polymers to reduce CO_2 emissions from cement manufacture (See section 7.4.5.1.), is also applicable to the industrial sector. Some materials substitution options, e.g. the production of lightweight materials for vehicles, can increase GHG emissions from the industrial sector, which will be more than offset by the reduction of emissions from other sectors (See section 7.4.9.). Use of bio-materials is a special case of materials substitution. No projections of the GHG mitigation potential of this option were found in the literature.

7.3.7 Carbon Dioxide Capture and Storage (CCS), Including Oxy-fuel Combustion

CCS can follow one of two paths: (1) the carbon in a fossil fuel can be reacted with air, oxygen, or steam to *yield* CO_2 and hydrogen, after which the CO_2 can be captured and the hydrogen used as a fuel, or (2) CO_2 can be captured from the exhaust from fossil fuel combustion. In both cases the captured CO_2 can then be stored geologically in depleted oil and gas fields or in saline aquifers, preventing its release to the atmosphere for very long periods of time. The IPCC Special Report on CCS (IPCC, 2005b) provides a full description of this technology, including its potential application in industry. It also discusses of industrial uses of CO_2, including its temporary retention in beverages. These uses are small compared with total industrial emissions of CO_2. A more general discussion of CCS appears in Section 4.4.3.4.

Large quantities of hydrogen are produced as feedstock for petroleum refining, and the production of ammonia and other chemicals. Hydrogen manufacture produces a CO_2-rich byproduct stream, which is a potential candidate for CCS technology. IPCC (2005b) estimated the representative cost of CO_2 capture from hydrogen manufacture at \$15/tCO_2 (\$55/tC). Transportation (250 km pipeline) injection and monitoring would add another \$2-16/tCO_2 (\$7-60/tC) to costs. IPCC's report also details the many challenges remaining before this technology could be commercialized.

CO_2 emissions from steelmaking are also a candidate for CCS technology. IEA (2006) estimates that CCS could reduce CO_2 emissions from blast furnaces and DRI plants by ~0.1 GtCO_2 (0.03 GtC) in 2030 a cost of \$20-30/tCO_2 (\$73-110/tC). Smelt reduction also allow the integration of CCS into the production of iron. CCS has been also investigated for the cement industry. Anderson and Newell (2004) estimate that it is possible to reduce CO_2 emissions by 65-70%, at costs of 50-250 US\$/tCO_2. IEA (2006) places the potential at up to 0.25 GtCO_2 in 2030.

Oxy-fuel combustion can be used to produce a CO_2-rich flue gas, suitable for CCS, from any combustion process. In the past, oxy-fuel combustion has been considered impractical because of the high flame temperature it creates. However, Gross, *et al.* (2003), report on the development of technology that allows oxy-fuel combustion to be used in industrial furnaces with conventional materials. Tests show up to a 73% reduction in natural gas use compared with a convention air-natural gas furnace. When the energy required to produce oxygen are taken into consideration, overall energy savings is reduced to 50-60% (Jupiter Oxygen Corp., 2006). The technology has also been demonstrated using coal and waste oils as fuel. Since much less nitrogen is present in the combustion chamber, NO_x emissions are very low, even without external control, and the system is compatible with integrated pollution removal technology for the control of mercury, sulphur and particulate emissions (Ochs, *et al.*, 2005).

7.4 Process-Specific Technologies and Measures

This section focuses on energy intensive industries: iron and steel, non-ferrous metals, chemicals, petroleum refining, minerals (cement, lime, and glass), and forest products (pulp, paper and wood products). IEA (2006) reports that these industries (ex-petroleum refining) accounted for 72% of industrial final energy use in 2003. With petroleum refining, the total is ~85%. A subsection is presented on the food industry, which is not a major contributor to global industrial GHG emissions, but is a large contributor to these emissions in many developing countries. Subsections are also presented on other industries and on cross industry options, where the use of one industry's waste as a feedstock or energy source by another industry can reduce overall emissions (See. Section 7.4.9).

7.4.1 Iron and Steel

Steel is by far the most world's important metal, with a total global production of 10575 Mt in 2004. In 2004, the most important steel producers were China (26%), EU (19%, EU-25), Japan (11%), U.S. (10%) and Russia (6%). The top-10 steel companies produce 28% of the world's steel (IISI, 2005). Three routes are used to make steel. In the primary route (~60%), iron ore is reduced to iron in blast furnaces using mostly coke or coal, then processed into steel. In 2004, 756 Mt of iron was produced in almost 50 countries. In the secondary route (~35%), scrap steel is melted in electric-arc furnaces to produce crude steel that is further processed. The secondary route uses only 30-40% of the energy used by the primary route, with CO_2 emissions reduction being a function of the source of electricity (De Beer, et al., 1998). In the balance of steel production (~5%), natural gas is used to produce direct reduced iron (DRI). DRI cannot be used in primary steel plants, and is mainly used as an alternative iron input in secondary steelmaking. Use of DRI in electric-arc furnaces can result in a 50% reduction in CO_2 emissions compared with primary steelmaking (IEA, 2006), and its use is projected to increase in the future (Hidalgo, et al., 2005).

Total CO_2 emissions of the global steel industry are estimated at 1500-1600 $MtCO_2$ (436 MtC), including emissions from coke manufacture and indirect emissions due to power consumption, or about 6-7% of global anthropogenic emissions (Kim and Worrell, 2002a). The total is higher for some countries, e.g. steel production accounts for over 10% of China's energy use and about 10% of its anthropogenic CO_2 emissions (Price, et al., 2002). Emissions per tonne steel vary widely between countries, from about 1.25 tCO_2 (0.35 tC) in Brazil, to 1.6 tCO_2 (0.44 tC) in Korea and Mexico, 2.0 tCO_2 (0.54 tC) in the U.S., and 3.1-3.8 tCO_2 (0.84-1.04 tC) in China and India (Kim and Worrell, 2002a). The differences are based on the production routes used, product mix, energy efficiency of the production, carbon intensity of the fuel mix, and carbon intensity of power production. Energy consumption by the steel industry in various regions in 2000 is shown in Figure 7.2.

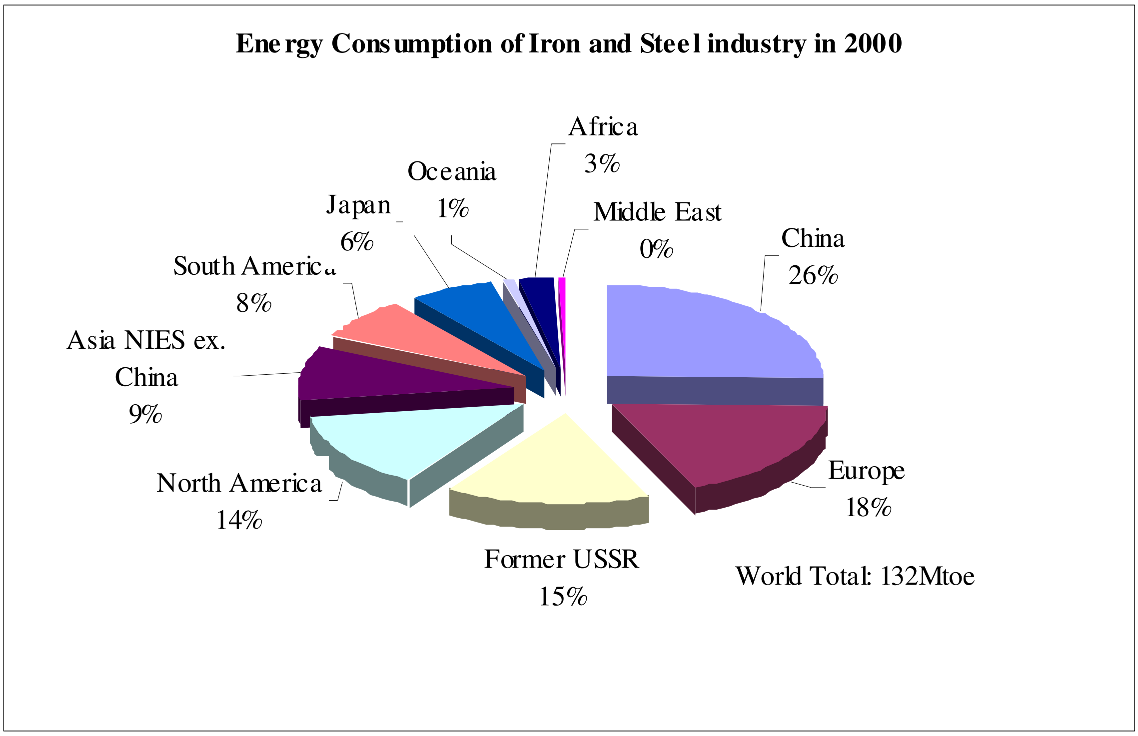
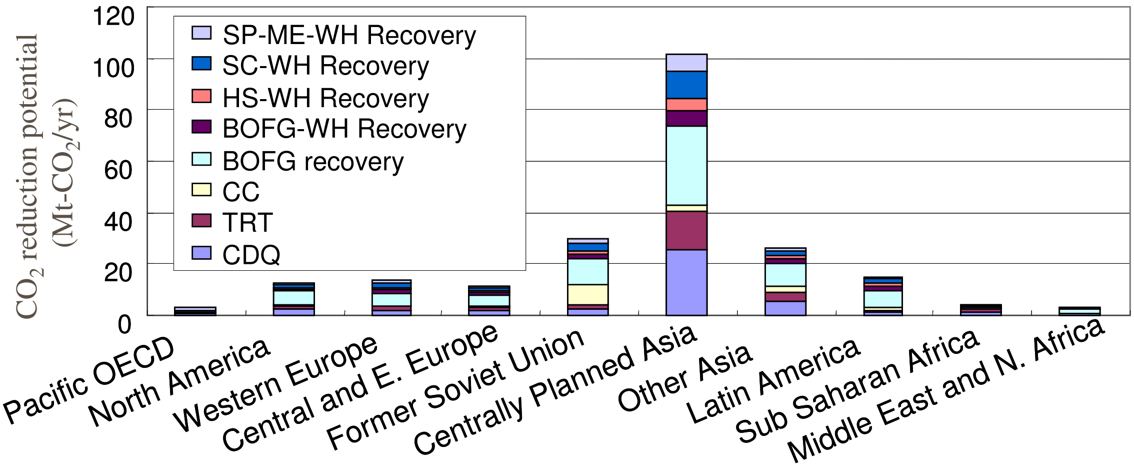


Figure 7.2: *Energy Consumption by the Steel Industries of the World (IEA, 2002)*

Energy Efficiency. Iron and steel production is a combination of batch processes. Steel industry efforts to improve energy efficiency include enhancing continuous production processes to reduce heat loss, increasing recovery of waste energy and process gases, and efficient design of electric arc furnaces e.g. scrap preheating, high-capacity furnaces, foamy slagging, fuel and oxygen injection. Continuous casting, introduced in the 1970s and 1980s, saves both energy and material. Today, 88% of global steel is cast continuously (IISI, 2005). Figure 7.3 shows the technical potential for CO_2 emission reductions by region in 2030 for eight energy savings technologies under the B2 SRES scenario, using a methodology developed by Tanaka, et al. (2005, 2006).



CDQ = Coke Dry Quenching
TRT = Top Pressure Recovery Turbine
CC = Continuous Casting
BOFG = Basic Oxygen Furnace Gas
WH = Waste Heat
HS = Hot Stove
SC = Sinter Cooling
SP = Sinter Plant
ME = Main Exhaust

Figure 7.3: *CO_2 Reduction Potential of Eight Energy Saving Technologies (2030, B2 Scenario, CO_2 emission reduction based n energy saving assuming 100% diffusion in 2030 less current diffusion rates (IISI, 2005))*

The potential for energy efficiency improvement varies based on the production route used, product mix, energy and carbon intensities, and boundary for the evaluation. The differences can be evaluated with benchmarking studies or penetration rates of key energy-efficient practices and technologies. Tanaka, et al. (2006) also used a Monte Carlo approach to estimate the uncertainty in their projections of technical potential for three steelmaking technologies. Kim and Worrell (2002a) estimated socio-economic potential by taking industry structure into account. They benchmarked the energy efficiency of steel production to the best practice performance in five countries with over 50% of world steel production, finding potential CO_2 emission reductions due to energy efficiency improvement varying from 15% (Japan) to 40% (China, India, U.S.). While China has made significant improvements in energy efficiency, reducing energy consumption/t steel from 29.3 GJ in 1990 to 23.0 GJ in 2000[5] (Price, et al., 2002), there is still considerable potential for energy efficiency improvement and CO_2 emission mitigation (Kim and Worrell, 2002a). Planned improvements include greater use of continuous casting and near-net shape casting, injection of pulverized coal, increased heat and energy recovery, and improved furnace technology (Zhou, et al., 2003). A recent study estimated the 2010 global technical potential for energy efficiency

[5] China uses various indicators to present energy intensity, including the comprehensive and comparable energy intensity. The indicators are not always easily comparable to energy intensities from other countries or regions. The above figures use the comparable energy intensity, which is a constructed indicator, making it impossible to compare to those of other studies. Only a detailed assessment of the energy data can result in an internationally comparable indicator (Price, *et al.*, 2002).

improvement with existing technologies at 24% (De Beer et al., 2000a) and an additional 5% could be achieved by 2020 using advanced technologies such as smelt reduction and near net shape casting. ULCOS, a consortium of 48 European companies and organizations, has as its goal developing steelmaking technology that reduces CO_2 emission by at least 50%. The technologies being evaluated, including CCS, biomass and hydrogen, show a potential for controlling emissions to 0.5-1.5 tCO_2/t steel (Birats, 2005).

Energy savings depend not only on the application of energy-efficient technology, but also on energy management in steel plants. Okazaki, et al. (2004) estimate that approximately 10% of total energy consumption in steel making could be saved through improved energy and materials management. Mozorov and Nikiforov (2002) reported an even larger 21.6% efficiency improvement in a Russian iron and steel facility.

Economics may limit the achievable emission reduction potential. A study of the U.S. steel industry found a 2010 technical potential for energy-efficiency improvement of 24% (Worrell, et al., 2001a), but economic potential, using a 30% hurdle rate, was only 18%, even accounting for the full benefits of the energy efficiency measures (Worrell, et al., 2003). A similar study of the European steel industry found an economic potential of less than 13% (De Beer, et al., 2001). These studies focused mainly on retrofit options. However, potential savings will be realized by a combination of stock turnover and retrofit of existing equipment (Ruth, 1995). A recent analysis of the efficiency improvement of electric arc furnaces in the US steel industry found that the average efficiency improvement between 1990 and 2002 was 1.3%/year, of which 0.7% was due to stock turnover and 0.5% due to retrofit of existing furnaces (Worrell and Biermans, 2005). Future efficiency developments will aim at further process integration. The most important are near net shape casting (Martin, et al., 2000), with current applications at multiple plants in the world, and smelt reduction, which integrates ore agglomeration, coke making, and iron production in a single process. While the current blast furnace is very efficient at large scale, at small to medium-scales smelt reduction will offer an energy-efficient alternative (De Beer, et al., 1998).

Fuel Switching. Coal (in the form of coke) is the main fuel in the iron and steel industry because it provides both the reducing agent and the flow characteristics required by blast furnaces in the production of iron. Steel-making processes produce large volumes of by-products (e.g. coke oven gas, blast furnace gas) that are used as fuel. Hence, a change in coke use will affect the energy balance of an integrated iron and steel plant.

Technology to use oil, natural gas, and pulverized coal to replace coke in iron-making has long been available. Use of this technology has been dictated by the relative costs of the fuels, and the process limitations in iron-making furnaces. Use of oil and natural gas could reduce CO_2 emissions. More recently, the steel industry has developed technologies that use wastes, such as plastics, as alternative fuel and raw materials (Ziebek and Stanek, 2001). Pre-treated plastic wastes have been recycled in coke ovens and blast furnaces (Okuwaki, 2004), reducing CO_2 emissions by reducing emissions from incineration and the demand for fossil fuels. In Brazil, charcoal has been used as an alternative to coke in blast furnaces. While recent data are not available, use of charcoal declined in the late 1990s, as merchant coke became cheaper than charcoal (Kim and Worrell, 2002a). The use of hydrogen to reduce iron ore is a longer-term technology discussed in section 7.12. CCS is another longer-term technology that might have applicability to steel making (see section 7.3.7).

7.4.2 Non-ferrous Metals

The commercially-relevant non-ferrous metals, and specific and absolute CO_2 emissions from electrode and reductant use are shown in Table 7.5. Annual production of these metals ranges from approximately 30 Mt for aluminium to a few hundred kt for metals and alloys of less commercial importance. Compared to some of the world's key industrial materials like cement, steel, or paper, production volumes are fairly low. However, primary production of some of these metals from ore can be far more energy intensive. In addition, the production phase of these metals can result in the emission of high-GWP GHGs, e.g. PFCs or SF_6, which can add significantly to CO_2 eq. emissions.

Table 7.5: *Emission factors and estimated global emissions from electrode use and reductant use for various non-ferrous metals. Indirect emissions and non-CO_2 greenhouse gas emissions are not included. After: Sjradin (2003)*

	CO_2-emissions (t CO_2/t product)[1]	Global CO_2 emissions (kt CO_2)
Primary aluminium	1.55	44,700
Titanium dioxide	0.49	900
Ferrosilicon	2.92	10,500
Silicon metal	4.85	3,500
Calcium silicon	2.71	n.a.
Ferromanganese	1.79	1,205
Silicomanganese	1.66	5,800
Ferrochromium	1.63	9,500
Ferrochromiumsilicon	2.82	(incl. in FeCr)
Lead	0.64	3,270
Nickel	0	0
Ferronickel	1.36	1,150
Magnesium	0.05	4
Tin	1.12	280
Zinc	0.43	3,175
Copper	0.18	2,480
Chromium	0	0
Calcium carbide	1.10	4,475
Silicon carbide	2.30	n.a.
TOTAL:		91,000

Generally, the following production steps need to be considered: mining, ore refining and enrichment, primary smelting, secondary smelting, metal refining, and rolling and casting. For most non-ferrous metals primary smelting is the most energy-intensive step, but significant levels of emissions of fluorinated GHGs have been reported from the refining and casting steps.

7.4.2.1 Aluminium

Global primary aluminium production was 29.9 Mt in 2004 (IAI, 2005), has grown an average of 5% per year over the last 10 years, and based on calculations using the industry's mass flow model. Production is expected to grow by 3% per year for the next 10 years. Recycled aluminium production was approximately 14 Mt in 2004, and is also expected to double by 2020 (Martchek, 2006).

Aluminium metal (Al) is produced by the electrolytic reduction of alumina (Al_2O_3) in a highly energy-intensive process. In addition to the CO_2 emissions associated with electricity generation, the process itself is GHG-intensive. It involves a reaction between Al_2O_3 and a carbon anode: 2 Al_2O_3 + 3 C = 4 Al + 3 CO_2. In the electrolysis cell, Al_2O_3 is dissolved in molten cryolite (Na_3AlF_6). If the flow of Al_2O_3 to the anode is disrupted, cryolite will react with the anode to form PFCs, CF_4 and C_2F_6 (IAI, 2001). CF_4 has a GWP of 5700 and C_2F_6, which accounts for about 10% of the mix, has a GWP of 11,900 (IPCC, 2001c). These emissions can be significantly reduced by careful attention to operating procedures and more use of computer-control that minimize disruptions in Al_2O_3 flow. Even larger reductions in emissions can be achieved by switching from older cell technology (e.g. Vertical Stud Södeberg or Side Worked Prebake) to more advanced technologies (e.g. Centre Work Prebake or Point Feed Prebake). The cost of a minor retrofit of the older technology can be recovered through improved productivity. Use of the newer technologies, which require a major retrofit, can cost up to \$75/tCO_2 eq. (\$275/tC eq.) (US EPA, 2006b).

The members of the International Aluminium Institute (IAI), which now are responsible for more than 70% of the world's primary aluminium production, have committed, for the industry as a whole, to an 80% reduction in PFC emissions intensity and for IAI member companies, a 10% reduction in smelting energy intensity by 2010 compared to 1990. IAI data (IAI, 2005) show a reduction in CF_4 emissions intensity from 0.60 to 0.16 kg/t Al, and a reduction in C_2F_6 emissions intensity from 0.058 to 0.016 kg/t Al between 1990 and 2004, with best available technology having a median emission rate of only 0.05 kg CF_4/t in 2004. IAI data (IAI, 2006) show a 6% reduction in smelting energy use between 1990 and 2004. Overall, PFC emissions from the electrolysis process dropped from 4.4 to 1.2 t CO_2 eq/t Al metal produced. The steps taken to control these emissions have been mainly low or no-cost, and have commonly been connected to smelter retrofit, conversion, or replacements (Harnisch, et al., 1998; IEA GHG 2000).

SF_6 (GWP = 22,200 (IPCC 2001c)) has been used for stirring and degassing of molten aluminium in secondary smelters and foundries (Linde, 2005). The process is not very common because of cost and technical problems (UBA, 2004). Current level of use is unknown, but is believed to be smaller than SF_6 used in magnesium production.

The main potentials for further CO_2 eq. emissions reduction are a further penetration of state-of-the art, pointfeed, prebake smelter technology and process control plus an increase of recycling rates for old-scrap (IEA GHG, 2001). Research is proceeding on development of an inert anode that would eliminate anode-related CO_2 and PFC emissions from Al smelting. A commercially viable design is expected by 2020 (The Aluminium Association, 2003). However, IEA (2006) notes that the ultimate technical feasibility of inert anodes has yet to be proven, despite 25 years of research.

7.4.2.2 Magnesium

Magnesium is produced in fairly low volumes, but its production is very energy intensive. Its growth rates have been high due to an expanding use of this light-weight metal in the transportation industry. SF_6 is quite commonly used as cover gas for casting the primary metal into ingots and for die casting magnesium. Estimates of global SF_6 emissions in 2000 are about 9 Mt CO_2 eq. (2.4 MtC eq.) for die-casting (US EPA, 2006b), and about 20 MtCO_2 eq.(5.5 MtC eq.) from die-casting and smelting (EDGAR 32F2000, 2005). The later value is about equal to energy related emissions from the production of magnesium. Harnisch and Schwarz (2003) found that the majority of these emissions can be abated at <\$1.2/t CO_2 eq. (<\$4.4/tC eq.) through the use of the traditional cover gas SO_2, which is toxic and corrosive, or of more advanced fluorinated cover gases with low GWPs. US EPA (2006b) report similar results. Significant parts of the global magnesium industry located in Russia and China still use SO_2 as a cover gas. The International Magnesium Association, which represented 44% of global magnesium production in 2002, has committed to phasing out SF_6 use its member companies by 2011 (US EPA, 2006b).

7.4.2.3 Total Emissions and Reduction Potentials

Table 7.6 gives an overview of the key emission sources in the non-ferrous metal industry. Respective values are lower bounds. Total annual GHG gas emissions from the non-ferrous metal industry were at least 560 Mt CO_2 eq. (150 MtC eq.) in 2000 (IEA GHG 2001). The GHG abatement options for the production of non-ferrous metals other than aluminium are still fairly uncertain. In the past, these industries have been considered too small or too complex in respect to raw materials, production technologies and product qualities, to be systematically assessed for reduction options.

Table 7.6: *Greenhouse gas emission from production of various non-ferrous metals*

Metal	**Global Emissions, $MtCO_2$ eq./yr.**	**Source and Year**
Aluminium		
CO_2 - Mining and Refining	109	IEA GHG, 2001 for 1995
CO_2 - Electrodes	48	IAI, 2005 for 2004
PFC - Emissions	35	IAI, 2005 for 2004
CO_2 - Electricity	300	IEA GHG, 2001 for 1995
Magnesium		
CO_2 - Electrode and Cell-Feed	4	Sjardin, 2003 for 1995
SF_6 - Casting	16	US-EPA, 2001 for 2000
CO_2 - Electricity	unknown	
CO_2 - Other steps of production process	unknown	
All other Non-Ferrous-Metals		
CO_2 - Process	40	Sjardin, 2003
CO_2 - Electricity	unknown	
CO_2 - Other steps	unknown	
All non-ferrous-metals	560 (lower bound)	

7.4.3 Chemicals and Fertilizers

The chemical industry is highly diverse, with thousands of companies producing tens of thousands of products in quantities varying from a few kilograms to thousand of tonnes. Because of this complexity, reliable data on GHG emissions are not available (Worrell, *et al*., 2000a). The majority of the CO_2 equivalent emissions from the chemical industry are in the form of CO_2, the largest sources being the production of ethylene and other petrochemicals, ammonia for nitrogen-based fertilizers, and chlorine. These emissions are from both energy use and venting and incineration of byproducts. In addition, some chemical processes create other GHGs as by-products, e.g. N_2O from adipic acid, nitric acid, and caprolactam manufacture; HFC-23 from HCFC-22 manufacture; and very small amounts of CH_4 from the manufacture of silicon carbide and some petrochemicals. In 2004, U.S. CH_4 emissions totalled 1.6 Mt CO_2 eq from petrochemical manufacture and less than 50 kt CO_2 eq from SiC manufacture (US EPA, 2006a). Pharmaceutical manufacture uses relatively little energy, most of which is used in the buildings that house industry facilities (Galitsky and Worrell, 2004).

The chemical industry makes use of many of the sector-wide technologies described in section 7.3. Much of the petro-chemical industry is co-located with petroleum refining, creating many opportunities for process integration and co-generation of heat and electricity. Both industries make use of the energy in byproducts that would otherwise be vented or flared, contributing to GHG emissions. Galitsky and Worrell (2004) identify separations, chemical synthesis, and process heating as the major energy consumers in the chemical industry, and list examples of technology advances that could reduce energy consumption in each area, e.g. improved membranes for separations, more selective catalysts for synthesis, and greater process integration to reduce process heating requirements. Longer-term, biological processing offers the potential of lower energy routes to chemical products (See Section 7.12.1.1).

7.4.3.1 Ethylene

Ethylene, which is used in the production of plastics and many other products, is produced by steam cracking hydrocarbon feedstocks, from ethane to gas oil. Hydrogen, methane, propylene, and heavier hydrocarbons are produced as by-products. The heavier the feedstock, the more and heavier the byproducts, and the more energy consumed per tonne of ethylene produced (Worrell, et al., 2000a). Ren, et al. (2006) report that steam cracking for olefin production is the most energy consuming process in the chemicals industry, accounting for emissions of about 180 $MtCO_2$/year, but that significant reductions are possible. Cracking consumes about 65% of the total energy used in ethylene production, but use of state-of-the-art technologies (e.g. improved furnace and cracking tube materials, co-generation using furnace exhaust) could save up to about 20% of total energy. The remainder of the energy is used for separation of the ethylene product, typically by low temperature distillation, and compression. Up to 15% total energy can be saved by improved separation and compression techniques (e.g. absorption technologies for separation). Catalytic cracking also offers the potential for reduced energy use, with a savings of up to 20% of total energy. This savings is not additive to the energy savings for improved steam cracking (Ren, et al., 2006). Processes have been developed for converting methane in natural gas to olefins as an alternative to steam cracking. However, Ren, et al., (2005) conclude that the most efficient of these processes uses more than twice as much primary energy as state-of-the-art steam cracking of naphtha.

7.4.3.2 Fertilizer Manufacture

Swaminathan and Sukalac (2004) report that the fertilizer industry consumes about 1.2 percent of world energy consumption and is responsible for about the same share of global GHG emissions. More than 90 percent of this energy is used in the production of ammonia (NH_3). However, as the result of energy efficiency improvements, modern ammonia plants are designed to use about half the energy per tonne of product than those designed in 1960s, (see Figure 7.4), with design energy consumption dropping from over 60 GJ/t NH_3 in the 1960s to 28.4 GJ/t NH_3 in the latest design plants, approaching the thermodynamic limit of about 19 GJ/t NH_3, and limiting scope for further efficiency increase. Benchmarking data indicate that the best-in-class performance of operating plants ranges from 28.0 to 29.3 GJ/t NH_3 (Chaudhary, 2001; PSI, 2004). The newest plants tend to have the best energy performance, and many of them are located in developing countries, which now account for 57 percent of nitrogen fertilizer production (IFA, 2004). Individual differences in energy performance are mostly determined by feedstock (natural gas vs. heavier hydrocarbons) and age of the ammonia plant (PSI, 2004, Phylipsen, et al., 2002). National and regional averages are strongly influenced by whether the sector has undergone restructuring, which tends to drive less efficient producers out of the market (Sukalac, 2005).

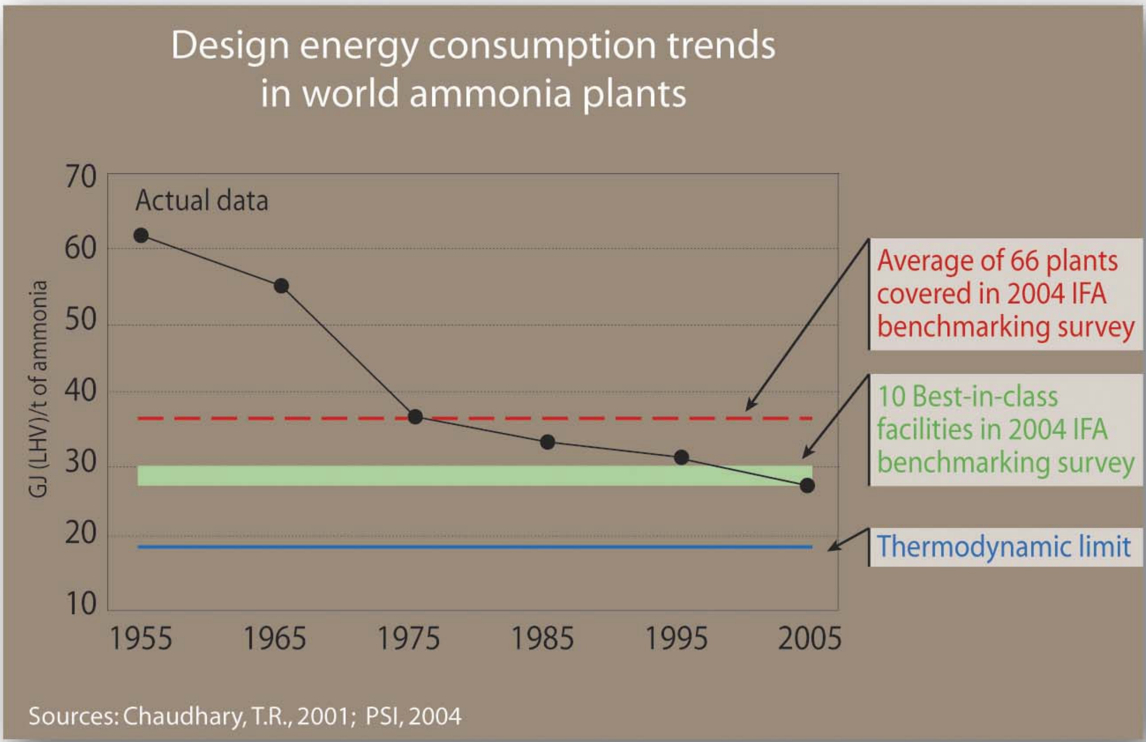


Figure 7.4: *Design energy consumption trends in world ammonia plants*

Ammonia plants that use natural gas as a feedstock have an energy efficiency advantage over plants that use heavier feedstocks, but today about 80 percent of global ammonia capacity is based on natural gas. Retrofit of old plants is feasible and offers a potential for improved efficiency. Verduijn and de Wit (2001) concluded that the energy efficiency of large single train ammonia plants, the bulk of existing capacity, could be improved at reasonable cost to levels approaching newly designed plants, provided that the upgrading is accompanied by an increase in capacity. About half the CO_2 from ammonia production is used in the production of urea and nitrophosphate (UNIDO and IFDC, 1998). Further significant reduction of GHG emissions from state-of-the-art ammonia plants could be achieved by using low carbon or carbon-free hydrogen, which could be obtained through the application of CCS technology (see Section 7.3.7.), biomass gasification, or electrolysis of water using electricity from nuclear or renewables.

7.4.3.3 Chlorine Manufacture

The TAR (IPCC, 2001a) reported on the growing use of more energy efficient membrane electrolysis cells for chlorine production. There have been no significant developments affecting GHG emissions from chlorine production since the TAR.

7.4.3.4 N_2O Emissions from Adipic Acid, Nitric Acid and Caprolactam Manufacture

N_2O emissions from nitric and adipic acid plants account for about 5% of anthropogenic N_2O emissions. Due to significant investment in control technologies by industry in North America, Japan and the EU, world-wide emissions of N_2O (GWP = 296) from adipic and nitric acid production decreased by 30%, from 223 Mt CO_2 eq. (61 MtC eq.) in 1990 to 154 Mt CO_2 eq. (42 MtC eq.) in 2000. Some of the reduction was due to the installation of NO control technology to meet regulatory requirements. By 2020, global emission from the manufacture of adipic acid (used as a feedstock for a variety of chemical products) and from the manufacture of nitric acid are projected to grow to 181 Mt CO_2 eq. (49 MtC eq.). Developed nations account for approximately 55% of emissions in both 2000 and 2020 (US EPA, 2006c). Experience in the U.S., Japan and the EU shows that thermal destruction can eliminate 96 percent of the N_2O emitted from an adipic acid plant. Catalytic reduction can eliminate 89 percent of the N_2O emitted from a typical nitric plant in a developed country (US EPA, 2006b). Potential mitigation at nitric acid plants can range from 77 percent to almost 100 percent depending on the catalyst and plant operating conditions (US EPA, 2001, Continental Engineering BV, 2001). Costs are less than US$ 1.5/tCO_2 eq. (US$ 5.5/tC eq.) using a 20% discount rate and a 40% corporate tax rate, and a maximum mitigation potential is of 165 Mt CO_2 eq. (45 Mt C eq.)in 2020.

No data was found on global N_2O emissions from caprolactam (used in the manufacture of nylon) production. IPCC (2006) gives N_2O emission factors of 9 and 14.5 kg/t caprolactam for modern plants and older plants, respectively, and indicates that these emissions can be controlled to a high degree by non-specific catalytic reduction.

7.4.3.5 HFC-23 Emissions from HCFC-22 Manufacture

Up to 4% HFC-23 (GW_p = 12,000 (IPCC, 2001c)) is produced as a byproduct of HCFC-22 manufacture. HCFC-22 has been used as a refrigerant, but under the Montreal Protocol this use is scheduled to end by 2020 in developed countries and over a longer period in developing countries. However, production of HCFC-22 for use as a feedstock in the manufacture of fluoropolymers is expected to grow, leading to increasing emissions through 2015 in the business-as-usual case. Data on production rates and control technologies are contained in the IPCC Special Report on Safeguarding the Ozone Layer and the Global Climate System (IPCC/TEAP, 2005). Capture and destruction by thermal oxidation is a highly effective option for reducing HFC-23 emissions at a cost of $0.20 - 0.32/t$CO_2$ eq. ($0.75-1.20/tC eq.) (IPCC/TEAP, 2005, US EPA, 2006b).

7.4.4 Petroleum Refining

As of the beginning of 2004, there were 735 refineries in 128 countries with a total crude oil distillation capacity of 82.3 million barrels per day. The U.S (20.5%), EU-25 (16.4%), Russia (6.6%), Japan (5.7%), and China (5.5%) had the largest shares of this capacity (EIA, 2005). Petroleum industry operations consume up to 15-20% of the energy in crude oil, or 5-7% of world primary energy, with refineries consuming most of that energy (Eidt, 2004). Comparison of energy or CO_2 intensities among countries is not practical because refining energy use is a complex function of crude and product slates and processing equipment. Simple measures (e.g. energy consumed/barrel refined) do not account for that complexity.

Worrell and Galitsky (2005), based on a survey of U.S. refinery operations, found that most petroleum refineries can economically improve energy efficiency by 10-20%, and provided a list over 100 potential energy saving steps. Key items included: use of co-generation, improved heat integration, combustion optimization, control of compressed air and steam leaks, and use of efficient electrical devices.

The petroleum industry has had long-standing energy efficiency programs for refineries and the chemical plants with which they are often integrated. These efforts have yielded significant results. ExxonMobil reported over 35% reduction in energy use in its refineries and chemical plants from 1974-1999, and in 2000 instituted a program whose goal was a further 15% reduction, which would reduce emissions by an addition 12 $MtCO_2$/yr. (Eidt, 2004). Chevron (2005) reported a 24% reduction in its index of energy use between 1992 and 2004. Shell (2005) reported energy efficiency improvements of 3-7% at its refineries and chemical plants.

Refineries use hydrogen to remove sulphur and other impurities from products, and to process heavy hydrocarbons into lighter components for use in gasoline and distillate fuels. The hydrogen is supplied from hydrogen-rich reformer gas, a byproduct of catalytic reforming, a process for upgrading gasoline components. If reformer hydrogen is insufficient for the refinery's needs, the refinery will manufacture hydrogen by gasification of fossil fuels, and U.S. refineries use about 8% of their energy input to produce hydrogen (Worrell and Galitsky, 2005). Hydrogen production produces a CO_2-rich stream, which is a candidate for CCS (see Section 7.3.7). Data on the amounts of CO_2 that might be mitigated in this fashion have not been found. NAM (Nederlandse Aardolie Maatschappij B.V.) and Shell have conducted a feasibility study on underground storage of CO_2 from the Shell Pernis Refinery for potential reuse in greenhouses or for enhanced gas recovery, which showed this option to be attractive compared with other sources of CO_2 (van Luijk, 2003). However, the special circumstances of this case study (availability of high purity CO_2, short transportation distance, and small scale), raise questions about its general applicability.

7.4.5 Minerals

7.4.5.1 Cement

Cement is produced in nearly all countries. Cement consumption is closely related to construction activity and general economic activity. Global cement production grew from 594 Mt in 1970 to 2130 Mt in 2004, with the vast majority of the growth occurring in developing countries, especially China. In 2004 developed countries produced 570 Mt (27% of world production) and developing countries 1560 Mt (73%) (USGS, 2005). China has almost one half of world's cement capacity and dominates current world cement production, manufacturing 934 Mt in 2004, followed by India with a production of 125 Mt in 2004 (USGS, 2005). Global cement consumption is growing at about 2.5%/year. While a group of 12 multinational companies controls nearly 75% of production in developed countries, regional and local players dominate most of the industry in Asia including China and India (Jain, 2005).

The production of clinker, the principal component of cement, emits CO_2 from the calcination of limestone. Cement production is also highly energy-intensive. The major energy uses are fuel for the production of clinker and electricity for grinding raw materials and the finished cement. Coal dominates in clinker making. Based on average emission intensities (see below), total emissions in 2003 are estimated at 1587 Mt CO_2 (432 MtC) to 1697 $MtCO_2$ (462 MtC), or about 5% of global CO_2 emissions, half from process emissions and half from energy use. Global average CO_2 emissions/t cement production is estimated by Worrell, et al. (2001b) at 814 kg (222 kg C), while Humphreys and Mahasenan (2002) estimated 870 kg (264 kg C). CO_2 emission/t cement vary by region from a low of 700 kg (190 kg C) in Western Europe and 730 kg (200 kg C) in Japan and South Korea, to a high of 900, 930, and 935 kg (245, 253, and 255 kg C) in China, India and the United States (Humphreys and Mahasenan, 2002; Worrell, et al., 2001b).

Emission intensities have decreased by approximately 0.9%/year since 1990 in Canada, 0.3%/yr (1970-1999) in the U.S., and 1%/year in Mexico (Nyboer and Tu, 2003; Worrell and Galitsky, 2004; Sheinbaum and Ozawa, 1998). A reduction in energy intensity in India since 1995-96 has led to a reduction in emissions from the industry despite the increase in output (Dasgupta and Roy, 2002). Analysis of CO_2 emission trends in four major cement-producing countries showed that energy efficiency improvement and reduction of clinker content in cement were the main factors contributing to emission reduction, while the carbon intensity of fuel mix in all countries increased slightly. The differences in emission intensity are due (in order of contribution) to differences in the clinker content of the cement produced, energy efficiency, carbon intensity of the clinker fuel, and carbon intensity of power generation (Kim and Worrell, 2002b).

CO_2 emissions from both energy use and calcination of limestone can be reduced. The combined technical potential of these opportunities is estimated at 30% globally, and varying between 20 and 50% for different regions (Humphreys and Mahasenan, 2002; Kim and Worrell, 2002b). Energy efficiency improvement has historically been the main contributor to emission reduction. Benchmarking and other studies have demonstrated a technical potential for up to 40% improvement in energy efficiency (Kim and Worrell, 2002b; Worrell, et al., 1995). Countries with a high potential still use outdated technologies, like the wet process clinker kiln. Studies for the US identified 30 opportunities, in every production step in the cement-making process, and estimated the economic potential for energy efficiency improvement in the US cement industry at 11%, reducing emissions by 5% (Worrell, et al., 2000b; Worrell and Galitsky, 2004). The cement industry is capital intensive and equipment can have a long lifetime, limiting the economic potential on the short term. The clinker kiln is an ideal candidate for the use of a wide variety of fuels, including waste-derived fuels, such as tyres, plastics, biomass, municipal solid wastes and sewage sludge (see section 7.3.2). Section 7.3.7 discusses the potential for applying CCS in the cement industry.

Standard Portland cement contains 95% clinker. Clinker production is responsible for the process emissions and most of the energy-related emissions. Use of blended cement, in which clinker is replaced by alternative cementatious materials, e.g. blast furnace slag, fly ash from coal-fired power stations, and natural pozzolanes, results in lower CO_2 emissions (Josa, et al., 2004). Humphreys and Mahasenan (2002) and Worrell, et al. (1995) estimate the potential for reduction of CO_2 emissions at more than 7%. Current use of blended cement is relatively high in Europe and low in the U.S. and U.K. Alternatives for limestone-based cement are also being investigated (Gartner, 2004; Humphreys and Mahasenan, 2002). Geopolymers have been applied in niche markets, but have yet to be proven economical for large scale application.

7.4.5.2 Lime

Generally lime refers both to high-calcium and dolomitic forms containing magnesium. Lime is produced by burning limestone or dolomite in small-scale, vertical or large-scale, rotary kilns. While in most industrialized countries the industry is concentrated in a small number of larger corporations, in most developing countries lime kilns are typically small operations using local technology. However, even in industrialized countries (e.g. Greece) independent small-scale vertical kilns operate. Pulp and sugar mills may have captive lime production to internally regenerate lime. Lime is mainly used in a small number of industries (especially steel, but also chemicals, paper and sugar), mining, as well as for flue gas desulphurization. There are no detailed statistics on global lime production, but Miller (2003) estimated global production at 120 Mt, excluding regenerated lime. The largest producers are China, United States, Russia, Germany, Mexico and Brazil.

CO_2 emissions are due to the decarbonization of limestone and dolomite, fuel combusted in the process, and indirect emissions from generation of the electric power consumed in the process. In efficient lime kilns about 60% of the emissions are due to decarbonization of the raw materials. No estimates of global CO_2 emissions due to lime production are available. In Europe process emissions are estimated at 750 kg CO_2/t lime (IPPC, 2001). Regeneration of lime in pulp and sugar mills does not necessarily lead to additional CO_2 emissions, as the CO_2 is from biomass sources (Miner and Upton, 2002). Emissions from fuel use vary with the kiln type, energy efficiency and fuel mix. Energy use is 3.6-7.5 GJ/t lime in the EU (IPPC, 2001), 7.2 GJ/t in Canada (CIEEDAC, 2004) and for lime kilns in US pulp mills (Miner and Upton, 2002), and up to 13.2 GJ/t for small vertical kilns in Thailand (Dankers, 1995). In Europe, fuel-related emissions are estimated at 0.2-0.45 tCO_2/t lime (IPPC, 2001). Electricity use for lime production is 40-140 kWh/t lime, depending on the type of kiln and the required fineness of the lime (IPPC, 2001).

Emission reductions are possible by use of more efficient kilns (Dankers, 1995; IPPC, 2001) and through improved management of existing kilns, using similar techniques as the cement industry (see section 7.4.5.1). Emission reductions (5-10% of total emissions) are possible by energy efficiency measures at payback periods of three years or less (CLI, 2001; Worrell and Galitsky, 2003). Switching to low-fossil carbon fuels can further reduce CO_2 emissions. The use of solar energy has been investigated for small-scale installations (Meier, *et al.*, 2004). It may also be possible to reduce the consumption of lime in various processes, e.g. in the sugar industry (Vaccari, *et al.*, 2005).

7.4.5.3 Glass

Glass is produced by melting raw materials (mainly silica, soda ash and limestone), and often cullet (recycled glass), in glass furnaces of different sizes and technologies. Typical furnace designs include: cross-fired or end-fired with regenerative air preheat, recuperative heat recovery and fuel-oxygen firing (EU-BREF Glass, 2001). The industry is capital intensive, furnaces have a life time of up to 12 years, and there are a limited number of technology providers. Natural gas and fuel oil are the main fuels used by the glass industry. Reliable international statistics on glass production are not available. The global glass industry is dominated by the production of container glass and flat glass. According to industry estimates the global production of container glass was 57 Mt in 2001 (ISO, 2004); production of flat glass was 38 Mt in 2004 (Pilkington, 2005). The production volumes of special glass, domestic glass, mineral wool and glass fibres are each smaller by roughly an order of magnitude.

Beerkens and van Limpt (2001) report the energy intensity of continuous glass furnaces in Europe and the US as 4-10 GJ/t of container glass and 5-8.5 GJ/t of flat glass, depending on the size and technology of the furnace and the share of cullet used. The energy consumption for batch production is higher, typically 12.5-30 GJ/t of product (Römpp, 1995). Assuming that half of this energy is provided by natural gas and half by fuel oil, and an average of 7 GJ/t of product, yields an emission factor of 450 kg energy related CO_2/t of product. Globally, energy used in the production of container and flat glass results emissions of approximately 40-50 $MtCO_2$ per year. Emissions from the decarbonisation of soda ash and limestone can contribute up to 200 kg CO_2/t of product depending on the specific composition of the glass and the amount of cullet used (EU-BREF Glass, 2001).

Short to mid-term emission reduction potential is estimated to be 30-40%, reflecting the range of efficiencies reported by Beerkens and van Limpt (2001). Main mitigation options in the industry include: improved process control, increased use (up to 100%) of cullet (Kirk-Othmer, 2005), increased furnace size, use of regenerative heating, oxy-fuel technology, batch and cullet pre-heating, and reduction of reject rates (Beerkens and van Limpt, 2001), and the use of natural gas instead of fuel oil, and CO_2 capture for large oxy-fuel furnaces. High caloric value biogas could be used to reduce net CO_2 emissions, but potential new break-through technologies are not in sight.

7.4.5.4 Ceramics

The range of commercial ceramics products is large, including bricks, roof and wall and floor tiles, refractory ceramics, sanitary ware, tableware and cookware, and other products. In terms of volume the production of bricks and tiles dominate. The main raw materials used in the brick industry include clay and kaolin. Production technologies and respective energy efficiencies vary tremendously from large industrial operations to cottage and artisan production, which are still very common in many developing countries. The main fuels used in modern design industrial kilns are natural gas and fuel oil. Specific energy consumption strongly varies for different products and kiln designs. The EU-BREF Ceramics (2005) reports specific energy consumptions for modern industrial brick production of 1.4-2.4 GJ/t of product.

In developing countries small scale kilns - mainly to produce bricks - using inexpensive manual labour are often used. Wood, agricultural residues, and coal (FAO, 1993) are the main fuels used, with specific energy consumptions of 0.8-2.8 GJ/t of brick for the small- to mid-size kilns, and 2-8 GJ/t of brick for the very small-scale kilns used by the cottage industry and artisans (FAO, 1993). It should be noted that specifications for bricks produced in different types of kilns differ strongly, e.g., solid, hollow or perforated bricks. Industrial, as well as small-scale producers, utilize, to a certain extent, the energy contained in the organic fraction of clay and shale as well as in pore forming agents (e.g. saw dust) added to the clay in the production process. CO_2 emissions from the calcination of carbonates contained in clay and shale typically contribute 20-50% of total emissions.

Reliable international statistics on the production of ceramics products are not available. The annual per capita consumption of bricks, tiles and other ceramic products in t per capita per year is estimated at 1.2 in China (Naiwei, 2004); 0.4 in the EU (EU-BREF Ceramics, 2005), 0.1 in the U.S. (USGS, 2004), and 0.25, 0.12, and 0.05 for Pakistan, India and Bangladesh (FAO, 1993). This suggests that the global production of ceramic products exceeds 2 Gt/year, leading to the emission of more than 400 $MtCO_2$ (110 MtC) per year from energy use and calcination of carbonates. Additional research to better understand the emission profile and mitigation options for the industry is needed

GHG mitigation options include the use of more efficient kiln design and operating practices, fuel switch away from coal into fuel oil, natural gas and biomass, and partial substitution of clay and shale by alternative raw materials such as fly ash. Mitigation options also include the use of alternative building materials like concrete or wood, as well as the use of bricks made from concrete or lime and sand. However, informed decisions will consider emissions over the whole life cycle of the products including their impact on the energy performance of the building. The current choices of building materials and kiln technologies are deeply related to local traditions, climate, and the costs of labour, capital, energy and transportation, as well as the availability of alternative fuels, raw materials and construction materials.

7.4.6 Forest Products

The forest products industry is a highly diverse and increasing global industry. In 2003, developing countries produced 26% of paper and paperboard and 29% of global wood products; 31% of paper and paperboard output was traded internationally (FAOSTAT, 2006). Direct emissions from the pulp, paper, paperboard, and wood products industries are estimated 264 $MtCO_2$/yr (72 MtC/yr) (Miner and Lucier, 2004). The industry's indirect emissions from purchased electricity are less certain but are estimated to be 130-180 $MtCO_2$/year (35-50 MtC/yr) (WBCSD, 2005).

7.4.6.1 Mitigation Options

Use of biomass fuels: The forest products industry is more reliant on biomass fuels than any other industry. In developed countries, biomass provides 64% of the fuels used by wood products facilities and 49% of the fuel used by pulp, paper and paperboard mills (WBCSD, 2005). Most of the biomass fuel used in the pulp and paper industry is spent pulping liquor, which contains dissolved lignin and other material from the wood that are not used in paper production. The primary biomass fuel in the wood-products sector is manufacturing residuals that are not suitable for use as by-products.

Use of combined heat and power: In 2002, the pulp and paper industry used cogeneration to produce 40% of its electricity requirements in the U.S.(US DOE, 2002) and over 30% in the EU (CEPI, 2002), and that use continues to grow.

Black liquor gasification: Black liquor is the residue from chemical processing to produce wood pulp for papermaking. It contains a significant amount of biomass and is currently being burned as a biomass fuel. R&D is underway on gasification of this material to increase the efficiency of energy recovery. Gasification would also create the potential to produced synfuels and apply CCS technology. IEA (2006) estimates a 10-30 $MtCO_2$ (2.7-8.1 MtC) mitigation potential for this technology in 2030.

Recycling: Recovery rates for used paper (defined as the percent of domestic consumption that is collected for reuse) in developed countries are typically at least 50% and are over 65% in Japan and parts of Europe (WBCSD, 2005). Globally, recycling supplied 44% of total feedstock in 2004 (IEA, 2006). The impact of this recycling is complex, affecting the emissions profile of paper plants, forests, and landfills. A number of studies examine the impacts of recycling on life cycle greenhouse gas emissions (Pickens, *et al.*, 2002, Bystrom and Ekvall, 1997). These and other studies vary in terms of boundary conditions and assumptions about end-of-life management, and none attempt to examine potential indirect impacts of recycling on market-based decisions to leave land in forest rather than convert it to other uses. Although most (but not all) of these studies find that paper recycling reduces life cycle emissions of GHG compared to other means of managing used paper, the analyses are so dependent on study boundary conditions and site-specific factors that it is not yet possible to develop reliable estimates of the global mitigation potential related to recycling. However, both the U.S. (US EPA, 2002) and EU (EC, 2004) identify paper recycling as a GHG emissions reduction option.

7.4.6.2 Emission Reduction Potential

Because of increased use of biomass and energy efficiency improvements, the greenhouse gas emissions from the forest products industry have been reduced over time. Since 1990, CO_2 emissions intensity of the European paper industry has decreased by approximately 25% (WBCSD, 2005), of the Australian pulp and paper industry about 20% (A3P, 2006), and of the Canadian pulp and paper industry over 40% (FPAC, n.d.). Fossil fuel use by the pulp and paper industry declined by more than 50% between 1972 and 2002 (AF&PA, 2004). However, despite these improvements, Martin, *et al*. (2000) found a technical potential for GHG reduction of 25% and a cost-effective potential of 14% through widespread adoption of 45 energy-saving technologies and measures in the U.S. pulp and paper industry.

Table 7.7 shows Tanaka, *et al.* (2005) estimates of the technical potentials for CO_2 emissions reductions by region in the pulp and paper industry. However, we should note the following structural factors that lead to the differences in the specific emissions for each country:
- production process (e.g., pulp/paper, mechanical/chemical/recycled pulp);
- fuel mix, including biomass and waste and use of combined heat and power;
- raw materials (domestic or imported wood, non-wood pulp).

These factors would have to be taken into account before the economic potential for CO_2 emission reduction could be assessed.

Table 7.7: *Technical Potential for CO_2 Emissions Mitigation in the Pulp and Paper Industry (Tanaka, et al., 2006)*

Region	Production in 2000	Projected Production in 2030	CO_2 Mitigation Potential in 2030
Centrally Planned Asia	+++	+++	++++
Other Asia	++	+++	++++
Latin America	++	+++	++++
North America	++++	+++	+++
Western Europe	+++	+++	+++
Central and Eastern Europe	+	+	+++
Pacific OECD	+++	+++	++
Former Soviet Union	+	+	+
Sub-Saharan Africa	+	+	+
Middle East and North Africa	+	+	+

Production: + = 0-10 Mt/yr; ++ = 10-30 Mt/yr; +++ = 30-100/yr; ++++ = >100 Mt/yr
Mitigation Potential: + = 0-1 MtC/yr; ++ = 1-3 MtC/yr; +++ = 3-10 MtC/yr, ++++ = > 10 MtC/yr.

7.4.7 Food

The food and beverages industry has a variety of products/processes including sugar, edible oils (e.g. peanuts, coconut, palm, cotton), starch, fruits and vegetables canning, bakeries, breweries, and meat processing. Most of these products constitute major commercial commodities, particularly for developing countries, and are quite energy-intensive (e.g. sugar, starch, breweries).

The sugar cane industry is one of the largest food industries, producing 1.2 Gt sugar/yr. (Banda, 2002) from about 1670 mills, most located in developing countries (India, Pakistan, South East Asia, China, Southern Africa, and Latin America) (Sims, 2002). Edible oils are another significant product with export potential supporting many developing countries economies. Malaysia, the world’s largest producer and exporter of palm oil, has 3.5 M ha under palm oil production (UNDP, 2002), whilst Sri Lanka, the world’s fourth producer of coconut oils, has 0.4 M ha under cultivation (Kumar, et al., 2003).

Corn refining, including wet corn milling, has been the fastest growing market for U.S. agriculture over the past twenty years (CRA, 2002). Wet milling of corn produces starch, ethanol, sweeteners such as high fructose corn syrup, feed products, vegetable oil, and other byproducts. Within food processing, corn wet milling is the most energy-intensive industry, using 15% of the total energy in the U.S. food industry (EIA, 2001). Over 100 technologies and measures for improving energy efficiency of corn wet milling have been identified (Galitsky, et al., 2003).

7.4.7.1 Production Processes, Emissions and Emission Intensities

The main production processes for the food industry are almost identical, involving preparatory stages including crushing, processing/refining, drying and packaging. Most produce process residuals, which typically go to waste. Food production requires electricity, process steam and thermal energy, which in most cases are produced from fossil fuels. Most food industry processes produce large volumes of wastewater, which is a serious problem for normal waste treatment plants due to its varying composition, high organic content, and unbalanced nutrients. Pre-treatment of the wastewater in a digester is normally required before it can be discharged into a sewer system (Yeoh, 2004). The major GHG emissions from the food industry are CO_2, from fossil fuel combustion in boilers and furnaces, and CH_4 (GWP=23) from wastewater systems due to anaerobic reactions occurring in the ponds. Wastewater systems are also a source of N_2O, directly from wastewater treatment plants and indirectly from discharged wastewater.

Although unit factory emissions from the food industry are low, their cumulative effect is significant in view of large numbers of such factories in both developed and developing countries. Energy intensities vary depending on the nature of operations, with typical energy intensities estimated at about 11 GJ/t for edible oils, 5 GJ/t for sugar, and 10 GJ/t for canning operations (UNIDO, 2002). The largest source of emissions is CH_4 from wastewater treatment. For example, in the palm oil industry in Malaysia, an estimated 5.17 Mt CO_2 eq. (1.4 MtC eq) now being generated from open-ponding systems could be used to generate 2.25 GWh of electricity while significantly reducing GHG emissions (Yeoh, 2004). In the Thai starch industry (Cohen, 2001), out of a total of 370 kt CO_2 eq.(101 ktC eq.) per year, 88% were from wastewater treatment, 8% from combustion of fuel oil, and 4% from grid electricity.

7.4.7.2 Mitigation Opportunities

Technologies and processes available to reduce food industry GHG emissions in the near- and medium-term include: good housekeeping and improved management, improvements in both cross-cutting systems (e.g. boilers, steam and hot water distribution, pumps, compressors and fans) and process-specific technologies, improved process controls, more efficient process designs, and process integration (Galitsky, et al., 2001), cogeneration to produce electricity for own use and export (Cornland, 2001), and anaerobic digestion of residues to produce biogas for electricity generation and/or process steam (Yeoh, 2004).

In Brazil, electricity sales to the grid from bagasse cogeneration reached 1.6 TWh in 2005 from an installed capacity of 400 MW. This capacity is expected to increase to 1000 MW with implementation of a government-induced voluntary industry program (Moreira, 2006). In India, the sugar industry has diversified into cogeneration of power and production of fuel ethanol. Cogeneration began in 1993-94, and as of 2004 reached 680 MW. Full industry potential is estimated at 3500 MW. In 2001, India instituted a mixed fuel programme requiring use of a 5% ethanol blend, which will create an annual demand for 500 M litres of ethanol (Balasubramaniam, 2005). A study on the application of traditional boilers with improved combustion and CEST

(Condensing Extraction Steam Turbines) in the Southern African sugar industry showed that by 2010, the sugar factories under consideration could be self sufficient in electricity generation with surpluses of 135MW for use for irrigation purposes and 1620 MW for export to the national grid (Yamba and Matsika, 2003). Application of CEST technologies, the study showed, will reduce GHG emissions by 8 Mt CO_2 eq. (2.2 MtC eq.)/year by the year 2010, and also improve financial performance of such industries from an Internal Rate Return (IRR) of 13.9% and Net Present Value (NPV) of US$32.7 million under business-as-usual operation to 15.3% IRR and US$ 51.6 million NPV when CEST technologies are applied to normal sugar operations (Cornland, et al., 2001). A similar study for Australia (Sims, 2002) indicated that if all 31 of the country's existing sugar mills were converted to CEST technology, they would have the potential to generate 20 TWh/year of electricity, and assuming that they replaced coal-fired electricity generation, reduce emissions by 16 $MtCO_2$ (4.4 MtC)/year. Gasifying the biomass and using it in combined cycle gas turbine could double the CO_2 savings (Cornland, 2001). Proposed CDM projects in the Malaysian palm oil industry (UNDP, 2002), and the Thai starch industry (Cohen, 2001) demonstrate that use of advanced anaerobic methane reactors to produce electricity would yield a GHG emission reduction of 56-325 kt CO_2 eq. (15-90 MtC eq.)/year. Application of improved energy management practices in the coconut industry (Kumar, et al., 2003) and bakery industry (Kannan, et al., 2003) showed significant saving of between 40-60 % in energy consumption for the former and a modest saving of 6.5 % for the latter. In the long term, use of residue biomass generated from the food industry in state-of-the-art Biomass Integrated Gasifier Combined Cycle (BIG/CC) technologies, once they become commercially available, will significantly improve electricity generation and GHGs savings by a factor of two (Yamba and Matsika, 2003; Cornland, et al., 2001) over the CEST technologies.

Virtually all countries have environmental regulations of varied stringency, which require installations including the food industry to limit final effluent BOD (Biochemical Oxygen Demand) in the wastewater before discharge into waterways. Such measures are compelling industries to use more efficient wastewater treatment systems. The recently introduced EU-directive requiring Best Available Techniques (BAT) on environmental permit conditions in the fruit and vegetable processing industry (Dersden, et al., 2002) will compel EU industry in this sector to introduce improved wastewater purification processes thereby reducing fugitive emissions due to anaerobic reactions.

7.4.8 Other Industries

This section covers a selection of industries with significant emissions of high GWP gases. The manufacture of semiconductors, liquid crystal display and photovoltaic cells can result in the emissions of PFCs, SF_6, NF_3, and HFC-23 (IPCC, 2006). The technology available to reduce these emissions from semiconductor manufacturing, and the World Semiconductor Council (WSC)'s commitment to reduce PFC emissions by at least 10% by 2010 from 1995 levels are discussed in the TAR (IPCC, 2001a). US EPA (2006b) reports that emission levels from semiconductor manufacture were about 40 $MtCO_2$ eq (11 MtC eq) in 2000, and that significant growth in emissions will occur unless the WSC commitment is implemented globally and strengthened after 2010. US EPA (2006b) estimates that this 10% reduction could occur cost effectively through replacement of C_2F_6 with C_3F_8 (which has a lower GW_p), NF_3 remote cleaning of the chemical vapour disposition chamber, or capturing and recycling of SF_6. Emissions from the production of liquid crystal displays and photovoltaic cells are growing rapidly and mitigation options need further research.

SF_6 emissions in 2000 from the production of medium and high voltage electrical transmission and distribution equipment were estimated at about 10 $MtCO_2$-eq (2.8 MtC-eq) (IEA GHG, 2001).

These emissions, mainly located in Europe and Japan, are estimated to have declined, despite a 60% growth in production, 1995-2003, mainly due to targeted training of staff and improved gas handling and test procedures at production sites. Emissions of SF_6 at the end-of-life of electrical equipment are growing in relevance, and US EPA (2006c) estimates total SF6 emissions from production, use and disposal of electrical equipment at 27 $MtCO_2$ in 2000 growing to 66 $MtCO_2$ in 2020, of no mitigation actions are taken. Emissions from disposal of electrical equipment could be reduced by implementation of a comprehensive recovery system, addressing all entities involved in handling and dismantling this equipment (Wartmann and Harnisch, 2005).

A third group of industries that emits hydrofluorocarbons (HFCs) includes those manufacturing rigid foams, refrigeration and air conditioning equipment, and aerosol cans, as well as industries using fluorinated compounds as solvents or for cleaning purposes. This group of industries previously used ozone depleting substances (ODS), which are subject to declining production and use quotas defined under the Montreal Protocol. As part of the phase out of ODS, many of them have switched to HFCs as replacements, or intend to do so in the future. Mitigation options include improved containment, training of staff, improved recycling at the end-of-life, the use of very low GWP alternatives, and the application of not-in-kind technologies. A detailed discussion of use patterns, emission projections, and mitigation options for these applications can be found in the IPCC/TEAP Special Report on Protecting the Ozone Layer and Safeguarding the Climate (IPCC/TEAP, 2005). IEA GHG (2001) estimated that global fugitive emissions from the production of HFCs from 2 $MtCO_2$-eq (0.6 MtC-eq) in 1996, to 8 $MtCO_2$-eq (2.2 MtC-eq) by 2010. Solvent and cleaning uses of HFCs and PFCs are commonly emissive despite containment and recycling measures. IEA GHG (2001) projected that these emissions will increase to up to 20 $MtCO_2$-eq (5.5 MtC-eq)/year by 2020. However, other analyses suggest a more moderate growth in emissions from solvent applications to about 5 $MtCO_2$-eq (1.4 MtC-eq)/year by 2020 (IPCC/TEAP, 2005).

7.4.9 Cross industry Options

Some options for reducing GHG emissions involve more than one industry, and may increase energy use in one industry to achieve a greater reduction in energy use in another industry or for the end-use consumer. For example, the use of granulated slag in Portland cement may increase energy use in the steel industry, but can reduce both energy consumption and CO_2 emissions during cement production by about 40%. Slag production is approximately 300 kg/t iron. Slag content can be as high as 60% of the cement, replacing an equivalent amount of clinker (Cornish and Kerkhoff, 2004). Light weight materials (high tensile steel, aluminium, magnesium, plastics, composites) often require more energy to produce than the heavier materials they replace, but their use in vehicles will reduce transportation sector energy use, leading to an overall reduction in global energy consumption. Life cycle calculations (IAI, 2000) indicate that the CO_2 emissions reduction in vehicles resulting from the weight reduction achieved by using aluminium more than offsets the GHG emissions from producing the aluminium.

Heat-cascading systems, where waste heat from one industry is used by another, are a promising cross-industry option to save energy. Based on the Second Law of Thermodynamics, Grothcurth, et al. (1989) estimated up to 60% theoretical energy saving potential from heat cascading systems. However, Matsuhashi, et al. (2000) found the practical potential of these systems was limited to approximately 5% energy saving.

7.5 Short- and Medium-Term Mitigation Potential and Cost

Limited information is available on mitigation cost and potential in industry, but it is sufficient to develop a global estimate for the industrial sector. Available studies vary widely with respect to system boundaries, baseline, time period, sub-sectors included, completeness of mitigation measures included, and economic factors (e.g. costs, discount rates). In many cases study assumptions are not specified, making it impossible to adjust the studies to a common basis, or to quantify overall uncertainty.

Table 7.8 presents an assessment of the industry-specific literature. Mitigation potential and cost for industrial CO_2 emissions were estimated as follows:

- Price, *et al*. (2006)'s estimates for 2030 production rate by industry and geographic area for the SRES A1 and B2 scenarios (IPCC, 2000b) were used.
- Literature estimates of mitigation potential were used, where available. In other cases, mitigation potential was estimated by assuming that current best practice could be achieved by all plants in 2030.
- Literature estimates of mitigation cost were used, where available. When literature values were not available, expert judgment (informed by the available literature and data) was used to assign costs to mitigation technology. Cost estimates are reported as 2030 mitigation potential below a given cost level. In most cases it was not possible to develop a marginal abatement cost curve that would allow estimation of mitigation potential as a function of cost.

Estimates also have not been made for some smaller industries (e.g. glass) and for the food industry. One or more of the critical inputs needed for these estimates were missing.

Estimates of mitigation cost and potential for N_2O (adipic and nitric acid production only) and fluorinated gas emissions from industry have been extrapolated from US EPA projections for 2020 (US EPA, 2006b). These estimates are based on the technologies discussed in Section 7.4 and the cost of implementing these technologies in the U.S., E.U. and Japan, but do include effects of SRES scenario differences. Calculations were made assuming a 10% discount rate and a 40% tax rate. Insufficient data were found to estimate mitigation cost or potential for N_2O emissions from caprolactam manufacture or for CH_4 emissions from the food or chemical industries.

Table 7.8 should be interpreted with care. The method described above results in large uncertainties. It is based on a limited number of studies, sometimes only one study per industry, and implicitly assumes that current trends will continue until 2030.

Table 7.5.1 shows that in 2030 under the A1B scenario, mitigation potential for the industrial sector is 3.6-6.9 $GtCO_2$ (0.98 -1.9 GtC). Mitigation potential under the B2 scenario is somewhat less, 2.6-5.5 $GtCO_2$ (0.71-1.5 GtC). Our analysis shows that most of the mitigation potential is located in the steel, cement, and petroleum refining industries, and in the control of non-CO_2 gases, and that much of the potential is available at $\$ \leq 20/tCO_2$ ($\leq \$73/tC$).

Some data are available on industrial sector mitigation potential and cost by country or region. However, an attempt to build-up a global estimate from these data was unsuccessful. Information was lacking for the former Soviet Union, Africa, Latin America, and parts of Asia.

Table 7.8 Mitigation Potential and Cost in 2030

		2030 Production, Mt (1)		GHG Intensity	Mitigation	Cost	Mitigation Potential, $MtCO_2$ eq.	
Product	Area (2)	A1	B2	tCO_2 eq/t Prod.	Potential, %	Range, $	A1	B2
GHG Emissions from Processes and Energy Use								
Steel (3,4)	Global	1163	1121	1.6 - 3.8	15 - 40	20 - 50	430 - 1500	420 - 1500
	OECD	370	326	1.6 - 2.0	15 - 40	20 - 50	90 - 300	80 - 260
	EIT	162	173	2.0 - 3.8	25 - 40	20 - 50	80 - 240	85 - 260
	Dev. Nat.	639	623	1.6 - 3.8	25 - 40	20 - 50	260 - 970	250 - 940
Primary	Global	38	37	1.8	~ 100	<100	72	67
Aluminium	OECD	12	11	1.8	~ 100	<100	22	20
(5,6)	EIT	9	6	1.8	~ 100	<100	16	11
	Dev. Nat.	19	20	1.8	~ 100	<100	34	36
Cement	Global	6517	5251	0.73 - 0.99	11 - 40	<50	720 - 2100	480 - 1700
(7,8,9)	OECD	600	555	0.73 - 0.99	11 - 40	<50	65 - 180	50 - 160
	EIT	362	181	0.81 - 0.89	11 - 40	<50	40 - 120	20 - 60
	Dev. Nat.	5555	4515	0.82 - 0.93	11 - 40	<50	610 - 1800	410 - 1500
Ethylene	Global	329	218	1.33	20	<20	85	58
(10)	OECD	139	148	1.33	20	<20	35	40
	EIT	19	11	1.33	20	<20	5	3
	Dev. Nat.	170	59	1.33	20	<20	45	15
Ammonia	Global	218	202	1.6 - 2.7	25	<20	110	100
(11, 12)	OECD	23	20	1.6 - 2.7	25	<20	11	10
	EIT	21	23	1.6 - 2.7	25	<20	10	12
	Dev. Nat.	175	159	1.6 - 2.7	25	<20	87	80
Petroleum	Global	4691	4508	0.32 - 0.64	10 - 20	half <20	150 - 300	140 - 280
Refining	OECD	2198	2095	0.32 - 0.64	10 - 20	half <50	70 - 140	67 - 130
(13)	EIT	384	381	0.32 - 0.64	10 - 20	“	12 - 24	12 - 24
	Dev. Nat.	2108	2031	0.32 - 0.64	10 - 20	“	68 - 140	65 - 130
Forest	Global	1321	920	0.22 - 1.40	5 - 40	<20	49 - 420	37 - 300
Products (14)	OECD	695	551	0.22 - 1.40	5 - 40	<20	28 - 220	22 - 180
	EIT	65	39	0.22 - 1.40	5 - 40	<20	3 - 21	2 – 13
	Dev. Nat.	561	330	0.22 - 1.40	5 - 40	<20	18 - 180	13 - 110

Carbon Capture and Storage								
		2030 Production, Mt (1)		CCS Potential, tCO_2/t	Mitigation Potential, %	Cost Range, $	Mitigation Potential, Mt CO_2 eq	
		A1	B2				A1	B2
Ammonia	Global	218	202	0.5	~100	<50	150	140
(15,16)	OECD	23	20	0.5	~100	<50	15	13
	EIT	21	23	0.5	~100	<50	14	16
	Dev. Nat.	175	159	0.5	~100	<50	120	110
Petroleum	Global	4691	4508	0.032 - 0.064	~100	<50	150 -300	140 -290
Refining	OECD	2198	2095	0.032 - 0.064	~100	<50	70 - 140	67 - 140
(13, 16, 17)	EIT	384	381	0.032 - 0.064	~100	<50	12 - 24	12 -24
	Dev. Nat	2108	2031				68 - 140	65 -130
Non-CO_2 Gases (18)								
	Global	1100				<20	560	
	OECD	510				<20	220	
	EIT	80				<20	40	
	Dev. Nat.	510				<20	300	
Other Industries, Electricity Conservation (19)						Cost Range, $	Mitigation Potential, Mt CO_2 eq.	
							A1	B2
	Global					25% <20	1100-1300	410 – 550
	OECD					25% <50	140 – 210	65 - 140
	EIT					50% <100	340 – 350	70 - 85
	Dev. Nat.					(4)	640 - 700	275 -325
Sum	Global						3600 – 6900	2600 – 5500
(20,21)	OECD						770 – 1500	650 – 1300
	EIT						570 – 860	280 – 550
	Dev. Nat.						2200 - 4500	1600 - 3700

Notes
(1) Price, *et al.*, 2006
(2) Global total may not equal sum of regions due to independent rounding.
(3) Kim and Worrell, 2002a
(4) Expert judgement
(5) Schwartz, *et al.*, 2001

(6) Assumes use of an inert electrode and non-carbon electricity.
(7) Humphreys and Mahasenan, 2002
(8) Hendriks, *et al.*, 1999
(9) Worrell, *et al*., 1995
(10) Ren, *et al*., 2005
(11) Basis for estimate: 10 GJ/tNH_3 difference between the average plant and the best available technology (Figure 7.4) and operation on natural gas (Section 7.4.3.2).
(12) Rafiqul, *et al*., 2005
(13) Worrell and Galitsky, 2005
(14) Farhini, *et al.*, 2004
(15) The process emissions from ammonia manufacturing (based on natural gas) are about 1.35 tCO_2/tNH_3 (De Beer, 1998). However, as noted in section 7.4.3.2, the fertilizer industry uses nearly half of the CO_2 it generates for the production of urea and nitrophosphates. The remaining CO_2 is suitable for storage. IPCC (2005a) indicates that it should be possible to store essentially all of this remaining CO_2 at a cost of <$20/t.
(16) IPCC, 2005a
(17) U.S. refineries use about 8% of their energy input to produce hydrogen (Worrell and Galitsky, 2005). Refinery hydrogen production is expected to increase as crude slates become heavier and the demand for clean products increases. We assume that in 2030, 10% of refinery energy use world-wide will be used for hydrogen production, and that the by-product CO_2 will be suitable for carbon storage.
(18) Extrapolated from EPA, 2006b. This publication does not use the SRES scenarios as baselines.
(19) See Section 7.5.1 for details of the estimation procedure.
(20) Due to gaps in quantitative information (see the text) the column sums in this table do not represent total industry emissions or mitigation potential. Global total may not equal sum of regions due to independent rounding.

(21) The mitigation potential of the main industries include electricity savings. To prevent double counting with the energy supply sector, these are shown separately in Chapter 11.

Two very recent studies provide global estimates of GHG mitigation potential in the industrial sector in 2030. IEA (2006) used its Energy Technology Perspectives Model (ETP), which belongs to the MARKAL family of bottom-up modelling tools, to estimate mitigation potential for CO_2 from energy use in the industrial sector to be 5.4 Gt (1.5 GtC) in 2050. IEA's base case was an extrapolation of its World Energy Outlook 2005 Reference Scenario, which projected energy use to 2030. IEA provides ranges for mitigation potential in 2030 for nine groups of technologies totalling about 2.5-3.0 $GtCO_2$ (0.68-0.82 GtC). Mitigation cost is estimated at $\leq$ \$25/tCO_2 ($\leq$\$92/tC) (2004\$). ABARE (Matysek, et al., 2006) used its general equilibrium model of the world economy (GTEM) to estimate that widespread adoption of advanced technologies, including those for control of non-CO_2 gases. In their most optimistic scenario, could reduce industrial sector GHG emissions by an average of about 3 $GtCO_2$ eq/yr (0.8 GtC eq/yr) over the 2030-2050 timeframe relative to the GTEM reference case, which assumes continuation of current or already announced future government policy and no significant shifts in climate policy. ABARE did not estimate the cost of these reductions. The IEA and ABARE global estimates of mitigation potential both are within the range developed using industry specific information, and offer support for that assessment.

The TAR (IPCC, 2001a) developed a bottom up estimate of mitigation potential in 2020 for the industrial sector of 1.4-1.6 GtC (5.1-5.9 $GtCO_2$) based on the evaluation of specific technologies. Extrapolating the TAR estimate to 2030 would give values at or above the upper end of the range developed in this assessment. The newer studies used in this assessment take industry-specific conditions into account, which reduces the risk of double counting.

7.5.1 Electricity Savings

Electricity savings are of particular interest, since they feedback into the mitigation potential calculation for the energy sector and because of the potential for double counting of the emissions reductions. Section 7.3.2 indicates that in the EU and U.S. electric motor driven systems account for ~65% of industrial energy use, and that efficient systems could reduce this use by 30%. This mitigation potential was included in the estimates of mitigation potential for energy intensive industries presented in Table 7.5.1. However, it is also necessary to consider the potential for electricity savings from non-energy-intensive industries, which are large consumers of electricity.

Table 7.5.1 shows a mitigation potential of 1.1 – 1.3 $GtCO_2$-eq (0.30 – 0.35 MtC-eq) in the A1B scenario and 0.41 – 0.55 $GtCO_2$-eq (0.11 – 0.15 MtC-eq) in the B2 scenario. The estimation procedure used to develop these numbers was as follows:

- EIA (2002) data on electricity as a fraction of total energy use by industry and on the fraction of electricity use consumed by motor driven systems for the U.S. were used for these parameters. Similar data were not found for other countries/regions, but the U.S. was taken as representative of global patterns.
- Based on De Keulenaer, *et al.* (2004) and Xenergy (1998), a 30% mitigation potential was assumed.
- Emission factors to convert electricity savings into CO2 reductions were derived from data in IEA (2004).
- Emissions reduction potential from non-energy-intensive industries were calculated by subtracting the savings from energy-intensive industries from total industrial emissions reduction potential.

7.6 Barriers to Industrial GHG Mitigation

In many areas of the world, GHG mitigation is neither demanded nor rewarded by the market or government. In these areas, companies can afford to invest in GHG mitigation only to the extent that their investments are compensated by lowered energy or raw material costs, or some similar benefit. As a result, most of the mitigation actions taken to date by industry have been "no-regrets" options, i.e., activities that show an economic or other return that compensates for their cost. For example, Nicholson (2004) reported that the projects BP undertook to lower its CO_2 emissions by 10% increased shareholder value by $650 M. There are, no doubt, many instances when companies have implemented energy efficiency or other projects, in response to market forces or government policy, without being aware of their GHG mitigation benefits.

Even though a broad range of cost-effective GHG mitigation technologies exist, a variety of economic barriers prevent their full realisation in either developed or developing countries. Policies and measures must overcome the effective costs of capital (Toman, 2003). Industry needs a stable transparent policy regime addressing both economic and environmental concerns to reduce the costs of capital.

The slow rate of capital stock turnover in many of the industries covered in this chapter is a barrier to mitigation (Ruth 1995, Worrell and Biermans, 2005). Policies that encourage capital stock turnover, such as Japan's programme to subsidize the installation of new high performance furnaces (WEC, 2001), will increase GHG mitigation. Companies must also take into consideration the risks involved with adopting a new technology, the pay back period of a technology, the appropriate discount rate and transaction costs. Newer, relatively expensive technologies have longer payback periods and represent a greater risk. Reliability is a key concern of industry, making new technologies less attractive (Rosenberg, 1999). Discount rates vary substantially across industries and little information exists on transaction costs of mitigation options (US EPA, 2003).

Resource constraints are also a significant barrier to mitigation. Unless legally mandated, GHG mitigation will have to compete for financial and technical resources against projects to achieve other company goals. Financial constraints can hinder diffusion of technologies within firms (Canepa and Stoneman, 2004). Projects to increase capacity or bring new products to the market typically have priority, especially in developing countries, where markets are growing rapidly, and where a large portion of industrial capacity is in SMEs. Energy efficiency and other GHG mitigation technologies can provide attractive rates of return, but they tend to increase initial capital costs, which can be a barrier, particularly in developing countries where capital is limited. If the technology involved is new to the market in question, even if it is well-demonstrated elsewhere, the problem of raising capital may be further exacerbated (Shashank, 2004).

Another barrier is the ability of industrial organizations to access and absorb the available information on these technologies. Access to information tends to be more of a problem in developing nations, but all companies, even the largest, have limited technical resources to interpret and translate the available information. The success of the voluntary information sharing programs discussed in section 7.9.2 is evidence of the pervasiveness of this barrier.

Industry must respond to a variety of government policy objectives, some of which can lead to increased GHG emissions. For example, Nordqvist (2005) found that differing policy objectives at national and local levels represents a barrier to modernization and lower CO_2 emissions in the Chinese cement industry. In other countries, local environmental regulations which result in switching away from coal use instead of using end-of-pipe control at plants may sacrifice energy efficiency, and may increase GHG emissions (Toman, 2003).

7.7 Sustainable Development (SD) Implications of Industrial GHG Mitigation

Although there is no universally accepted, practical definition of SD, the concept has evolved as the integration of economic, social, and environmental aims (IPCC, 2000a; Munasinghe, 2002). Companies world-wide adopted Triple Bottom Line (financial, environmental, and social responsibility) reporting in the late 90's. The Global Reporting Initiative (GRI, n.d.) a multi-stakeholder process has enabled business organizations to elucidate their contributions to sustainable development. Many companies are trying to demonstrate that that their operation minimize water use and carbon emissions and produce zero solid waste (ITC, 2006). SD consequences can be observed or monitored through various indicators grouped under the three major categories. (See Section 12.1.1.2 for more detail).

Table 7.9 shows that SD consequences of the mitigation options mentioned in sections 7.3 and 7.4 are not automatic. GHG mitigation, *per se*, has little impact on four of the SD indicators: poverty reduction, empowerment/gender, water pollution, and solid waste. The available literature indicates that supplementing mitigation options with appropriate national macroeconomic policies, and with social and local waste reduction strategies at the company level, could achieve sustainability goals.

Table 7.9: *Sustainable Development Implication of Mitigation Strategies*

Activity Category	Relation with different dimensions of Sustainable Development									
	Social			Economic				Environmental		
	Employment	Poverty Reduction	Empower-ment/ Gender	Company Profitability No-Regrets	Company Profitability Non- No Regrets	Balance of Payment	National Income	Local/ Regional Air Pollution	Water Pollution	Solid Waste
Energy Efficiency	Positive 1	Uncertain	Uncertain 4	Positive	Negative	Positive 6	Positive	Positive	Uncertain 11	Uncertain 11
Fuel Switching	Uncertain 2	Uncertain 3	Uncertain 4	Positive	Negative	Negative 7	Uncertain	Positive	Uncertain 11	Uncertain 11
Power Recovery	Uncertain 2	Uncertain 3	Uncertain 4	Positive	Negative	Uncertain	Positive	Positive	Uncertain 11	Uncertain 11
Renewables	Uncertain 2	Uncertain 3	Uncertain 4	Positive	Negative	Uncertain 8	Uncertain	Positive	Uncertain 11	Uncertain 11
Feedstock Change	Uncertain 2	Uncertain 3	Uncertain 4	Positive	Negative	Uncertain 8	Uncertain	Positive	Uncertain 11	Uncertain 11
Product Change	Uncertain	Uncertain 3	Uncertain 4	Positive	Negative	Uncertain 8	Uncertain	Positive	Uncertain 11	Uncertain 11
Material Efficiency	Uncertain 2	Uncertain 3	Uncertain 4	Positive	Negative	Uncertain 8	Positive	Positive	Uncertain 11	Uncertain 11
Non-CO_2 GHG	Uncertain 2	Uncertain 3	Uncertain 4	Positive	Negative	Uncertain 8	Positive 9	Positive	Uncertain 11	Uncertain 11
CO_2 Sequestration	Uncertain 2	Uncertain 3	Uncertain 4	Uncertain 5	Negative	Uncertain 8	Negative 10	Positive	Uncertain 11	Uncertain 11

Footnotes for explaining uncertainties in matrix:

1. If economy wide impact is considered. Unknown if partial impact
2. Depends on inter input substitution possibilities
3. Depends on targeted redistribution
4. Depends if there are targeted policies
5. Cannot be no-regrets
6. If efficiency of important fuel
7. If biased towards imported fuel
8. Depends how much is imported
9. If usable material is recovered e.g. landfill CH4
10. Net cost in all cases
11. Depends on type of fuel and if additional waste recycling/reduction measures are adopted

GHG emissions mitigation policies induce increased innovation that can reduce the energy and capital intensity of industry. But this could come at the expense of other, even more valuable, productivity-enhancing investments or learning-by-doing efforts (Goulder and Schneider, 1999). If policies are successful in stimulating economic activity, they also are likely to stimulate increased energy use. GHG emissions would increase unless policies decreased the carbon-intensity of economic activity by more than the increase in activity. In OECD countries (Schipper, et al., 2000; Liskas, et al., 2000), as well as in developing countries like India (Dasgupta and Roy, 2001), China (Zhang, 2003), Korea (Choi and Ang, 2001; Chang, 2003), and Bangladesh (Bain, 2005), energy and carbon intensity has decreased, for industry sector in general and for energy-intensive industries in particular, due to energy efficiency improvement and fuel switching. For OECD countries, structural change has also played an important role in emissions reduction. However, overall economic activity has increased more rapidly, resulting in higher total carbon emissions. Studies (Sathaye, et al., 2005, Phadke, et al., 2005) have shown that in developing countries like India adoption of efficient electricity technology can lead to higher employment and income generation.

7.8 Interaction of Mitigation Technologies with Vulnerability and Adaptation

The TAR chapter on adaptation contained no specific references to industry, and the chapter on human settlements, energy, and industry contained only one paragraph on the vulnerability of industry to climate change, which concluded: “Very little is known concerning the effects of warming on industry, and most information remains highly speculative.” (IPCC, 2001b). However, that paragraph does mention that industry could be affected by government climate policies or by changes in consumer behaviour resulting from climate change.

Industry’s vulnerability to extreme weather events arises from site characteristics e.g., coastal areas or flood-prone river basins. Because of their financial and technical resources, large industrial organizations typically have a significant adaptive capacity for addressing vulnerability to weather extremes. SMEs typically have fewer financial and technical resources and therefore less adaptive capacity. The food processing industry, which relies on agricultural resources that are vulnerable to extreme weather conditions like floods or droughts, is engaging in dialogue with its supply chain to reduce GHGs emissions. Companies are also attempting to reduce vulnerability through product diversification (Kolk and Pinkse, 2005).

Linkages between adaptation and mitigation in the industrial sector are limited. Many mitigation options (e.g. energy efficiency, heat and power recovery, recycling) are not vulnerable to climate change and therefore create no adaptation link. Others, such as fuels switching can be vulnerable to climate change under certain circumstances. Use of solar or biomass energy will be vulnerable to both weather extremes and climate change. And as the 2005 Atlantic hurricane season demonstrated, the oil and gas infrastructure is vulnerable to weather extremes. Adaptation, the construction of more weather resistant facilities and provision of back-up energy supplies, could reduce this vulnerability.

As noted in the TAR (IPCC, 2001b), industrial enterprises of all sizes are also vulnerable to changes in government policy and consumer preferences. While the specifics of government climate policies will vary greatly, all will have one of two fundamental objectives: constraining GHG emissions or adapting to existing or projected climate change. And while consumers may become more sensitive to the GHG impacts of the products and services they use, it is almost certain that they will continue to seek the traditional qualities of low cost, reliability, etc. The challenge to industry will be to continue to provide the goods and services on which society depends in a GHG-constrained world. Industry can respond to the potential for increased government regulation or changes in consumer preferences in two ways: by mitigating its own GHG emissions or by developing new, lower GHG emission products and services. To the extent that industry does this before required by either regulation or the market, it is demonstrating the type of anticipatory, or planned, adaptation advocated in the TAR (IPCC, 2001b).

Many SMEs have played a part in advancing the SD agenda. For example, there have been advancements where such enterprises are part of coordinated supply chain or industrial park initiatives, or where they have participated in research and innovation (Dutta, *et al*., 2004) in sustainable goods and services.

7.9 Effectiveness of and Experience With Policies

7.9.1 Kyoto Mechanisms (CDM and JI)

The Clean Development Mechanism (CDM) was created under the Kyoto Protocol to allow Annex I countries to obtain GHG emission reduction credits for projects that reduced GHG emission in non-Annex I countries, provided that those projects contributed to the sustainable development of the host country (UNFCCC, 1997). Private sector involvement was specifically permitted by the Protocol, which allowed credits to be earned beginning in 2000. The first CDM project was registered (approved) in November, 2004. As of May, 2006, 180 projects had been registered, with another 600 in some phase of the approval process. Total emission reduction potential of both approved and proposed projects is nearly 1 $GtCO_2$ (270 MtC). The majority of these projects are in energy sector; as of March, 2006, only 5% of approved CDM projects were in the industrial sector UNFCCC, CDM, n.d.).

Even industrial groups such as IETA (International Emissions Trading Association), which are highly supportive of the CDM have expressed concern its complexity, which discourages its integration into normal business processes, and the elements of regulatory subjectivity involved in assessing additionality (IETA, 2005a). These concerns have been recognized, and at COP-11 a set of decisions were taken to provide greater support to the CDM Executive Board and to clarify aspects of the CDM approval mechanism.

The concept of Joint Implementation (JI), GHG-emissions reduction projects carried out jointly by Annex I countries or business from Annex I countries, is mentioned in the UNFCCC, but amplified in the Kyoto Protocol. However, since the Kyoto Protocol does not allow JI credits to be transferred before 2008, progress on JI implementation has been slow. Both CDM and JI build on experience gained in the pilot-phase Activities Implemented Jointly (AIJ) program created by the UNFCCC in 1995 (UNFCCC, 1995). A fuller discussion of CDM, JI, and AIJ appears in Section 13.2.2.3.4.

7.9.1.1 Regional Differences

Project-based mechanisms are still in their early stages of implementation, but significant differences have emerged in the ability of developing countries to take advantage of them. This is particularly true of Africa, which, as of May, 2006, lagged behind other regions in their implementation. Only 2 of 50 AIJ projects were in Africa. None of the 20 projects recently approved under The Netherlands carbon purchase programme, CERUPT, were in Africa (CDM for Sustainable Africa, 2004), and only 3% of the projects in the CDM pipeline were in Africa (UNFCCC, CDM, n.d.).

Yamba and Matsika (2004) identified financial, policy, technical, and legal barriers inhibiting participation in the CDM in sub-Saharan Africa. Financial barriers pose the greatest challenges: low market value of carbon credits, high CDM transaction costs, and lack of financial resources discourage industry participation. Policy barriers include limited awareness in government and the private sector of the benefits of CDM and the project approval process, non-ratification of the Kyoto Protocol, and failure to establish the Designated National Authorities required by CDM. Technical barriers include limited awareness on the availability of energy-saving and other appropriate technologies for potential CDM projects. Legal barriers include limited awareness in government and the private sector of the Kyoto Protocol, and the legal requirements for development of CDM projects. Limited human resources for the development of CDM projects, and CDM's requirements on additionality are additional constraints. Other countries, e.g. Brazil, china and India (Silayan, 2005), have more capacity to develop CDM projects. The Government of India (GOI, 2004) has identified energy efficiency in the steel industry as one of the priorities for Indian CDM projects.

7.9.2 Voluntary GHG Programs and Agreements

7.9.2.1 Government-initiated GHG Programs and Voluntary Agreements

Government-initiated GHG programs and agreements that focus on energy-efficiency improvement or reduction of energy-related GHG emissions are found in many countries. There are also examples of programs directed toward reduction of non-CO_2 GHG emissions. Program elements can include information-sharing, energy and GHG emissions management, financial assistance, awards and recognition, standards, and target-setting (APERC, 2003; CLASP, 2005; Galitsky, et al., 2004; WEC, 2004).

Voluntary Agreements (VAs) for energy efficiency improvement and reduction of energy-related GHG emissions by industry have been implemented in industrialized countries since the 1990s. Negotiated agreements that include explicit targets are the most effective type of VA (UNFCCC, 2002). As a part of negotiated VAs, companies or industry organizations set targets for reducing energy use or GHG emissions in exchange for government support including the program elements described above. Negotiated agreements typically cover a period of five to ten years, so that strategic energy-efficiency investments can be planned and implemented. There are also VAs covering process emissions in Australia, Bahrain, Brazil, Canada, France, Germany, the Netherlands, New Zealand, Norway, Japan, the UK, and the U.S. (Bartos, 2001; EFCTC, 2000; US EPA, 1999). A number of national-level agreement programs have recently modified and strengthened, while additional countries, including some newly industrialized and developing countries, are adopting such agreements in an effort to increase the energy efficiency of their industrial sectors (Price, 2005).

Independent assessments find that experience with VAs has been mixed, with some programs, such as the French Voluntary Agreements on CO_2 Reductions and Finland's Action Programme for Industrial Energy Conservation, appearing to have been poorly designed, failing to meet targets, or only achieving business-as-usual savings (Bossoken, 1999; Chidiak, 2000; Chidiak, 2002; Hansen and Larsen, 1999; OECD, 2002; Starzer, 2000). However, more successful programs, such as the Dutch Long-Term Agreements, the Danish Agreements on Industrial Energy Efficiency, and the UK Climate Change Agreements (see Box 13.3), have provided significant energy savings (Bjørner and Jensen, 2002; Future Energy Solutions, 2004; Future Energy Solutions, 2005) and are cost-effective (Phylipsen and Blok, 2002). The Long-Term Agreements, for example, stimulated between 27% and 44% (17 to 28 PJ) of the observed energy savings, which was a 50% increase over historical autonomous energy efficiency rates in The Netherlands prior to the agreements (Kerssemeeckers, 2002; Rietbergen, et al., 2002). The UK Climate Change Agreements saved 3.5-9.8 $MtCO_2$ over the baseline during the first target period (2000-2002) and 5.1-8.9 $MtCO_2$ during the second target period (2002-2004) depending upon whether the adjusted steel sector target is accounted for (Future Energy Solutions, 2005). In addition to the energy and carbon savings, these agreements have important longer-term impacts (Delmas and Terlaak, 2000; Dowd, et al., 2001) including:

- changing attitudes and awareness of energy efficiency,
- reducing barriers to innovation and technology adoption,
- creating market transformations to establish greater potential for sustainable energy-efficiency investments,
- promoting positive dynamic interactions between different actors involved in technology research and development, deployment, and market development, and
- facilitating cooperative arrangements that provide learning mechanisms within an industry.

The most effective agreements are those that set realistic targets, include sufficient government support, often as part of a larger environmental policy package, and include a real threat of increased government regulation or energy/GHG taxes if targets are not achieved (Bjørner and Jensen, 2002; Price, 2005).

7.9.2.2 Company or Industry-initiated Voluntary Actions

Many companies participate in GHG emissions reporting programs as well as taking voluntary actions to reduce energy use or GHG emissions through individual corporate programs, non-governmental organization (NGO) programs, and industry association initiatives. Some of these companies report their GHG emission in annual environmental or sustainable development reports, or in their Corporate Annual Report. Beginning in the late 1990s, a number of individual companies initiated in-house energy or GHG emissions management programs and made GHG emissions reduction commitments (Margolick and Russell, 2001; PCA, 2002).

Questions have been raised as to whether such initiatives, which operate outside regulatory or legal frameworks, often without standardized monitoring and reporting procedures, just delay the implementation of government-initiated programs without delivering real emissions reductions (OECD, 2002). Early programs appear to have produced little benefit. For example, an evaluation of the Germany industry's self-defined global warming declaration found that achievements in the first reporting period appeared to be equivalent to business-as-usual trends (Jochem and Eichhammer, 1999; Ramesohl and Kristof, 2001). However, more recent efforts appear to have yielded positive results. Examples of targets and the actual reductions achieved include:

- DuPont's reduction of GHG emissions by over 72% while holding energy use constant, surpassing its pledge to reduce GHG emissions by 65% by 2010 and hold energy use constant compared to a 1990 baseline (DuPont, 2002; McFarland, 2005),
- BP's target to reduce GHG emissions by 10% in 2010 compared to a 1990 baseline which was reached in 2001 (BP, 2003; BP, 2005),
- United Technologies Corporation's goal to reduce energy and water consumption by 25% as a percent of sales by the year 2007 using a 1997 baseline that was exceeded by achieving a 27% energy reduction and 34% water use reduction through 2002 (Rainey and Patilis, 2000; UTC, 2003), and
- Hewlett-Packard's commitment to reduce PFC emissions by 10% from 1990 levels by 2005, which was not met but is expected to be achieved in 2006 (Hewlett-Packard, 2002 Hewlett-Packard, 2006).

Many of these companies have now set more stringent targets.

Often these corporate commitments are formalized through GHG reporting programs or registries such as the World Economic Forum Greenhouse Gas Register where 13 multi-national companies disclose the amount of GHGs their worldwide operations produce (WEF, 2005) and through NGO programs such as the Pew Center on Global Climate Change's Business Environmental Leadership Council (Pew Center on Global Climate Change, 2005), the World Wildlife Fund's Climate Savers Program (WWF, 2005), as well as programs of the Chicago Climate Exchange (CCX, 2005).

Industrial trade associations provide another platform for organizing and implementing GHG mitigation programs.

- The International Aluminium Institute initiated the Aluminium for Future Generations sustainability program in 2003, which established 9 sustainable development voluntary objectives (increased to 12 in 2006), 22 performance indicators, and a programme to provides technical services to member companies (IAI, 2004). Performance to date against GHG mitigation objectives was discussed in section 7.4.2.1.
- The World Semiconductor Council (WSC), comprised of the national semiconductor industry associations of the United States, Japan, Europe, Republic of Korea, and Chinese Taipei, established a target of reducing PFC emissions by at least 10% below the 1995 baseline level by 2010 (Bartos, 2001).
- The World Business Council for Sustainable Development (WBCSD) started the Cement Sustainability Initiative in 1999 with ten large cement companies and it has now grown to 16 (WBCSD, 2005). The Initiative conducts research related to actions that can be undertaken by cement companies to reduce GHG emissions (Battelle Institute/WBCSD, 2002) and outlines specific member company actions (WBCSD, 2002). As of 2004, 94% of the 619 kilns of CSI member companies had developed CO_2 inventories and three had established emissions reduction targets (WBCSD, 2005). By 2003, the Japanese chemical industry had reduced its CO_2 emissions intensity by 9% compared with 1990 levels (Nippon Keidanren, 2004), but due to increased production, overall CO_2 emissions were up by 10.5%.
- The European Chemical Industry Council established a Voluntary Energy Efficiency Program (VEEP) with a commitment to improve energy efficiency by 20% between 1990 and 2005, provided that no additional energy taxes are introduced (CEFIC, 2002).

In 2003, the members of the International Iron and Steel Institute, representing 38% of global steel production, committed to voluntary reductions in energy and GHG emission intensities. In most countries this program is too new to provide meaningful results (IISI, 2006). However, as part of a larger voluntary program in Japan, Japanese steelmakers committed to a voluntary action program to mitigate climate change with the goal of a 10% reduction in energy consumption in 2010 against 1990. In FY 2003, this program resulted in a 6.4% reduction in CO_2 intensity emissions against 1990, through improvement of blast furnaces, upgrade of oxygen production plants, installation of regenerative burners, and other steps (Nippon Keidanren, 2004).

7.9.3 GHG Financial Instruments

Financial instruments are used to stimulate investment in energy-saving measures by reducing investment cost. Important types of financial instruments in the industrial sector include: grants and subsidies, favourable loans, and fiscal incentives. Fiscal incentives include measures to reduce taxes on energy-efficient equipment, accelerated depreciation, tax credits and tax deductions. Many developed and developing countries have financial schemes available to promote energy saving in industry (Price, et al., 2005).

According to a WEC survey 28 countries provide some sort of grant or subsidy for industrial energy efficiency projects; most subsidies were found in European countries (WEC, 2004). Subsides can be fixed amounts, a percentage of the investment (with a ceiling), or proportional to the amount of energy saved. In Japan the New Energy and Industrial Technology Development Organisation (NEDO) pays up to one-third of the cost of each high performance furnace. NEDO estimates that the project will result in energy savings equalling 5% of Japan's final energy consumption by 2010 (WEC, 2001). Favourable loans are loans offered at lower than the market rate to investors in energy efficient techniques. The Korean Energy Management Corporation (KEMCO) provides long-term and low interest loans to certified companies. (IEA, 2005). According to WEC (2004), soft loans are less popular than subsidies in the countries surveyed.

Fiscal measures are also frequently used to stimulate energy savings in industry. Some examples are:

- In The Netherlands, the Energy Investment Deduction (Energie Investeringsaftrek, EIA) stimulates investments in low-energy capital equipment and renewable energy by means of tax deductions (deduction of the fiscal profit of 55% of the investment) (IEA, 2005).
- In France, investments in energy efficiency are stimulated through lease credits. In addition to financing equipment, these credits can also finance associated costs such as construction, land and transport (IEA, 2005).
- The UK's Enhanced Capital Allowance Scheme allows businesses to write off the entire cost of energy-savings technologies specified in the "Energy Technology List" during the year they make the investment (HM Revenue & Customs, n.d.).
- Under Singapore's Income Tax Act, companies that invest in qualifying energy-efficient equipment can write-off the capital expenditure in one year instead of three. (NEEC, 2005).
- In the Republic of Korea, a 5% income tax credit is available for energy-efficiency investments (UNESCAP, 2000).
- Romania has a program where imported energy-efficient technologies are exempt from customs taxes and the share of company income directed for energy efficiency investments is exempt from income tax (CEEBICNet Market Research, 2004).
- In Mexico, the Ministry of Energy has linked its energy efficiency programs with Energy Service Companies (ESCOs). These are engineering and financing specialised enterprises that provide integrated energy services with a wide range and flexibility of technologies to the industrial and service sectors.

Developing countries tend to have weak financial institutions. Developmental financial and technological institutions often play a crucial role in mitigation policies in those countries. Their role often goes beyond the provision of financial means for project investment, and may directly influence technology choice and the direction of innovation (George and Prabhu, 2003). The retreat of national development banks in some developing countries (derived from both financial liberalisation and financial crisis of federal governments) may counteract widespread adoption of mitigation technologies because of insufficient financial mechanisms for risk absorption.

Evaluations show that financial incentives for industry may lead to energy savings and corresponding greenhouse gas emission reductions, and can create a larger market for energy efficient technologies (De Beer, et al., 2000b; WEC, 2001). However, a drawback to financial incentives is that they are often also are used by investors who would have made the investment without the incentive. Possible solutions to improve cost effectiveness are to restrict schemes to specific target groups and/or techniques (selected list of equipment, only innovative technologies), or use a direct criterion of cost-effectiveness.

7.9.4 Regional and National GHG Emissions Trading Programs

Several established or evolving national, regional or sectoral CO_2 emissions trading systems exist e.g. in the EU, the UK, Norway, Denmark, New South Wales (Australia), Canada, and several U.S. States. IETA (2005b) provides an overview of systems. This section focuses on issues relevant to the industrial sector. A more in-depth discussion of emission trading can be found in section 13.2.1.2.

Results of an assessment of the first two years of the UK scheme (NERA, 2004) show that reduction of non-CO_2 GHG emissions from industrial sources provided the least cost options. It also found that the heterogeneity of industrial emitters may require a tiered approach for the participation of small, medium-sized and large emitters e.g. in respect to monitoring and verification, and described the impacts of individual industrial emitters gaining dominating market power on allowance prices.

In January 2005, the European Union Greenhouse Gas Emission Trading Scheme (EU ETS) was launched as the world's largest multi-country, multi-sector GHG emission trading scheme (EC, 2005). A number of assessments have analysed current and projected likely future impacts of the EU-ETS on the industrial sector in the EU (IEA, 2005; Egenhofer, *et al*., 2005). Re-appearing themes with specific relevance to industry include: allocation approaches based on benchmarking, grandfathering, and auctioning; the impact on electricity prices; competitiveness of energy-intensive industries; specific provisions for new entrants, closures, capacity expansions, and organic growth; and compliance costs for small emitters. The further refinement of these trading systems could be informed by evidence which suggests that in some important aspects participants from industrial sectors face a significantly different situation than those from the electricity sector (Carbon Trust, 2006):

- The range of products from industry sectors is generally more diverse (e.g. in the paper, glass or ceramics industry) making it difficult to define sector specific best practice values to be used for the allocation of allowances (see discussion in DTI (2005)).
- While grid connections limit electricity to regional or national markets, many industrial products are globally traded commodities, constrained only by transportation costs. This increasingly applies as value per mass or volume goes up i.e. from bulk ceramics products and cement, to petrochemicals, to base metals, making the impacts of trading schemes on international competitiveness a matter of varying concern for the different sub-sectors.
- Only a few industrial enterprises are prepared to actively participate in the early phase of trading schemes, leading to reduced liquidity and higher allowance prices, suggesting that specific instruments are needed to improve involvement.
- Responses to carbon emission price in industry tend to be slower because of the more limited technology portfolio and absence of short term fuel switching possibilities, making predictable allocation mechanisms and stable price signals a more important issue for industry.

7.9.5 Energy and Technology Policies

Some of the energy technologies needed by energy-intensive industries require enormous amount of investment and long period of time to construct capital equipment (Yamaji, 1999), e.g. town gas pipelines, power plants, and grids. The huge amount of capital equipment and long replacement period involved make the investment risk prohibitively high for private companies, even if some innovative energy carriers or technologies are available. Government is expected to lower financial risk and promote the investment through technology policy, which includes diverse options: budget allocation for R&D on innovative technologies, subsidy or legislation to stimulate specific environmental technologies, or regulation to suppress unsustainable technologies.

7.9.6 Sustainable Development Policies

Appropriate sustainable development policies; focusing on energy efficiency, dematerialization, and use of renewables; can support GHG mitigation objectives. For example, the policy options selected by the Commission on Sustainable Development 13th session to provide a supportive environment for new business formation and the development of small enterprises, included:

- reduce information barriers for energy efficiency technology for industries,
- build capacity for industry associations, and
- stimulate technological innovation and change to reduce dependency on imported fuels, to improve local air pollution, and to generate local employment (CSD, 2005).

Individual countries are also trying to achieve these objectives. Most policies are stated in general terms, but their implementation would have to include the industrial sector.

The EU's strategy for sustainable development highlights addressing climate change, through the reduction of energy use in all sectors, and the control of non-CO_2 GHGs (EC, 2002).
The UK's sustainable development policy incorporates the UK's emissions trading and climate levy policies for the control of CO_2 emissions from industry (UK-DEFRA, 2005).
As part of its sustainable development policy, Sweden is emphasizing energy efficiency and a long-term goal of obtaining all energy from renewable sources (OECD, 2002).
China faces a significant challenge in achieving its sustainable development goals because from 2002-2004 its primary energy use grew faster than its GDP, with over two-thirds of that increase coming from coal. Proposals to address that imbalance include increased investment in energy efficiency and restructured incentives to favour production and consumption of cleaner energy (Sinton, *et al*, 2005).
India has launched a series of reforms aimed at achieving industrial sector sustainable development. The 2001 Energy Conservation Act mandated a Bureau of Energy Efficiency charged with ensuring efficient use of energy and use of renewables (GOI, 2004).

All of these countries are trying to improve resources use efficiency, waste management, water and air pollution reduction, and enhance use of renewables, while providing health benefits and improved services to communities. Many developed (Sutton, 1998) and developing countries (Jindal Power and Steel, Ltd, 2006, ITC, 2006) encourage companies to help achieve these goals thought dematerialization, habitat restoration, recycling and commitment to social responsibility.

7.9.7 Air Quality Policies

Section 4.7.2.2 contains a more general discussion of the relationships between air quality policies and GHG mitigation. In general air quality and climate change are treated as separate issues in national and international policies, even though most practices and technologies that will reduce GHG emissions will also cause a net reduction of emissions of air pollutants. However, air pollutant reduction measures do not always reduce GHG emissions as many require the use of additional energy (STAPPA/ALAPCO, 1999). Examples of policies dealing with air pollution and GHG emissions in an integrated fashion include:

the EU IPPC Directive (96/61/EC), which lays down a framework requiring Member States to issue operating permits for certain industrial installations, and

the Netherlands plan for a NO_x emission trading system, which will be implemented through the same legal and administrational infrastructure as the European CO_2 emission trading system (Dekkers, 2003).

7.9.8 Waste Management Policies

Waste management policies can reduce industrial sector GHG emissions by reducing energy use through the re-use of products (e.g. of refillable bottles) and the use of recycled materials in industrial production processes. Recycled materials significantly reduce the specific energy consumption of the production of paper, glass, steel, aluminium, and magnesium. The amount, quality, and price of recycled materials is largely determined by waste management policies. These policies can also influence the design of products - including the choice of materials, with its implications on production levels and emissions. Prominent examples can be found in the packaging sector, e.g., the use of cardboard rather than plastic for outer sales packages, or PET instead of conventional materials in the beverage industry. Vertical and horizontal integration of business provide synergies in the use of raw materials and reuse of wastes. The paper and paper boards wastes generated in cigarettes packaging and printing are used as raw materials in paper and paper board units (ITC 2006).

Another important influence of waste policies on industrial GHG emissions are their influence on the availability of secondary (“waste”) fuels and raw materials for industrial use. For example, the “EU Landfill Directive” (EU-OJ, 1999), which limits the maximum organic content of wastes acceptable for landfills, resulted in the restructuring of the European waste sector currently taking place. It makes available substantial amounts of waste containing significant biomass fractions. Typically there is competition between the different uses for these wastes: dedicated incineration in the waste sector, co-combustion in power plants, or combustion in industrial processes, e.g. cement kilns. In order to provide additional inexpensive disposal routes, several countries have set incentives to promote the use of various wastes in industrial processes in direct competition with dedicated incineration. Emissions trading systems or project based mechanisms like CDM/JI can provide additional economic incentives to expand the use of secondary fuels or biomass as substitutes for fossil fuels. The impact of switching from a fossil fuel to a secondary fuel on the energy efficiency of the process itself is commonly negative, but is often compensated by energy savings in other parts of the economy.

Mineral wastes, such as fly-ash or blast-furnace slag, can have several competing use alternatives in the waste, construction, and industrial sectors. The production of cement, brick and stone-wool offers energy saving use options for these material in industry. For secondary fuels and raw materials, life-cycle assessment can help to quantify the net effects of these policies on emission across the affected parts of the economy (Smith, et al., 2001). The interactions between climate policies and waste policies can be complex, sometimes leading to unexpected results because of major changes of industry practices and material flows induced by minor price differences.

7.10 Co-benefits of Industrial GHG Mitigation

The TAR explained that “co-benefits are the benefits from policy options implemented for various reasons at the same time, acknowledging that most policies resulting in GHG mitigation also have other, often at least equally important, rationales.” (IPCC, 2001a) Significant co-benefits arise from reduction of emissions, especially local air pollutants. These are discussed in Section 11.8.2. Here we focus on co-benefits of industrial GHG mitigation options that arise due to reduced emissions and waste (which in turn reduced environmental compliance and waste disposal costs), increased production and product quality, improved maintenance and operating costs, an improved working environment, and other benefits such as decreased liability, improved public image and worker morale, and delaying or reducing capital expenditures (see Table 7.10) (Pye and McKane, 2000; Worrell, et al., 2003).

Table 7.10: *Greenhouse Gas Mitigation or Energy-Efficiency Programs of Selected Countries*

Category of Ancillary Benefit	Examples
Health	Reduced medical/hospital visits, reduced lost work days, reduced acute and chronic respiratory symptoms, reduced asthma attacks, increased life expectancy
Emissions	Reduction of dust, CO, CO_2, NO_x, SO_x; reduced environmental compliance costs
Waste	Reduced use of primary materials; reduction of waste water, hazardous waste, waste materials; reduced waste disposal costs; use of waste fuels, heat, and gas
Production	Increased product output or yield; improved product quality or purity; improved equipment performance and capacity utilization; reduced process cycle times; increased production reliability; increased customer satisfaction
Operation and maintenance	Reduced wear on equipment; increased facility reliability; reduced need for engineering controls; lower cooling requirements; lower labour requirements
Working environment	Improved lighting, temperature control and air quality; reduced noise levels; reduced need for personal protective equipment; increased worker safety
Other	Decreased liability; improved public image; delayed or reduced capital expenditures; creation of additional space; improved worker morale

Source: Aunan *et al*., 2004; Pye and McKane, 2000; Worrell, *et al*., 2003

A review of 41 industrial motor system optimization projects implemented between 1995 and 2001 found that 22 resulted in reduced maintenance requirements on the motor systems, 14 showed improvements in productivity in the form of production increases or better product quality, 8 reported lower emissions or reduction in purchases of products such as treatment chemicals, 6 projects forestalled equipment purchases, and others reported increases in production or decreases in product reject rates (Lung, et al., 2003). Motor system optimization projects in China are seen as an activity that can reduce operating costs, increase system reliability, and contribute to the economic viability of Chinese industrial enterprises faced with increased competition (McKane, et al., 2003).

A review of 54 emerging energy-efficient technologies, produced or implemented in the U.S., EU, Japan and other industrialized countries for the industrial sector, found that 20 of the technologies had environmental benefits in the areas of "reduction of wastes" and "emissions of criteria air pollutants." The use of such environmentally-friendly technologies is often most compelling when it enables the expansion of incremental production capacity without requiring additional environmental permitting. In addition, 35 of the technologies had productivity or product quality benefits (Martin, et al., 2000).

Quantification of the co-benefits of industrial technologies is often done on a case-by-case basis. One evaluation identified 52 case studies from projects in the U.S., Netherlands, UK, New Zealand, Canada, Norway, and Nigeria that monetized non-energy savings. These case studies had an average simple payback time of 4.2 years based on energy savings alone. Addition of the quantified co-benefits reduced the simple payback time to 1.9 years (Worrell, et al., 2003). Inclusion of quantified co-benefits in an energy-conservation supply curve for the U.S. iron and steel industry doubled the potential for cost-effective savings (Worrell, et al., 2001a; Worrell, et al., 2003).

Difficulties associated with quantifying co-benefits include the fact that not all benefits are easily quantified in financial terms (e.g. increased safety or employee satisfaction), there are variations in regulatory regimes vis-à-vis specific emissions and the value of their reduction, and there is a lack of time series and plant-level data on co-benefits. Also, there is a need to assess not only co-benefits, but also negative impacts that may be associated with some technologies, such as increased risk, increased training requirements, and production losses association with technology installation (Worrell, et al., 2003).

7.11 Technology Research, Development, Deployment and Diffusion (RDD&D)

Most industrial processes use at least 50% more than the theoretical minimum energy requirement determined by the laws of thermodynamics, suggesting a large potential for energy-efficiency improvement and GHG emission mitigation (IEA, 2006). However, RDD&D is required to capture these potential efficiency gains and achieve significant GHG emission reductions. Studies have demonstrated that new technologies are being developed and entering the market continuously, and that new technologies offer further potential for efficiency improvement and cost reduction (Worrell, et al., 2002).

While this chapter has tended to discuss technologies only in terms of their GHG emissions mitigation potential and cost, it is important to realize that successful technologies also must meet a host of other performance criteria, including cost competitiveness, safety, and regulatory requirements; and win consumer acceptance. (These topics are discussed in more detail in Section 7.11.2.) While some technology is marketed as energy-efficient, other benefits may drive the development and diffusion of the technology, as evidenced by a case study of impulse drying in the paper industry, in which the driver was productivity (Luiten and Blok, 2004). This is understandable given that energy cost is just one of the drivers for technology development. Innovation and the technology transfer process are discussed in Section 2.9.2.

Technology research, development, deployment and diffusion are carried out by both governments (public sector) and companies (private sector). Ideally, the roles of the public and private sectors will be complementary. Flannery (2001) argued that it is appropriate for governments to identify the fundamental barriers to technology and find solutions that improve performance, including environmental, cost and safety performance, and perhaps customer acceptability; but that the private sector should bear the risk and capture the rewards of commercializing technology. Case studies of specific successful energy-efficient technologies, i.e. shoe press in papermaking (Luiten and Blok, 2003a) and strip casting in the steel industry (Luiten and Blok, 2003b), have shown that a better understanding of the technology and the development process are essential in the design of effective government support of technology development. The government can play also an important role in cultivating "champions" for technology development, as well to "anchor" energy and climate as an important continuous driver for technology development (Luiten and Blok, 2003a).

While GHG mitigation is not the only objective of energy R&D, IEA studies show a mismatch between R&D spending and the contribution of technologies to CO_2 emissions reductions. In its analysis of its Accelerated Technology scenarios, IEA (2006) found that end-use energy efficiency, much of it in the industrial sector, contributed most to mitigation of CO_2 emissions from energy use, accounting for 39-53% of the projected reduction, except in the scenario that deemphasized these technologies. However, IEA countries spent only 17% of their public energy R&D budgets on energy-efficiency (IEA, 2005).

Many studies have indicated that the technology required to reduce GHG emissions and eventually stabilize their atmospheric concentrations is not currently available (Jacoby, 1998; Hoffert, et al., 2002; Edmonds, et al., 2003). While these studies concentrate on energy supply options, they also indicate that significant improvements in end-use energy efficiency will be necessary. Much of the necessary research and development is being carried out in public-private partnerships. One such partnership is the U.S. Department of Energy's Industrial Technologies Program (US DOE, n.d.). Under this program a number of industries have developed technology roadmaps, laying out the new technology they will need to meet the array of challenges they face, including control of GHG emissions. For example, the aluminium industry's roadmap defines the technological need to reduce energy use and to develop inert anodes that will eliminate the potential for PFC emissions (The Aluminum Association, 2003). Similar programs exist in other regions (NEDO, n.d.) and in individual industrial sectors (US DOE, n.d.). These programs provide adaptive capacity for industry by creating the technology needed to meet potential government regulation or changed consumer preference.

7.11.1 Public Sector

A more complete discussion of public sector policies is presented in Section 7.9 and in Chapter 13. While government use many policies to spur RDD&D in general, this section focuses specifically on programs aimed at improving energy efficiency and reducing GHG emissions.

7.11.1.1 Domestic Policies

Governments are often more willing than companies to fund higher-risk technology research and development. This willingness is articulated in the U.S. Department of Energy's Industrial Technologies Program role statement: "The program's primary role is to invest in high-risk, high-value research and development that will reduce industrial energy requirements while stimulating economic productivity and growth" (US DOE, n.d.). The Institute for Environment and Sustainability of the EU's Joint Research Centre has a similar mission, albeit focusing on renewable energy (Joint Research Centre, n.d.a), as does the program of the Japanese government's New Energy and Industrial Technology Development Organization (NEDO, n.d.).

Selection of technology is a crucial step in any technology adoption. Governments can play an important role in technology diffusion by disseminating information about new technologies and by providing an enabling environment that encourages the implementation of energy-efficient technologies. For example, energy audit programs (see Section 7.3.1), which exist in numerous countries, provide a more targeted type of information transaction than simple advertising. Audits by the U.S. Department of Energy's Industrial Assessment Center program in small and medium-sized enterprises resulted in implementation of about 42% of the suggested measures (Muller and Barnish, 1998). Programs or policies that promote or require reporting and benchmarking of energy consumption can have a similar function. These programs have been implemented in many countries, including Canada, Denmark, Germany, The Netherlands, Norway, the U.K., and the U.S.

(Sun and Williamson, 1999), and in specific industrial sectors such as the petroleum refining, ethylene and aluminium industry. (See Section 7.3.1).

Many of the voluntary programs discussed in Section 7.9.2 include information exchange activities to promote technology diffusion at the national level and across sectors. For example, for 2002, the U.S. Industrial Technologies Program claimed energy savings of approximately 0.3 EJ as the result of diffusion of more than 90 technologies across the U.S. industrial sector. Reductions in CO_2 emission were not given for 2002, but scaling the energy savings information to the cumulative carbon emissions data provided indicates a 2002 CO_2 emission reduction in the order of 19 Mt (US DOE, n.d.). EU programs, e.g. Lights of the Future and the Motor Challenge Programme (Joint Research Centre, n.d.b), have similar objectives, as do programs in other regions.

A wide array of policies has been used and tested in the industrial sector in industrialized countries, with varying success rates (Galitsky, et al., 2004; WEC, 2004). No single instrument will reduce all of the barriers to technology diffusion; an integrated policy accounting for the characteristics of technologies, stakeholders, and regions addressed is needed.

A recent study (Evenson, 2002) suggests that the presence of a domestic research and development program in a developing country increase the county's ability to adapt and adopt new technologies. Preliminary analysis seems to suggest that newly industrialized countries are becoming more active in the generation of scientific and technical knowledge, although there is no accurate information on the role of technology development and investments in scientific knowledge in developing countries (Amsden and Mourshed, 1997).

7.11.1.2 Foreign or International Policies

In contrast to agricultural RDD&D programs, which assume a need for domestic research because of geographic specificity, industrial RDD&D programs assume that technologies are easily adapted across regions with little innovation. This is not always the case. While many industrial facilities in developing nations are new and include the latest technology, as in industrialized countries, many older, inefficient facilities remain. The problem is exacerbated by the presence of large numbers of small-scale, much less energy-efficient plants in some developing nations; e.g. the iron and steel, aluminium, cement, and pulp and paper industries in China, and in the iron and steel industry in India (IEA, 2006). This creates a huge demand for technology transfer to developing countries to achieve energy efficiency and emissions reductions.

Internationally, there are a growing number of bilateral technology RD&D programs to address the slow and potentially sporadic diffusion of technology across borders. A December, 2004 U.S. Department of State Fact Sheet lists 20 bilateral agreements with both developed and developing nations (U.S. Dept. of State, 2004), many of which include RDD&D.

Multilaterally, the UNFCCC has resulted in the creation of two technology diffusion efforts, the Climate Technology Initiative (CTI) and the UNFCCC Secretariat's TT:CLEAR technology transfer database. CTI was established in 1995 by 23 IEA/OECD member countries and the European Commission, and as of 2003 has been recognized as an IEA Implementing Agreement. Its focus is the identification of climate technology needs in developing countries and countries with economies-in-transition and filling those needs with training, information dissemination and other support activities (CTI, 2005). TT:CLEAR is a more passive technology diffusion mechanism that depends on users accessing the data base and finding the information they need (UNFCCC, 2004). Additionally, in 2001, the UNFCCC established an Expert Group on Technology Transfer (EGTT)

(UNFCCC, 2001). EGTT has promoted a number of activities including workshops on enabling environments and innovative financing for technology transfer. Ultimately, the Kyoto Protocol's CDM and JI should act as powerful tools for the diffusion of GHG mitigation technology.

7.11.2 Private Sector

In September, 2004, the IPCC convened an expert meeting on industrial technology development, transfer and diffusion, which had as one of its objectives of identifying the key drivers of these processes in the private sector (IPCC, 2005a). Among the key drivers for private sector involvement in the technology process discussed at the meeting were:

Maintaining competitive advantage in open markets
Consumer acceptance in response to environmental stewardship
Country-specific characteristics: economic and political as well as its natural resource endowment
Scale of facilities, which affects the type of technology that can be deployed
Intellectual property rights (IPR): protection of IPR is critical to achieving competitive advantage through technology
Regulatory framework, including: government incentives; government policies on GHG emissions reduction, energy security and economic development; rule of law; and investment certainty.

The meeting concluded that each of these drivers could either be stimulants or barriers to the technology process, depending on their level, e.g. a high level of protection for IPR would stimulate the deployment of innovative technology in a specific country while a low level would be a barrier. However, it was also recognized that that these drivers were only indicators, and that actual decisions had to consider interactions between the drivers, as well as non-technology factors.

7.12 Long-term Outlook, System Transitions, Decision-making, and Inertia

7.12.1 Longer-term Mitigation Options

Four technologies offer the potential for significant further reduction in industrial CO_2 emissions: CCS (discussed in Section 7.3.7), biological processing, use of hydrogen, and nanotechnology.

Biological processing. Theoretically many industrial organic chemicals can be manufactured from biomass. In the petrochemical industry simple hydrocarbons undergo reaction to incorporate side chains with oxygen or nitrogen atoms, which provide different functionalities. Biomass components are often functionalised, thus in many cases reactions to incorporate functionality are not required. This potentially represents reduction in the energy requirement for chemical processes.

An example is the use of ammonia to incorporate nitrogen. Globally 143 Mt of ammonia were produced in 2005(IFA, 2005) consuming about 30 GJ/tonne (Heaton, 1996), a total of 4.3 EJ/year. Ammonia is used in the production of acrylonitrile, which is used in the manufacture of amines and some plastics, and has a production volume of about 4 Mt/year. (The Innovation Group, 2002; Weissermel and Arpe, 1993) Acrylonitrile, from the reaction of propylene with ammonia, requires a process energy of about 6 GJ/tonne (Brown, 2003). Thus, depending on route, about 24PJ/yr is used in acrylonitrile manufacture purely for nitrogen incorporation. Using a biomass component as a feedstock for acrylonitrile manufacture would reduce process energy requirements by eliminating the need to incorporate nitrogen and the use of ammonia. Research is underway on the use of leguminosae, which uses symbiosis to bind atmospheric nitrogen in desirable functionalities, to produce nitrogen-containing organic chemicals with a significant reduction in the use of fossil resources. Commercialization of this technology is not expected before 2030. Research is also underway on biological processing in the minerals industry.

Hydrogen. Hydrogen, produced from fossil fuels in conjunction with CCS can provide a low or zero GHG emission energy carrier; when produced from biomass, in conjunction with CCS, can provide negative carbon emissions. The production and distribution of hydrogen is discussed in Section 4.4.2.2. Here we discuss potential industrial end uses hydrogen.

Theoretically, it is possible to convert iron oxide to iron using hydrogen as the reducing agent, eliminating process CO_2 emissions from steelmaking. About 650 Nm^3 of hydrogen is required to produce 1 tonne of iron (De Beer, *et al*., 1998). However, no commercial experience with hydrogen reduction of iron oxides is yet available. Hydrogen could also be used to reduce non-ferrous metal ores, but there is even less information about the economic potential for these technologies. If hydrogen were generally available, it also could be used by industry as a fuel. Research on the use of hydrogen as a fuel is underway. BP is studying the use of hydrogen in gas turbines to generate electricity in remote areas. (API, 2003). Alternatively, industry could use hydrogen in fuel cells to efficiently generate electricity. While this approach would require much less change in end-use technology, it is dependent on the development of cost effective, durable fuel cell technology.

Nanotechnology. Nanotechnology refers to approaches that use structures whose characteristic size is less than 100 nm (10^{-7} m, or 1000 Angstrom units). The chemical and petroleum industries have been using “nanotechnology” for decades, since zeolites and many other catalyst types have structures which are much smaller than 100 nm. The current emphasis on understanding these structures is likely to result in better catalysts, which will save some energy by improving product yields and reducing the energy required to separate products from byproducts and waste. A more interesting application of nanotechnology is the potential it provides for thermoelectric devices to convert low level waste heat into electricity. While many heat recovery technologies currently exist, all become uneconomical as the temperature of the waste heat drops. Thermoelectric devices can generate electricity directly when a junction of two dissimilar metals is heated, even slightly. The efficiency of thermoelectric devices increases (up to the Carnot cycle limit) as the diameter of the wire connecting the heat source and heat sink decreases. With current technology, the efficiency of these devices is too low to be practical for industrial application, but if nanotechnology could produce much finer wires, application to industrial heat recovery could become attractive, raising the overall efficiency of a wide variety of processes (Hillhouse and Tuominen, 2001).

7.12.2 System Transitions, Inertia and Decision-making

Given the complexity of the industrial sector, the changes required to achieve low GHG emissions cannot be characterized in terms of a single system transition. For example, development of an inert electrode for aluminium smelting would significantly lower GHG emissions from this process, but would have no impact on emissions from other industries.

Inertia in the industrial sector is characterized by capital stock turnover rate. As discussed in section 7.6, the capital stock in many industries has lifetimes measured in decades. While opportunities exist for retrofitting some capital stock, basic changes in technology occur only when the capital stock is installed or replaced. This inertia is often referred to as “technology lock-in,” a concept first proposed by Arthur (1988). IEA (2006) discusses the potential effects of technology lock-in in electric power generation, where much of the capital stock in developed nations will be replaced, and much of the capital stock in developing nations, will be installed in the next few decades. Installation of lower-cost, but less efficient technology will then impact GHG emission for decades thereafter. The same concerns and impacts apply in the industrial sector.

Industrial companies are hierarchical organizations and have well-established decision-making processes. In large companies, these processes have formal methods for incorporating technical and economic information, as well as regulatory requirements, consumer preferences, and stakeholder inputs. Procedures in SMEs are often informal, but all successful enterprises have to address the same set of inputs.

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