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Technological and Economic Potential of Greenhouse Gas Emissions Reduction

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EXECUTIVE SUMMARY

The technological and economic potential to reduce greenhouse gas (GHG) emissions is large enough to hold annual global greenhouse gas emissions to levels close to or even below those of 2000 by 2010 and even lower by 2020. Realization of these reductions requires combined actions in all sectors of the economy including adoption of energy-efficient technologies and practices, increased fuel switching toward lower carbon fuels, continued growth in the use of efficient gas turbines and combined heat and power systems, greater reliance on renewable energy sources, reduced methane emissions through improved farm management practices and ruminant methane reduction strategies, diversification of land use to provide sinks and offsets, increased recovery of landfill methane for electricity production and increased recycling, reduction in the release of industrial gases, more efficient vehicles, physical sequestration of CO_2, and improving end-use efficiency while protecting the ozone layer. Countervailing socioeconomic and behavioural trends that cause greenhouse gas emissions to increase also exist, including increased size of dwelling units, increased sales of heavier and more powerful vehicles, growing vehicle kilometers travelled, reduced incentives for efficient use of energy or the purchase of energy efficiency technologies as a result of low real retail energy prices, increased consumption of consumer goods, and stimulated demand for energy-consuming products as a result of increased electrification.

A number of new technologies and practices have gained importance since the Second Assessment Report (SAR). As a result, greater opportunities for energy efficiency are available, often at lower cost than was expected. Annual growth in global consumption of primary energy and related carbon dioxide emissions dropped to 1.3% and 1.4%, respectively, between 1990 and 1998 after experiencing much higher growth rates of 2.4% and 2.1% between 1971 and 1990. This decrease in growth rate is because of the combined effects of improved energy efficiency technologies, increased fuel switching and adoption of renewable energy sources, and the dramatic decrease in emissions of countries with economies in transition (EITs) as a result of economic changes (*Figures 3.1* and *3.2*).

Sustained progress in the development and adoption of technologies and practices to reduce greenhouse gas emissions requires continued efforts in the areas of research and development, demonstration, dissemination, policies, and programmes. There has been a reduction in both public and private resources devoted to research and development to develop and implement new technologies that will reduce greenhouse gas

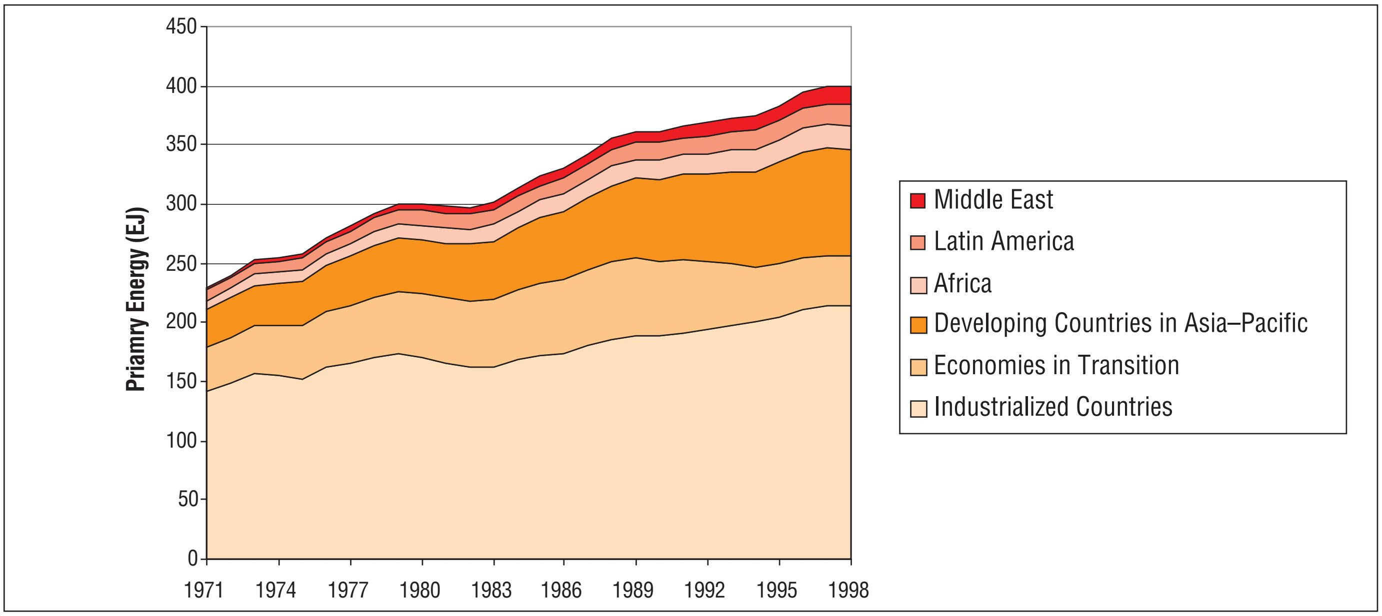

Figure 3.1: *World primary energy use per region 1971 - 1998.*

Note: Primary energy calculated using the IEA's physical energy content method based on the primary energy sources used to produce heat and electricity (IEA, 2000).

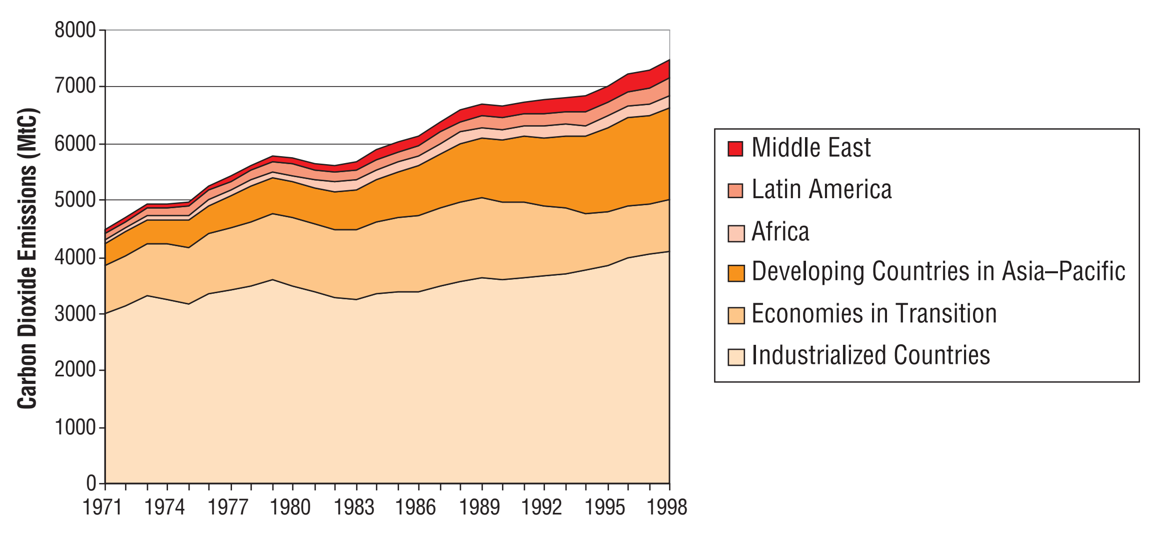

Figure 3.2: *World CO_2 emissions by region, 1971 - 1998.*

emissions. Despite the development of new, efficient technologies, current rates of energy efficiency improvements alone will not be sufficient to significantly reduce greenhouse gas emissions in the near term. In addition, policies or programmes to increase energy efficiency and promote renewable energy technology are lacking in many countries.

Technological innovation and change are influenced by the differing needs of different economies and sectors. A large percentage of capital is invested in a relatively small number of technologies that are responsible for a significant share of the energy supply and consumption market (automobiles, electric power generators, industrial processes, and building heating and cooling systems). There is a tendency to optimize these few technologies and their related infrastructure development, gaining them advantages and locking them into the economy. That makes it more difficult for alternative, low-carbon technologies to compete. For example, a particular technological configuration such as road-based automobiles has become "locked-in" as the dominant transportation mode. In industrial countries, technologies are developed as a result of corporate innovation or government-supported R&D, and in response to environmental regulations, utility deregulation, energy tax policies, or other incentives. In many developing countries, where electric power capacity and much end-use demand is growing most rapidly, there is often greater emphasis on getting technology such as electric power generation established in order to enhance economic development, with less concern for environmental and other issues. Capital flows and differing types of technology transfer may also determine technology choices. It is important to recognize that often values other than energy efficiency or greenhouse gas emissions are the dominant shapers of technological choice and innovation.

This chapter describes technologies and practices to reduce greenhouse gas emissions in the end-use sectors of the economy as well as through changes in energy supply. The end-use sectors addressed are buildings, transport, industry, agriculture, and waste. Energy supply includes non-renewable resources, renewable resources, and physical carbon dioxide sequestration. In addition, options for reducing global warming contributions from substitutes for ozone depleting substances are discussed in the Appendix to this chapter.

The buildings sector contributes about 31% of global energy-related carbon dioxide emissions and these emissions grew at an average annual rate of almost 2.0% between 1971 and 1995. Growth in emissions varied significantly by region; between 1990 and 1995 the largest annual increases were experienced in developing countries (around 5.0% per year), moderate growth was seen in developed countries (around 1.0% per year), and emissions declined in the EITs (–3.0% per year). The growth in emissions in the developing and developed countries is largely caused by the increased amenity that consumers demand – in terms of increased purchase and use of appliances, larger dwellings, and the modernization and expansion of the commercial sector – as economies grow. Technology has continued on an evolutionary trajectory with incremental gains during the past decade in windows, lighting, insulation, space heating, refrigeration, air conditioning, building controls, passive solar design, and infiltration reduction. Although CFCs have been eliminated in developed countries as working fluids in heat pumps, air conditioners, and refrigerators, and as foam blowing agents for insulation, research and development (R&D) has been able to continue to improve energy efficiency of refrigerators and cooling and heating systems. Integrated building design has demonstrated very large reductions in energy use and greenhouse gas emissions. Expanded R&D is needed to assure continued technology improvement, but implementation policies remain the major hurdle to their rapid introduction.

The transport sector contributes 22% of carbon dioxide emissions; globally, emissions from this sector are growing at a rate of approximately 2.5% annually. Between 1990 and 1995, growth was highest in the developing countries (7.3% per year in the developing countries of Asia–Pacific and 4.6% per year in the remaining developing countries), moderate in the developed countries (1.9% per year) and is actually declining at a rate of –5.0% per year for the EITs. Technology improvements may generate operational cost reductions that have a rebound effect that stimulates further personal transportation use. These issues show the necessity of both policies and behavioural changes to lower emissions from the transport sector. Hybrid gasoline-electric vehicles have been introduced on a commercial basis with fuel economies 50% to 100% better than that of comparably sized four-passenger vehicles. The development of extremely low-polluting engines may reduce the incentive for hybrid and battery electric vehicles that were previously thought to encourage the adoption of vehicles that would also reduce greenhouse gases. Lightweight materials have the potential to improve fuel economy for all land transport. Fuel cell powered vehicles are developing rapidly, and could be introduced to the market sometime during the coming decade. Substantial potential for improving the fuel economy of heavy-duty trucks seems feasible. Only incremental improvements of the order of 1%/yr are expected for aircraft over the next several decades. There appears to be little attention being given to rail or public transportation systems, but waterborne transport of freight is already highly efficient, and has potential for additional gains.

Industrial emissions account for over 40% of carbon dioxide emissions. Global industrial sector carbon dioxide emissions grew at a rate of 1.5% per year between 1971 and 1995, slowing to 0.4% per year between 1990 and 1995. This is the only sector that has shown an annual decrease in carbon emissions in industrial economies (–0.8% per year between 1990 and 1995) as well as in the EITs (–6.4% per year between 1990 and 1995). Emissions from this sector in developing countries, however, continue to grow (6.3% per year in developing countries of Asia–Pacific and 3.4% per year in the remaining developing countries). Substantial differences in the energy efficiency of industrial processes between countries exist. Improvement of energy efficiency is the most important emission reduction option in the short term. However, industries continue to find new, more energy efficient processes which makes this option also important for the longer term. The larger part of the energy can be saved at net negative costs. In addition, material efficiency improvement (including more efficient product design, recycling, and material substitution) can greatly contribute to reducing emissions. For many sources of non-CO_2 emissions, like those from the aluminium industry, and adipic acid and HCFC-22 production, substantial emission reductions are possible or are already being implemented.

The agricultural sector has the smallest direct CO_2 emissions, contributing 4.0% of total global emissions. Growth in these emissions between 1990 and 1995 was greatest in the developing countries (6.0% per year in the developing countries of Asia–Pacific and 9.3% per year in the remaining developing countries), modest in the developed countries (1.3% per year), and declined at a rate of –5.4% per year in the EIT. However, methane and nitrous oxide emissions dominate the agricultural sector, which contributes over 20% of global anthropogenic greenhouse gas emissions in terms of CO_2 equivalents. Reductions can be made by improved farm management practices such as more efficient fertilizer use, better waste treatment, use of minimum tillage techniques, and ruminant methane reduction strategies. Biotechnology and genetic modification developments could provide additional future gains and also lead to reduced energy demand, but the conflict between food security and environmental risk is yet to be resolved. Mitigation solutions exist overall for 100–200MtC_{eq}/yr but farmers are unlikely to change their traditional farming methods without additional incentives. Diversification of land use to energy cropping has the technical potential to provide both carbon sinks and offsets in regions where suitable land and water are available. Transport biofuel production costs remain high compared with oil products, but do provide additional value in the form of oxygenates and increased octane (ethanol). Because of market liberalization policies, the potential for biofuels has declined, though there is a growing demand for biodiesel in Germany. Improvements in biofuel conversion routes, such as the enzymatic hydrolysis of lignocellulosic material to ethanol, may help narrow the cost disadvantage versus fossil fuels.

Greenhouse gas emissions are being lowered substantially by increased utilization of methane from landfills and from coal beds for electric power generation. Significant energy-related greenhouse gas reductions are identified for improved waste recycling in the plastics and carpet industries, and through product remanufacturing. A major discussion is taking place over whether the greater reduction in lifecycle CO_2 emissions occurs through paper recycling or by utilizing waste paper as a biofuel in waste to energy facilities. In several developed countries, and especially in Europe and Japan, waste-to-energy facilities have become more efficient with lower air pollution emissions.

Abundant fossil fuel reserves that are roughly five times the total carbon already burned are available. The electric power sector accounts for 38% of total CO_2 emissions. Low cost, aero-derivative, combined cycle gas turbines with conversion efficiencies approaching 60% have become the dominant option for new electric power generation plants, wherever adequate natural gas supply and infrastructure are available. With deregulation of the electric power sector, additional emission reductions have occurred in most countries through the utilization of waste heat in combined heat and power systems that are capable of utilizing 90% of the fossil fuel energy. Low carbon-emitting technologies such as nuclear power have managed to significantly increase their capacity factor at existing facilities, but relatively few new plants are being proposed or built because of public concern about safety, waste storage, and proliferation. There has also been rapid deployment of wind turbines and smaller, but expanding markets for photovoltaic solar power systems. The annual growth rate from a small base for both wind and solar currently exceeds 25% per year, and together with an increasing number of bioenergy plants, accounts for around 2% of global electricity generation. Modern biomass gasification is increasing the opportunities for this renewable resource. There remains additional hydropower potential in some locations, but most large sites have already been developed in many regions of the world. Fuel cells appear to be a promising combined heat and electric power source as part of evolving distributed generation systems.

Further analysis since the SAR suggests that physical sequestration of CO_2 underground in aquifers, in depleted gas and oil fields, or in the deep ocean is potentially a viable option. Technical feasibility has been demonstrated for CO_2 removal and storage from a natural gas field, but long-term storage and economic viability remain to be demonstrated. Environmental implications of ocean sequestration are still being evaluated. The utilization of hydrogen from fossil fuels, biomass, or solid waste followed by sequestration appears particularly attractive. Along with biological sequestration, physical sequestration might complement current efforts at improving energy efficiency, fuel switching, and the further development and implementation of renewables, but it must compete economically with them.

Hydrofluorocarbon (HFCs) and perfluorocarbon (PFCs) use is growing as CFCs and, to a much lesser extent HCFCs, are eliminated. There is a variety of uses for these substances as alternatives in refrigeration, mobile and stationary air-conditioning, heat pumps, in medical and other aerosol delivery systems, insulating plastic foams, and for fire suppression and solvents. The replacement of ozone-depleting substances with HFCs and PFCs has been about one-tenth on a mass basis, with the difference being attributed to improved containment, recovery of fluids, and the use of alternative substances. The importance of considering energy efficiency simultaneously with ozone layer protection is discussed in the Appendix, especially in the context of developing countries.

This chapter concludes with a quantification of the potential for reducing greenhouse gas (GHG) emissions in the various end-use sectors of the economy and through changes in energy supply. It is found that sufficient technological potential exists to stabilize or lower global greenhouse gas emissions by 2010, and to provide for further reductions by 2020. The quantification is based on sector-specific analyses and, thus, caution should be taken when adding up the various estimates resulting from interactions between different types of technologies. These sector-based analyses can be used to provide further understanding of the results of global mitigation scenarios, such as those presented in Chapter 2, which account for intersectoral interactions, but typically do not provide estimates of sectoral level GHG emissions reduction potential or costs.

Some of the costs associated with sector specific options for reducing GHG emissions may appear high (for example US\$300/tC_{eq}). However, we estimate that there is technological potential for reductions of between 1,900 and 2,600MtC_{eq}/yr in 2010 and 3,600 to 5,050MtC_{eq}/yr in 2020. Half of these reductions are achievable at net negative costs (value of energy saved is greater than capital, operating and maintenance costs), and most of the remainder is available at a cost of less than US\$100tC_{eq}/yr. The continued development and adoption of a wide range of greenhouse gas mitigation technologies and practices will result not only in a large technical and economic potential for reducing greenhouse gas emissions but will also provide continued means for pursuing sustainable development goals.

3.1 Introduction

Technologies and measures to reduce greenhouse gas emissions are continuously being developed (Nadel *et al*., 1998; National Laboratory Directors, 1997; PCAST, 1997; Martin *et al*., 2000). Many of these technologies focus on improving the efficiency of fossil fuel use since more than two-thirds of the greenhouse gas emissions addressed in the Kyoto Protocol (in carbon dioxide equivalents) are related to the use of energy. Energy intensity (energy consumed divided by gross domestic product (GDP)) and carbon dioxide intensity (CO_2 emitted from burning fossil fuels divided by the amount of energy produced) have been declining for more than 100 years in developed countries without explicit government policies for decarbonization and both have the potential to decline further. Non-fossil fuel energy sources are also being developed and implemented as a means of reducing greenhouse gas emissions. Physical and biological sequestration of CO_2 can potentially play a role in reducing greenhouse gas emissions in the future. Other technologies and measures focus on reducing emissions of the remaining major greenhouse gases - methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6)(see Section 3.5 and Appendix to this Chapter).

Table 3.1 shows energy consumption in the four end-use sectors of the global economy – industry, buildings, transport, and agriculture–over time[1]. Data are displayed for six world regions – developed countries, countries with economies in transition (EITs), developing Asia-Pacific countries, Africa, Latin America and the Middle East. Comparing global annual average growth rates (AAGRs) for primary energy use in the period 1971 to 1990 and 1990 to 1995 a significant decrease is noticed– from 2.5% in the first period to about 1.0% in the latter, due almost entirely to the economic crisis in the EITs. Overall, growth averaged about 2.0% per year from 1971 to 1995. *Table 3.1* also shows carbon dioxide emissions from energy consumption for four world regions. The AAGR of global carbon dioxide emissions from the use of energy also declined (from 2% to 1%) in the same periods. A different picture emerges if the countries with economies in transition are excluded. In this case, growth in world energy use averaged about 2.5% per year in both the 1971 to 1990 and 1990 to 1995 periods, while average annual growth in carbon dioxide emissions was 2.0% and 2.6% during the same time periods, respectively.

Uncertainty in *Table 3.1* arises in a number of areas. First, the quality of energy data from the International Energy Agency (IEA) is not homogeneous because of the use of various reporting mechanisms and "official" sources of national data (IEA, 1997a; IEA, 1997b; IEA, 1997c)[2]. Second, for the economies in transition, primary energy use data and carbon dioxide data are from two different sources (BP, 1997; IEA, 1997a; IEA, 1997b; IEA, 1997c). There are inconsistencies between the two sources, and no analysis has yet been done to resolve them. Third, IEA statistics report sectoral data for the industrial and transport sectors, but not for buildings and agriculture, which are reported as "other". These sectors have been estimated using an allocation scheme described in Price *et al*. (1998)[3]. In general, the most uncertainty is associated with data for the economies in transition region, and for the commercial and residential sub-categories of the buildings sector in all regions.

It is likely that total commercial energy production and demand estimates will be known accurately for most developed countries (within one or a few per cent), relatively accurately for some developing countries (with an uncertainty of 1% to 5%), and less accurately for developing countries with poorly functioning data gathering and statistical systems. Converting the energy data into carbon emissions introduces some increased uncertainty – primarily as a consequence of the fraction of natural gas that leaks to the atmosphere and the fraction of all fossil fuels that are left uncombusted – the uncertainty in carbon emissions is greater than that of energy use. Uncertainties in non-CO_2 greenhouse gas emissions are greater than those for carbon emissions.

In general, energy supply statistics, and their disaggregation into fuel types, are more reliable than statistics for energy demand. In particular, the estimates of sectoral energy demand (buildings, industry, transportation, agriculture) and the further disaggregation into subsectors (e.g., residential and commercial buildings; auto transportation; specific industries), and then into end uses has relatively high levels of uncertainty for at least two reasons. First, the full data to perform these disaggregations are rarely gathered at the national level, so that assumptions and approximations need to be made. Second, the conventions vary among different countries as to what energy use belongs to which sector or subsector (e.g., the distinction

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[1] The data in this table differ slightly from the data presented in *Figures 3.1* and *3.2* because those figures are based on IEA data alone while the data in the table represents a combination of IEA and British Petroleum data (further described in the next paragraph of the text). Also, in *Figure 3.1*, primary energy was calculated using IEA's physical energy content method which is based on the primary energy sources used to produce heat and electricity (IEA, 2000) while in *Table 3.1*, primary energy was calculated using a standard electricity conversion efficiency of 33% (Price *et al*., 1998).

[2] The IEA explains: "Countries often have several 'official' sources of data such as a Ministry, a Central Bureau of Statistics, a nationalized electricity company, etc. Data can also be collected from the energy suppliers, the energy consumers or the customs statistics. The IEA tries to collect the most accurate data, but does not necessarily have access to the complete data set that may be available to national experts calculating emissions inventories for the UNFCCC" (IEA, 1997c).

[3] The results of this allocation scheme were compared to the Lawrence Berkeley National Laboratory (LBNL) sectoral energy data for a number of developed countries. In general, the sectoral energy consumption values based on allocated IEA data compare favourably to LBNL data for total buildings and agriculture for most countries. Larger discrepancies were seen between the LBNL data and the allocated IEA data at the level of commercial and residential buildings.

Table 3.1: *World carbon dioxide emissions and primary energy use by sector and region – 1971 to 1995*
(Price *et al*., 1998, 1999)

	Carbon dioxide emissions (MtC)									**Primary energy use (EJ)**								
							Average annual growth rate									Average annual growth rate		
Buildings sector	1971	1975	1980	1985	1990	1995	1971-1990	1990-1995	1971-1995	1971	1975	1980	1985	1990	1995	1971-1990	1990-1995	1971-1995
Developed Countries	790	836	886	887	915	958	0.8%	0.9%	0.8%	44.4	48.9	52.3	56.8	62.3	68.5	1.8%	1.9%	1.8%
Residential	522	543	549	537	539	560	0.2%	0.8%	0.3%	28.3	30.5	33.0	34.6	36.7	40.6	1.4%	2.0%	1.5%
Commercial	268	293	336	350	377	398	1.8%	1.1%	1.7%	16.1	18.4	19.3	22.2	25.6	27.9	2.5%	1.7%	2.3%
Economies in Transition	240	296	362	381	373	320	2.3%	-3.0%	1.2%	10.7	13.0	18.2	21.0	23.0	16.2	4.1%	-6.8%	1.7%
Residential	164	213	266	290	279	256	2.9%	-1.8%	1.9%	8.1	9.8	12.9	14.3	15.1	10.4	3.3%	-7.2%	1.1%
Commercial	76	83	97	92	94	64	1.1%	-7.3%	-0.7%	2.6	3.2	5.3	6.7	7.9	5.8	6.0%	-6.1%	3.4%
Dev. countries Asia-Pacific	67	88	131	179	232	292	6.7%	4.7%	6.3%	3.6	4.6	5.6	7.9	10.2	12.9	5.7%	4.8%	5.5%
Residential	57	75	110	145	180	210	6.2%	3.1%	5.6%	3.0	3.9	4.6	6.3	7.9	9.3	5.2%	3.4%	4.8%
Commercial	10	14	21	33	51	81	9.0%	9.7%	9.1%	0.6	0.8	1.0	1.6	2.3	3.6	7.8%	9.0%	8.1%
Africa	*15*	*18*	*23*	*30*	*38*	*48*	*5.0%*	*5.1%*	*5.0%*	*0.6*	*0.8*	*1.1*	*1.4*	*1.9*	*2.5*	*6.0%*	*5.4%*	*5.9%*
Residential	*11*	*12*	*16*	*22*	*29*	*39*	*5.1%*	*6.0%*	*5.2%*	*0.5*	*0.6*	*0.8*	*1.1*	*1.5*	*2.0*	*6.1%*	*6.0%*	*6.0%*
Commercial	*3*	*6*	*7*	*8*	*8*	*9*	*4.8%*	*1.7%*	*4.2%*	*0.1*	*0.2*	*0.3*	*0.3*	*0.4*	*0.5*	*5.8%*	*3.1%*	*5.2%*
Latin America	*18*	*21*	*24*	*24*	*30*	*34*	*2.6%*	*2.8%*	*2.7%*	*1.7*	*2.1*	*2.8*	*3.3*	*4.1*	*5.0*	*4.9%*	*4.1%*	*4.7%*
Residential	*14*	*16*	*19*	*19*	*22*	*24*	*2.5%*	*1.6%*	*2.3%*	*1.3*	*1.6*	*2.0*	*2.3*	*2.9*	*3.4*	*4.2%*	*3.3%*	*4.0%*
Commercial	*4*	*5*	*6*	*5*	*8*	*10*	*3.2%*	*5.9%*	*3.7%*	*0.3*	*0.5*	*0.8*	*0.9*	*1.2*	*1.6*	*7.0%*	*5.8%*	*6.8%*
Middle East	*9*	*13*	*23*	*41*	*58*	*80*	*10.5%*	*6.7%*	*9.7%*	*0.4*	*0.7*	*1.2*	*2.2*	*4.1*	*4.6*	*12.3%*	*2.8%*	*10.3%*
Residential	*7*	*10*	*17*	*30*	*41*	*59*	*10.0%*	*7.6%*	*9.5%*	*0.4*	*0.7*	*1.1*	*2.0*	*3.4*	*3.7*	*11.5%*	*1.8%*	*9.4%*
Commercial	*2*	*4*	*6*	*12*	*17*	*21*	*12.0%*	*4.3%*	*10.3%*	*0.0*	*0.0*	*0.1*	*0.2*	*0.7*	*1.0*	*20.2%*	*7.0%*	*17.3%*
Rest of World	42	52	71	95	125	162	6.0%	5.3%	5.8%	2.7	3.7	5.1	6.9	10.1	12.1	7.1%	3.8%	6.4%
Residential	32	38	52	70	92	122	5.7%	5.8%	5.7%	2.2	2.8	3.9	5.4	7.8	9.1	6.8%	3.2%	6.0%
Commercial	10	14	19	25	33	40	6.7%	4.0%	6.2%	0.5	0.8	1.2	1.5	2.3	3.0	8.5%	5.7%	7.9%
World	1140	1273	1450	1542	1646	1732	2.0%	1.0%	1.8%	61.5	70.3	81.3	92.6	105.6	109.8	2.9%	0.8%	2.4%
Residential	775	869	977	1042	1091	1148	1.8%	1.0%	1.6%	41.7	47.1	54.5	60.6	67.4	69.4	2.6%	0.6%	2.2%
Commercial	364	404	473	500	555	584	2.2%	1.0%	2.0%	19.8	23.2	26.8	31.9	38.2	40.3	3.5%	1.1%	3.0%

(continued)

***Table 3.1:** continued*

	Carbon dioxide emissions (MtC)									**Primary energy use (EJ)**								
							Average annual growth rate									Average annual growth rate		
Transport sector	1971	1975	1980	1985	1990	1995	1971-1990	1990-1995	1971-1995	1971	1975	1980	1985	1990	1995	1971-1990	1990-1995	1971-1995
Developed Countries	494	554	612	636	743	816	2.2%	1.9%	2.1%	26.2	29.4	32.5	33.8	39.4	43.3	2.2%	1.9%	2.1%
Economies in Transition	69	75	77	83	87	67	1.2%	-5.0%	-0.1%	6.0	7.3	8.0	9.2	10.0	7.3	2.7%	-6.0%	0.8%
Dev. Countries Asia-Pacific	51	54	69	87	122	173	4.7%	7.3%	5.2%	2.0	2.4	3.3	4.3	6.0	8.7	5.9%	7.6%	6.2%
Africa	*17*	*21*	*26*	*30*	*31*	*33*	*3.2%*	*1.5%*	*2.9%*	*0.8*	*1.0*	*1.3*	*1.5*	*1.6*	*1.7*	*3.6%*	*1.6%*	*3.2%*
Latin America	*33*	*44*	*53*	*55*	*62*	*79*	*3.4%*	*5.0%*	*3.7%*	*2.2*	*2.9*	*3.8*	*3.9*	*4.5*	*5.5*	*3.9%*	*4.2%*	*4.0%*
Middle East	*7*	*13*	*24*	*34*	*33*	*46*	*8.6%*	*6.6%*	*8.2%*	*0.4*	*0.7*	*1.3*	*1.8*	*1.7*	*2.4*	*8.6%*	*6.5%*	*8.1%*
Rest of World	57	77	104	119	126	159	4.3%	4.6%	4.4%	3.3	4.6	6.3	7.2	7.8	9.6	4.6%	4.2%	4.5%
World	672	760	862	925	1078	1215	2.5%	2.4%	2.5%	37.5	43.6	50.1	54.4	63.3	69.0	2.8%	1.7%	2.6%
Industrial sector																		
Developed Countries	932	911	970	859	887	852	-0.3%	-0.8%	-0.4%	48.6	49.3	55.0	52.3	54.3	56.8	0.6%	0.9%	0.7%
Economies in Transition	416	494	597	615	621	447	2.1%	-6.4%	0.3%	26.0	31.6	34.0	36.9	38.0	26.0	2.0%	-7.3%	0.0%
Dev. Countries Asia-Pacific	223	287	384	483	632	859	5.6%	6.3%	5.8%	8.8	11.5	15.5	20.0	26.1	34.8	5.9%	5.9%	5.9%
Africa	*35*	*43*	*57*	*63*	*68*	*66*	*3.5%*	*-0.4%*	*2.6%*	*1.4*	*1.8*	*2.5*	*2.8*	*3.1*	*3.1*	*4.5%*	*0.0%*	*3.5%*
Latin America	*33*	*41*	*55*	*53*	*58*	*70*	*3.1%*	*3.8%*	*3.2%*	*2.5*	*3.4*	*4.8*	*5.7*	*6.3*	*7.4*	*5.1%*	*3.4%*	*4.7%*
Middle East	*13*	*19*	*31*	*38*	*28*	*45*	*4.0%*	*10.2%*	*5.3%*	*0.7*	*1.1*	*1.6*	*2.1*	*1.5*	*2.4*	*3.9%*	*9.6%*	*5.1%*
Rest of World	81	104	143	154	154	182	3.4%	3.4%	3.4%	4.6	6.2	8.9	10.5	11.0	13.0	4.7%	3.5%	4.5%
World	1653	1796	2094	2110	2293	2340	1.7%	0.4%	1.5%	88.0	98.5	113.5	119.8	129.4	130.8	2.1%	0.2%	1.7%
Agricultural sector																		
Developed Countries	35	33	38	45	48	51	1.7%	1.3%	1.6%	1.8	1.8	2.1	2.6	2.7	3.0	2.2%	1.6%	2.0%
Economies in Transition	44	53	72	88	96	72	4.2%	-5.4%	2.1%	1.3	1.6	1.8	2.4	3.0	1.7	4.5%	-10.6%	1.1%
Dev. Countries Asia-Pacific	17	23	36	38	51	68	5.9%	6.0%	5.9%	0.9	1.2	1.6	1.7	2.3	3.0	4.8%	5.6%	5.0%
Africa	*2*	*3*	*4*	*4*	*4*	*7*	*2.9%*	*11.3%*	*4.6%*	*0.1*	*0.1*	*0.2*	*0.2*	*0.2*	*0.3*	*3.1%*	*9.8%*	*4.5%*
Latin America	*3*	*4*	*6*	*6*	*7*	*10*	*4.1%*	*7.2%*	*4.7%*	*0.2*	*0.3*	*0.5*	*0.6*	*0.6*	*0.8*	*4.6%*	*6.2%*	*5.0%*
Middle East	*1*	*2*	*4*	*5*	*5*	*8*	*7.6%*	*10.2%*	*8.1%*	*0.0*	*0.0*	*0.1*	*0.0*	*0.1*	*0.5*	*11.3%*	*35.7%*	*16.0%*
Rest of World	7	10	13	15	16	25	4.6%	9.3%	5.5%	0.4	0.5	0.7	0.8	0.9	1.6	4.7%	12.6%	6.3%
World	103	120	159	186	210	217	3.8%	0.6%	3.1%	4.4	5.1	6.1	7.5	8.9	9.3	3.8%	0.8%	3.1%

(continued)

Table 3.1: *continued*

	Carbon dioxide emissions (MtC)									Primary energy use (EJ)								
							Average annual growth rate									Average annual growth rate		
World Total	1971	1975	1980	1985	1990	1995	1971-1990	1990-1995	1971-1995	1971	1975	1980	1985	1990	1995	1971-1990	1990-1995	1971-1995
Developed Countries	2252	2334	2506	2426	2593	2678	0.7%	0.6%	0.7%	121.0	129.3	141.8	145.5	158.8	171.7	1.4%	1.6%	1.5%
Economies in Transition	770	918	1108	1167	1177	907	2.3%	-5.1%	0.7%	44.0	53.5	62.0	69.5	74.0	51.3	2.8%	-7.1%	0.6%
Dev. Countries Asia-Pacific	358	453	620	787	1036	1392	5.8%	6.1%	5.8%	15.4	19.7	26.0	33.9	44.7	59.5	5.8%	5.9%	5.8%
Africa	*70*	*85*	*110*	*127*	*141*	*155*	*3.8%*	*2.0%*	*3.4%*	*2.9*	*3.8*	*5.1*	*5.9*	*6.9*	*7.7*	*4.6%*	*2.3%*	*4.1%*
Latin America	*87*	*110*	*138*	*139*	*157*	*194*	*3.1%*	*4.3%*	*3.4%*	*6.5*	*8.7*	*11.8*	*13.4*	*15.5*	*18.8*	*4.7%*	*3.9%*	*4.5%*
Middle East	*30*	*48*	*83*	*118*	*124*	*179*	*7.7%*	*7.7%*	*7.7%*	*1.6*	*2.5*	*4.2*	*6.1*	*7.4*	*10.0*	*8.5%*	*6.0%*	*8.0%*
Rest of World	187	243	330	383	422	528	4.4%	4.6%	4.4%	11.0	14.9	21.1	25.4	29.8	36.4	5.4%	4.1%	5.1%
World	3567	3948	4565	4763	5227	5504	2.0%	1.0%	1.8%	191.4	217.5	251.0	274.2	307.2	318.8	2.5%	0.7%	2.1%

Notes: Emissions from energy use only; does not include feedstock or CO_2 from calcination in cement production. Biomass = no emissions. Rest of World = Africa, Latin America, Middle East. Primary energy use and CO_2 emissions for Economies in Transition are from different sources and thus cannot be compared to each other.

Primary energy calculated using a standard 33% electricity conversion rate.

between residential and commercial buildings; the issue of whether energy use in industrial buildings counts as industrial or building energy use).

The least accurate data are for non-commercial energy use, especially in developing countries – dung, plant or forest waste, logs, and crops used for energy. Energy use from these sources is generally estimated from surveys, and is known very poorly. Because of uncertainty about whether these sources are used in sustainable ways and, even more importantly, because the release of products of incomplete combustion – which are potent greenhouse gases – are poorly characterized, the overall contribution of non-commercial energy sources to greenhouse gas emissions is only somewhat better than an educated guess at this time.

An important observation from *Table 3.1* is the high AAGR in the transport sector for energy and carbon emission. AAGR is not only the greatest for the transport sector, but it has slowed only slightly since 1960 despite significant improvements in technology. Because of the increase in the number of vehicles, and the recent decline in energy efficiency gains as vehicles have become larger and more powerful, transportation now is responsible for 22% of CO_2 emission from fuel use (1995). Unlike electricity, which can be produced from a variety of fuels, air and road transport is almost entirely fuelled with petroleum, except for ethanol and biodiesel used in a few countries. Biomass-derived fuels and hydrogen production from fossil fuels with carbon sequestration technology, in parallel with improved fuel efficiency conversion, are some of the few more promising alternatives for reducing significantly carbon emissions in the transport sector for the next two decades. The accelerated introduction of hybrid and fuel cell vehicles is also promising, but these gains are already being offset by increased driving, and the rapid growth of the personal vehicle market worldwide.

Oil, gas, and coal availability is still recognized to be very extensive. Fossil fuel reserves are estimated to be approximately five times the carbon content of all that have been used since the beginning of the industrial revolution. The possibility of using gas hydrates and coal bed methane as a source of natural gas has increased since the SAR.

Greenhouse gas (GHG)-reducing technologies for energy systems for all sectors of the economy can be divided into three categories – energy efficiency, low or no carbon energy production, and carbon sequestration (Acosta Moreno *et al.*, 1996; National Laboratory Directors, 1997). Even though progress will continue to be made in all categories, it is expected that energy efficiency will make a major contribution in the first decade of the 21st century. Renewable technologies are expected to begin to be significant around 2010, and pilot plants for the physical carbon sequestration from fossil fuels[4] will be the last mitigation option to be adopted because of cost (National Laboratory Directors, 1997). Nevertheless, with appropriate policies, economic barriers can be minimized, opening possibilities for all the three categories of mitigation options. Considering the large number of available technologies in all categories and the still modest results obtained to date (see *Table 3.1*), it is possible to infer that their commercial uses are being constrained by market barriers and failures as well as a lack of adequate policies to induce the use of more costly mitigation options (see Chapters 5 and 6). This should not be interpreted as a reason to reduce R&D efforts and funding, since technological advances always help to cut costs and consequently reduce the amount and intensity of policies needed to overcome the existing economic barriers. Implementing new technological solutions could start soon by establishing policies that will encourage demand for these devices and practices. Complex technological innovations advance through a non-linear, interactive innovation process in which there is synergy between scientific research, technology development, and deployment activities (OTA, 1995a; Branscomb *et al.*, 1997; R&D Magazine, 1997). Early technology demand can be stimulated through well-placed policy mechanisms.

In this chapter numerous technologies are discussed that are either already commercialized or that show a probable likelihood to be in the commercial market by the year 2020, along with technologies that might possibly contribute to GHG abatement by 2010. For the quantification of the abatement capacity of some of the technologies a horizon as far as 2050 must be considered since the capital stock turnover rate, especially in the energy supply sector, is very low.

A number of new technologies and practices have gained importance since the preparation of SAR, including:

Buildings
- Off-grid building photovoltaic energy supply systems;
- Integrated building design for greater efficiency.

Transportation
- Hybrid electric vehicles;
- Fuel cell vehicles.

Industry
- Advanced sensors and controls for optimizing industrial processes;
- Large reductions in process gases such as CF_4, N_2O and HFCs through improved industrial processes;
- Reduced energy use and CO_2 emissions through improvements in industrial processing, remanufacturing, and use of recycled materials;
- Improved containment and recovery of CFC substitutes, the use of low Global Warming Potential (GWP) alternatives, and the use of alternative technologies.

Agriculture
- Biotechnology development for crop improvements (including energy crops), alternative fuels other than biomass, carbon cycle manipulation/sequestration, bio-

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[4] Biological carbon sequestration is discussed in Chapter 4.

processing for fuels and chemicals and biological/biochemical hydrogen production;
- Minimum tillage practices in agriculture to reduce energy requirements and soil erosion, and improved management systems that lower N_2O emissions.

Energy
- Grid-connected Alternating Current (AC) solar panels;
- Combined cycle gas turbines for standard electric power production;
- Distributed combined heat and power systems;
- Fuel cells for distributed power and low temperature heat applications;
- Conversion of cellulosic materials for production of ethanol;
- Wind-based electricity generation;
- Carbon sequestration in aquifers and depleted oil and gas wells;
- Increased coal bed methane and landfill gas use;
- Replacement of grid connected electricity by PV;
- Nuclear plants life extension.

Cost data are presented in this chapter for many mitigation options. They are derived from a large number of studies and are not fully comparable. However, in general, the following holds for the studies quoted in this Chapter. The specific mitigation costs related to the implementation of an option are calculated as the difference of levelized costs[5] over the difference in greenhouse gas emissions (both in comparison to the situation without implementation of the option). Costs are generally calculated on a project basis (for a definition see Chapter 7, Section 7.3.1). The discount rates used in the cost calculation reflect real public sector discount rates (for a discussion of discount rates, see Chapter 7, Section 7.2.4). Generally, the discount rates in the quoted studies are in the range of 5%–12% per year. It should be noted that the discount rates used here are lower than those typically used in private sector decision making. This means that options reported in this chapter to have negative net costs will not necessarily be taken up by the market. Furthermore, it should be noted that in some cases even small specific costs may form a substantial burden for companies.

3.2 Drivers of Technological Change and Innovation

Reduction of greenhouse gas emissions is highly dependent upon both technological innovation and practices. The rate of introduction of new technologies, and the drivers for adoption are, however, different in industrial market economies, economies in transition and developing countries.

In industrial countries, technologies are developed as a result of corporate innovation or government-supported R&D, and in response to environmental regulations, energy tax policies, or other incentives. The shift of electric and gas utilities from regulated monopolies to competing enterprises has also played a major role in the strong shift to combined cycle gas turbines, often with utilization of the waste heat in the electric power sector.

The most rapid growth in the electric power sector and many energy intensive industries is now occurring in developing countries, which have come to rely heavily upon technology transfer for investments in energy infrastructure. Capital for investment flows from industrial countries to developing countries through several pathways such as multilateral and bilateral official development assistance (ODA), foreign direct investments (FDI), commercial sales, and commercial and development bank lending. During the period 1993 to 1997, ODA experienced a downward trend with an increase in 1998, while FDI has increased substantially by a factor of five (see *Figure 3.3*) (OECD, 1999; Metz *et al*., 2000). This shift is a consequence of the many opportunities that have opened for private capital in developing countries, and a reluctance by some industrial countries to increase ODA. The energy supply sector of developing countries is also undergoing deregulation from state to private ownership, increasing the role of the private sector in technology innovation.

A large percentage of capital is invested in a relatively small number of technologies that are responsible for a significant share of the energy supply and consumption market (automobiles, electric power generators, and building heating and cooling systems). There is a tendency to optimize these few technologies and their related infrastructure development, gaining them advantages that will make it more difficult for subsequent competing technologies to catch up. For example, a particular technological configuration such as road-based automobiles can become "locked-in" as the dominant transportation mode. This occurs because evolution of technological systems is as important as the evolution of individual new technologies. As their use expands their development becomes intertwined with the evolution of many other technologies and institutional and social developments. The evolution of technologies for oil exploration and extraction and for automobile production both affect and are affected by the expansion of infrastructures such as efficient refineries and road networks. They also affect and are affected by social and institutional developments, such as political and military power and settlement patterns, and business adaptation to changed transportation options, respectively.

Lock-in effects have two implications. First, early investments and early applications are extremely important in determining which technologies will be most important in the future. Second, learning and lock-in make technology transfer more difficult. Learning is much more dependent on successful building and using technology than on instruction manuals. Furthermore, technological productivity is strongly dependent upon complementary networks of suppliers, repair persons and

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[5] Levelized costs include capital costs, operation and maintenance costs, fuel costs, *etc*.

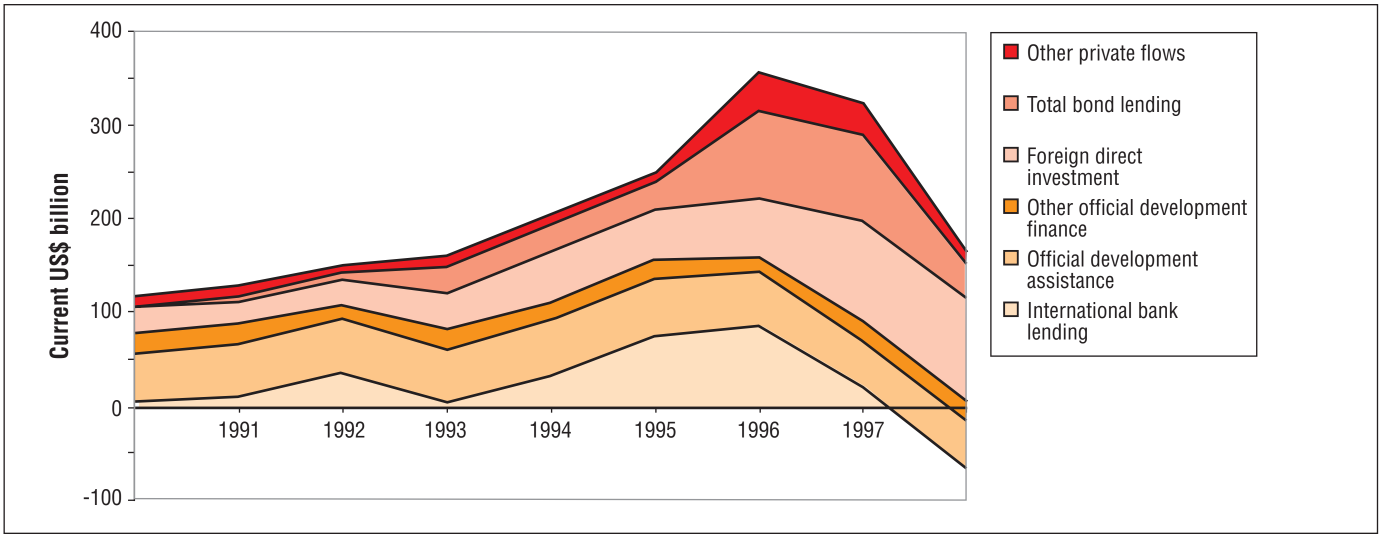

Figure 3.3: *Total net resource flows to aid recipient countries.*

training which is difficult to replicate in another country or region (IIASA/WEC, 1998; Unruh, 1999, 2000).

There are multiple government-driven pathways for technological innovation and change. Through regulation of energy markets, environmental regulations, energy efficiency standards, and market-based initiatives such as energy and emission taxes, governments can induce technology changes and influence the level of innovations. Important examples of government policies on energy supply include the Clean Air Act in the USA, the Non Fossil Fuel Obligation in the UK, the Feed-in-Law in Germany, the Alcohol Transport Fuel Program in Brazil, and utility deregulation that began in the UK and has now moved to the USA, Norway, Argentina, and many other countries. Voluntary agreements or initiatives implemented by the manufacturing industry, including energy supply sections, can also be drivers of technological change and innovation.

In the energy-consuming sector, major government actions can promote energy efficient use and the replacement of high (like coal) to lower carbon fuels (like natural gas and renewables). Energy efficiency standards for vehicles, appliances, heating and cooling systems, and buildings can also substantially encourage the adoption of new technologies. On the other hand, continued subsidies for coal and electricity, and a failure to properly meter electricity and gas are substantial disincentives to energy efficiency gains and the uptake of renewable and low carbon technologies. Government-supported R&D has also played a significant role in developing nuclear power, low carbon technologies such as gas turbines, and carbon-free energy sources including wind, solar, and other renewables. Such government actions in the energy-consuming sector can ensure increasing access to energy required for sustainable development.

While regulation in national energy markets is well established, it is unclear how international efforts at GHG emission regulation may be applied at the global level. The Kyoto Protocol and its mechanisms represent opportunities to bring much needed energy-efficient practices and alternative energy to the continuously growing market of developing countries and in reshaping the energy markets of the economies in transition.

Important dimensions and drivers for the successful transfer of lower GHG technologies to developing countries and economies in transition are capacity building, an enabling environment, and adequate mechanisms for technology transfer (Metz *et al*., 2000). Markets for the use of new forms of energy are often non-existent or very small, and require collaboration among the local government and commercial or multilateral lending banks to promote procurement. It may also be necessary to utilize temporary subsidies and market-based incentives as well. Because energy is such a critical driver of development, it is essential that strategies to reduce GHG emissions be consistent with development goals. This is true for all economies, but is especially true for developing countries and economies in transition where leap-frogging to modern, low emitting, highly efficient technologies is critical (Moomaw *et al*., 1999a; Goldemberg, 1998).

Non-energy benefits are an important driver of technological change and innovation (Mills and Rosenfeld, 1996; Pye and McKane, 2000). Certain energy-efficient, renewable, and distributed energy options offer non-energy benefits. One class of such benefits accrues at the national level, e.g. via improved competitiveness, energy security, job creation, environmental protection, while another relates to consumers and their decision-making processes. From a consumer perspective, it is often the non-energy benefits that motivate decisions to adopt such technologies. Consumer benefits from energy-efficient technologies can be grouped into the following categories: (1) improved indoor environment, comfort, health, safety, and productivity; (2) reduced noise; (3) labour and time savings; (4)

improved process control; (5) increased reliability, amenity or convenience; (6) water savings and waste minimization; and (7) direct and indirect economic benefits from downsizing or elimination of equipment. Such benefits have been observed in all end-use sectors. For renewable and distributed energy technologies, the non-energy benefits stem primarily from reduced risk of business interruption during and after natural disasters, grid system failures or other adverse events in the electric power grid (Deering and Thornton, 1998).

Product manufacturers often emphasize non-energy benefits as a driver in their markets, e.g. the noise- and UV-reduction benefits of multi-glazed window systems or the disaster-recovery benefits of stand-alone photovoltaic technologies. Of particular interest are attributes of energy-efficient and renewable energy technologies and practices that reduce insurance risks (Mills and Rosenfeld, 1996). Approximately 80 specific examples have been identified with applications in the buildings and industrial sectors (Vine *et al.*, 1998), and insurers have begun to promote these in the buildings sector (Mills, 1999). The insurance sector has also supported transportation energy efficiency improvements that increase highway safety (reduced speed limits) and urban air quality (mass transportation) (American Insurance Association, 1999). Insurance industry concern about increased natural disasters caused by global climate change also serves as a motivation for innovative market transformation initiatives on behalf of the industry to support climate change adaptation and mitigation (Mills 1998, 1999; Vellinga *et al.*, 2000; Nutter, 1996). Market benefits for industries that adopt low carbon- emitting processes and products have also been increasingly recognized and documented (Hawken *et al.*, 1999; Romm, 1999).

3.3 Buildings

3.3.1 Introduction

This section addresses greenhouse gas emissions and emissions reduction opportunities for residential and commercial (including institutional) buildings, often called the residential and service sectors. Carbon dioxide emissions from fossil fuel energy used directly or as electricity to power equipment and condition the air (including both heating and cooling) within these buildings is by far the largest source of greenhouse gas emissions in this sector. Other sources include HFCs from the production of foam insulation and for use in residential and commercial refrigeration and air conditioning, and a variety of greenhouse gases produced through combustion of biomass in cookstoves.

3.3.2 Summary of the Second Assessment Report

The Second Assessment Report (SAR) reviewed historical energy use and greenhouse gas emissions trends as well as mitigation options in the buildings sector in Chapter 22, Mitigation Options for Human Settlements (Levine *et al.*, 1996a). This chapter showed that residential and commercial buildings accounted for 19% and 10%, respectively, of global carbon dioxide (CO_2) emissions from the use of fossil fuels in 1990. More recent estimates increase this percentage to 21% for residential buildings and 10.5% for commercial buildings, both for 1990 and 1995, as shown in *Table 3.1*. Globally, space heating is the dominant energy end-use in both residential and commercial buildings. Developed countries account for the vast majority of buildings-related CO_2 emissions, but the bulk of growth in these emissions over the past two decades was seen in developing countries. The SAR found that many cost-effective technologies are available to reduce energy-related CO_2 emissions, but that consumers and decision-makers often do not invest in energy efficiency for a variety of reasons, including existing economic incentives, levels of information, and conditions in the market. The SAR concluded that under a scenario with aggressive adoption of energy-efficiency measures, cost-effective energy efficiency could likely cut projected baseline growth in carbon emissions from energy use in buildings by half over the next two decades.

3.3.3 Historic and Future Trends

CO_2 from energy use is the dominant greenhouse gas emitted in the buildings sector, followed by HFCs used in refrigeration, air conditioning, and foam insulation, and cookstove emissions of methane and nitrous oxide (see *Table 3.2*). Developed countries have the largest emissions of CO_2 and HFCs, while developing countries have the largest emissions of greenhouse gases from non-renewable biomass combustion in cookstoves (Smith *et al.*, 2000). It is noted, however, that the biomass energy source is being replaced with non-renewable carbon-based fuels (Price *et al.*, 1998). This trend is expected to continue.

Energy use in buildings exhibited a steady growth from 1971 through 1990 in all regions of the world, averaging almost 3% per year. Because of the decline in energy use in buildings in the former Soviet Union after 1989, global energy use in buildings has grown slower than for other sectors in recent years. Growth in commercial buildings was higher than growth in residential buildings in all regions of the world, averaging 3.5% per year globally between 1971 and 1990. Energy-related CO_2 emissions also grew during this period. By 1995, CO_2 emissions from fuels and electricity used in buildings reached 874MtC and 858MtC, respectively, for a total of 1732MtC, or 98% of all buildings-related GHG emissions. Growth in these CO_2 emissions was slower than the growth in primary energy in both the developed countries and the rest-of-world region, most likely the result of fuel switching to lower carbon fuels in these regions. In contrast, growth in energy-related CO_2 emissions in the developing countries — Asia Pacific region — was 6.3% per year between 1971 and 1995, greater than the 5.5% per year growth in primary energy use, reflecting a growing reliance on more carbon-intensive fuels in this region.[6]

Table 3.2: *Overview of 1995 greenhouse gas emissions in the buildings sector (in MtC) by region*
(Price *et al*., 1998, 1999; Smith *et al*., 2000).

Greenhouse gas source	Developed Countries	Countries with Economies in Transition	Developing Countries in Asia-Pacific	Rest of World	Total
Fuel CO_2	397	235	167	75	874
Electricity CO_2[a]	561	85	125	87	858
Refrigeration, A/C, foam insulation HFCs					45[b]
Biomass cookstove CH_4					40[c]
Total					1817

a CO_2 emissions from production of electricity.

b Based on an estimated range of 47 to 50MtC in the year 2000 (see Appendix to this Chapter).

c Based on an estimate of global annual emissions of 7 Tg of CH_4. Estimates for N_2O emissions from biomass cookstoves are not available (Smith *et al*., 2000).

Non-CO_2 greenhouse gas emissions from the buildings sector are hydrofluorocarbons (HFCs)[7] used or projected to be used in residential and commercial refrigerators, air conditioning systems, and in open and closed cell foam for insulation. HFCs in the building sector were essentially zero in 1995, but are projected to grow as they replace ozone-depleting substances (see Appendix to this chapter). In addition, methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), and nitrogen oxides (NO_x) (along with CO_2) are produced through combustion of biomass in cookstoves (Levine *et al*., 1996b; Smith *et al*., 2000). It is estimated the biomass cookstoves emit about 40MtC_{eq}, 2% of total buildings-related GHG emissions (Smith *et al*., 2000). These emissions are concentrated in developing countries, where biomass fuels can account for more than 40% of the total energy used in residences (UNDP, 1999).[8]

Key drivers of energy use and related GHG emissions in buildings include activity (population growth, size of labour force, urbanization, number of households, per capita living area, and persons per residence), economic variables (change in GDP and personal income), energy efficiency trends, and carbon intensity trends. These factors are in turn driven by changes in consumer preferences, energy and technology costs, settlement patterns, technical change, and overall economic conditions.

Urbanization, especially in developing countries, is clearly associated with increased energy use. As populations become more urbanized and commercial fuels, especially electricity, become easier to obtain, the demand for energy services such as refrigeration, lighting, heating, and cooling increases. The number of people living in urban areas almost doubled between 1970 and 1995, growing from 1.36 billion, or 37% of the total, in 1970 to 2.57 billion, or 45% of the total, in 1995 (UN, 1996).

Driving forces influencing the use of HFCs include both its suitability as a replacement for CFCs and HCFCs, as well as an awareness of the contribution of HFCs to global climate change. It is expected that this awareness will continue to drive decisions to use HFCs only in highest value applications. Some countries have enacted regulations limiting emissions of HFCs while others have established voluntary agreements with industry to reduce HFC use (see Appendix to this chapter).

Global projections of primary energy use for the buildings sector show a doubling, from 103EJ to 208EJ, between 1990 and 2020 in a baseline scenario (WEC, 1995a). The most rapid growth is seen in the commercial buildings sector, which is projected to grow at an average rate of 2.6% per year. Increases in energy use in the EITs are projected to be as great as those in the developing countries, as these countries recover from the economic crises and as the growth in developing countries begins to slow. Under a scenario where state-of-the-art technology is adopted, global primary energy consumption in the buildings sector will only grow to about 170EJ in 2020. A more aggressive "ecologically driven/advanced technology" scenario, which assumes an international commitment to energy efficiency as well as rapid technological progress and widespread application of policies and programmes to speed the adoption of energy-efficient technologies in all major regions of the world, results in primary energy use of 140EJ in 2020 (WEC, 1995a).

The IPCC's IS92a scenario projected baseline global carbon dioxide emissions from the buildings sector to grow from 1900 MtC to 2700MtC between 1990 and 2020. An analysis of the

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[6] Trends in primary energy use and CO_2 emissions in the EIT region cannot be compared because these values are from two different data sources (see Price *et al*., 1998).

[7] HFCs are used as a replacement gas for chlorofluorocarbons (CFCs) which are being phased out globally under the Montreal Protocol on Substances that Deplete the Ozone Layer.

[8] For example, traditional fuels based on biomass account for a large share of residential energy consumption in Nicaragua (43%), El Salvador (44%), Honduras (50%), Paraguay (51%), Guatemala (61%) and Haiti (87%) (UNDP, 1999).

potential reductions from implementation of energy-efficient technologies found that annual global carbon dioxide emissions from the buildings sector could be reduced by an estimated 950MtC in 2020 compared to the IS92a baseline scenario (Acosta Moreno *et al*., 1996). Over 60% of these projected savings are realized through improvements in residential equipment and the thermal integrity of buildings globally. Carbon dioxide emissions from commercial buildings grow from 37% to 41% of total buildings emissions between 1990 and 2020 as a result of expected increases in commercial floor space (which implies increases in heating, ventilation, and air conditioning systems (HVAC)) as well as increased use of office and other commercial sector equipment (Acosta Moreno *et al*., 1996; WEC, 1995a).

The B2 scenario from the IPCC's Special Report on Emissions Scenario projects buildings sector carbon dioxide emissions to grow from 1,790MtC in 1990 to 3,090MtC in 2020. The most rapid growth is seen in the developing countries, which show an average growth in buildings-related carbon dioxide emissions of over 3% per year. In contrast, this scenario envisions that the emissions from buildings in the EIT region continue to decline, at an average annual rate of –1.3% (Nakicenovic *et al*., 2000).

3.3.4 New Technological and Other Options

There are myriad opportunities for energy efficiency improvement in buildings (Acosta Moreno *et al*., 1996; Interlaboratory Working Group, 1997; Nadel *et al*., 1998) (see *Table 3.3*). Most of these technologies and measures are commercialized but are not fully implemented in residential and commercial buildings, while some have only recently been developed and will begin to penetrate the market as existing buildings are retrofitted and new buildings are designed and constructed.

A recent study identified over 200 emerging technologies and measures to improve energy efficiency and reduce energy use in the residential and commercial sectors (Nadel *et al*., 1998). Individual country studies also identify many technologies and measures to improve the energy efficiency and reduce greenhouse gas emissions from the buildings sector in particular climates and regions.[9] For example, a study for South Africa discusses 15 options for the residential sector and 11 options for the commercial sector (Roos, 2000). Examples of other studies that identify energy efficiency or greenhouse gas mitigation options for the buildings sector include those for Brazil (Schaeffer and Almeida, 1999), Bulgaria (Tzvetanov *et al*, 1997), Canada (Bailie *et al*., 1998); China (Research Team of China Climate Change Country Study, 1999); Czech Republic (Tichy, 1997), the European Union (Blok *et al*., 1996; van Velsen *et al*., 1998), India (Asian Development Bank, 1998), Indonesia (Cahyono Adi *et al*., 1997), Mexico (Mendoza *et al*., 1991), Poland (Gaj and Sadowski, 1997); Ukraine (Raptsoun and Parasyuk, 1997), and the US (Interlaboratory Working Group, 1997; National Laboratory Directors, 1997; STAPPA/ALAPCO, 1999). Below examples are given of three new developments out of many that could be cited: integrated building design, reducing standby power losses in appliances and equipment, and photovoltaic systems for residential and commercial buildings. These examples focus on options for reducing greenhouse gas emissions from the buildings sector in which there has been significant recent research: improving the building shell, improving building equipment and appliances, and switching to lower carbon fuels to condition the air and power the equipment and appliances in buildings. In addition, recent developments in distributed power generation for buildings are briefly described (see also Section 3.8.5.3).

3.3.4.1 Integrated Building Design

Integrated building design focuses on exploiting energy-saving opportunities associated with building siting as well as synergies between building components such as windows, insulation, equipment, and heating, air conditioning, and ventilation systems. Installing increased insulation and energy-efficient windows, for example, allows for installation of smaller heating and cooling equipment and reduced or eliminated ductwork.[10] Most importantly, it will become possible in the future to design a building where operation can be monitored, controlled, and faults detected and analyzed automatically. For large commercial buildings, such systems (which are currently under development) have the potential to create significant energy savings as well as other operational benefits. Two recent projects that used integrated building design for residential construction found average energy savings between 30% and 60% per cent (Elberling and Bourne, 1996; Hoeschele *et al*., 1996; Parker *et al*., 1996), while for commercial buildings energy savings have varied between 13% and 71% (Piette *et al*., 1996; Hernandez *et al*., 1998; Parker *et al*., 1997; Thayer, 1995; Suozzo and Nadel, 1998). Assuming an average savings of 40% for integrated building design, the cost of saved energy for residential and commercial buildings has been calculated to be around US$3/GJ (the average cost of energy in the US buildings sector is about US$14/GJ) (Nadel *et al*., 1998; US DOE/EIA, 1998).

3.3.4.2 Reducing Standby Power Losses in Appliances and Equipment

Improving the energy efficiency of appliances and equipment can result in reduced energy consumption in the range of 10 to 70%, with the most typical savings in the 30% to 40% range (Acosta Moreno *et al*., 1996; Turiel *et al*., 1997).

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[9] Many countries provide a discussion of these technologies and measures in their National Communications to the UNFCCC (http://www.unfccc.int/text/resource/natcom/).

[10] It is noted that production of these efficient products increases energy use for materials production in the industrial sector (Gielen, 1997).

Table 3.3: *Overview of opportunities for energy efficiency improvement in buildings*
(Acosta Moreno *et al*., 1996; Interlaboratory Working Group, 1997; Nadel *et al*., 1998; Suozzo and Nadel, 1998).

End use	**Energy efficiency improvement opportunities**
Insulation	Materials for buildings envelopes (e.g., walls, roofs, floors, window frames); materials for refrigerated spaces/cavities; materials for highly heated cavities (e.g., ovens); solar reflecting materials; solar and wind shades (e.g., vegetation, physical devices); controls; improved duct sealing
Heating, ventilation, and air conditioning (HVAC) systems	Condensing furnaces; electric air-source heat pumps; ground-source heat pumps; dual source heat pumps; Energy Star residential furnaces and boilers; high efficiency commercial gas furnaces and boilers; efficient commercial and residential air conditioners; efficient room air conditioners; optimization of chiller and tower systems; desiccant coolers for supermarkets; optimization of semiconductor industry cleanroom HVAC systems; controls (e.g., economizers, operable windows, energy management control systems); motors; pumps; chillers; refrigerants; combustion systems; thermal distribution systems; duct sealing; radiant systems; solar thermal systems; heat recovery; efficient wood stoves
Ventilation systems	Pumps; motors; air registers; thermal distribution systems; air filters; natural and hybrid systems
Water heating systems	High efficiency electric resistance water heaters; water heaters; air-source heat pump water heaters; exhaust air heat pump water heaters; integrated space/water heating systems; integrated gas-fired space/water heating systems, high efficiency gas water heaters; instantaneous gas water heaters; solar water heaters; low-flow showerheads
Refrigeration	Efficient refrigerators; high efficiency freezers; commercial refrigeration technologies
Cooking	Improved biomass stoves; efficient wood stoves; Turbochef combination microwave/convection oven; high efficiency gas cooking equipment
Other appliances	Horizontal axis washing machine; increase washing machine spin speed; heat pump clothes dryer; efficient dishwashers; consumer electronics with standby losses less than 1 watt; consumer electronics with efficient switch-mode power supplies
Windows	Double and triple-glazed windows; low-emittance windows; spectrally selective windows; electrochromic windows
Lighting systems	Compact fluorescents (including torchères); halogen IR lamps; electronic ballasts; efficient fluorescents and fixtures; HIDs, LED exit signs; LED traffic lights; solid state general purpose lighting (LEDs and OLEDs); lighting controls (including dimmers); occupancy controls; lighting design (including task lighting, reducing lighting levels);daylighting controls; replacement of kerosene lamps
Office equipment	Efficient computers; low-power mode for equipment; LCD screens
Motors	Variable speed drives; high efficiency motors; integrated microprocessor controls in motors; high quality motor repair practices
Energy management	Buildings energy management systems; advanced energy management systems; commercial building retro-commissioning
Design	Integrated building design; prefabricated buildings; solar design (including heat or cold storage); orientation; aspect ratio; window shading; design for monitoring; urban design to mitigate heat islands; high reflectance roof surfaces
Energy sources	Off-grid photovoltaic systems; cogeneration systems

Implementation of advanced technologies in refrigerator/freezers, clothes washers, clothes dryers, electric water heaters, and residential lighting in the US is estimated to save 3.35EJ/yr by 2010, reducing energy use of these appliances by nearly 50% from the base case (Turiel *et al*., 1997).

A number of residential appliances and electronic devices, such as televisions, audio equipment, telephone answering machines, refrigerators, dishwashers, and ranges consume electricity while in a standby or off mode (Meier *et al*., 1992; Herring, 1996; Meier and Huber, 1997; Molinder, 1997; Sanchez, 1997). These standby power losses are estimated to consume 12% of Japanese residential electricity, 5% of US residential electricity, and slightly less in European countries (Nakagami *et al*., 1997; Meier *et al*., 1998). Metering studies have shown that such standby losses can be reduced to one watt in most of these mass-produced goods (Meier *et al*., 1998). The costs of key low-loss technologies, such as more efficient switch-mode power supplies and smarter batteries, are low (Nadel *et al*., 1998) and a recent study found that if all US appliances were replaced by units meeting the 1-watt target, aggregate standby losses would fall at least 70%, saving the USA over US$2 billion annually (Meier *et al*., 1998).

Table 3.4: *Buildings sector 1995 fuel, electricity, primary energy, CO_2 emissions, and average annual growth rates (AAGRs) for 1971 to 1990 and 1990 to 1995 by region*
(Price *et al*., 1998, 1999).

	Fuels			**Electricity**			**Primary energy**			**CO_2 emissions**		
	1995 Energy (EJ)	AAGR 1971-1990	AAGR 1990-1995	1995 Energy (EJ)	AAGR 1971-1990	AAGR 1990-1995	1995 Energy (EJ)	AAGR 1971-1990	AAGR 1990-1995	1995 CO_2 (MtC)	AAGR 1971-1990	AAGR 1990-1995
Developed Countries	25.45	-0.7%	0.7%	14.21	4.5%	2.7%	68.51	1.8%	1.9%	958.46	0.8%	0.9%
Countries with Economies in Transition	11.98	3.4%	-6.4%	1.39	6.6%	-7.9%	16.19	4.1%	-6.8%	319.83	2.3%	-3.0%
Developing Cos. In Asia-Pacific	7.34	4.3%	1.5%	1.85	10.4%	10.5%	12.93	5.7%	4.8%	291.62	6.7%	4.7%
Rest of World	5.14	6.2%	0.5%	2.31	8.2%	6.7%	12.15	7.1%	3.8%	162.32	6.0%	5.3%
World	49.91	1.3%	-1.2%	19.76	5.3%	2.6%	109.78	2.9%	0.8%	1732.23	2.0%	1.0%

Note: Data sources are IEA, 1997a; IEA, 1997b, IEA, 1997c and BP, 1997. For the EIT region only, energy data from British Petroleum were used instead of IEA data. Thus, primary energy and CO_2 emissions for the EIT region cannot be compared. For a more detailed description of the data, see Price *et al*., 1998, 1999.

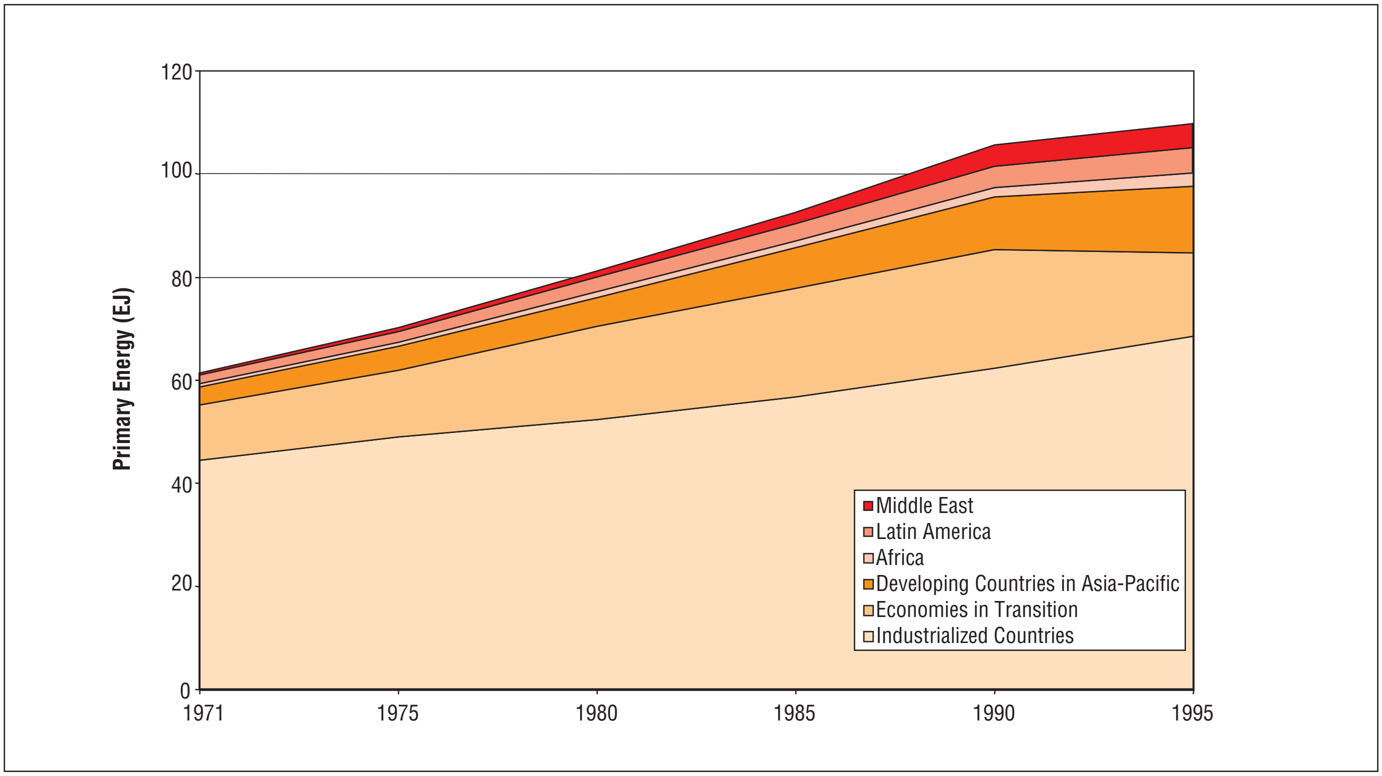

Figure 3.4: *Primary energy use in the buildings sector, 1971-1995.*

3.3.4.3 Photovoltaic Systems for Buildings

Photovoltaic systems are being increasingly used in rural off-grid locations, especially in developing countries, to provide electricity to areas not yet connected to the power infrastructure or to offset fossil fuel generated electricity. These systems are most commonly used to provide electricity for lighting, but are also used for water pumping, refrigeration, evaporative cooling, ventilation fans, air conditioning, and powering various electronic devices. In 1995, more than 200,000 homes worldwide depended on photovoltaic systems for all of their electricity needs (US DOE, 1999a). Between 1986 and 1998, global PV sales grew from 37MW to 150MW (US DOE, 1999b). Rural electrification programmes have been established in many developing countries. In Brazil, more than 1000 small stand-alone systems that provide power for lighting, TVs, and radios were recently installed in homes and schools, while two hybrid (PV-wind-battery) power systems were installed in the Amazon Basin to reduce the use of diesel generators that supply power to more than 300 villages in that area (Taylor, 1997). Similar projects have been initiated in South Africa (Arent, 1998), Egypt (Taylor and Abulfotuh, 1997), India (Stone and Ullal, 1997; US DOE, 1999b), Mexico (Secretaria de Energia, 1997), China, Indonesia, Nepal, Sri Lanka, Vietnam, Uganda, Solomon Islands, and Tanzania (Williams, 1996). Recent developments promoting increased adoption of photovoltaic systems include the South African Solar Rural Electrification Project (Shell International, 1999), the US Million Solar Roofs Initiative (US DOE, 1999a), the effort to install 5000MW on residences in Japan by 2010 (Advisory Committee for Energy, 1998), and net metering, which allows the electric meters of customers with renewable energy generating facilities to be reversed when the generators are producing energy in excess of residential requirements (US DOE, 1999b).

3.3.4.4 Distributed Power Generation for Buildings

Distributed power generation relies on small power generation or storage systems located near or at the building site. Several small scale (below 500kW), dispersed power-generating technologies are advancing quite rapidly. These technologies include both renewable and fossil fuel powered alternatives, such as photovoltaics and microturbines. Moving power generation closer to electrical end-uses results in reduced system electrical losses, the potential for combined heat and power applications (especially for building cooling), and opportunities to better co-ordinate generation and end-use, which can together more than compensate for the lower conversion efficiency and result in overall energy systems that are both less expensive and emit less carbon dioxide than the familiar central power generating station. The likelihood of customer sites becoming net generators will be determined by the configuration of the building and/or site, the opportunities for on-site use of cogenerated heat, the availability and relative cost of fuels, and utility interconnection, environmental, building code, and other regulatory restrictions (NRECA, 2000).

3.3.5 ***Reginal Differences***

There are significant regional differences in levels of energy use and related GHG emissions from the buildings sector. *Table 3.4* presents 1995 buildings sector's fuels, electricity, primary energy, and CO_2 emissions and historical growth rates for the 1971 to 1990 and 1990 to 1995 periods for four regions (Price *et al*., 1998, 1999). *Figure 3.4* provides a graphical presentation of the data on primary energy use in buildings, with the fourth region (Rest of World) desegregated into Middle East, Latin America, and Africa. Three very important trends are apparent:

- Developed countries have by far the largest CO_2 emissions from the buildings sector and have exhibited a relatively steady long-term trend of annual primary energy growth in the 1.8% to 1.9% range (with lower growth through 1985 and higher growth thereafter).
- Since the late 1980s, energy use and related CO_2 emissions from buildings in the developing countries, particularly in the Asia–Pacific region, have grown about five times as fast as the global average (and more than twice as fast as in developed countries).
- The growth rate of buildings' energy use globally has declined since 1990 because of the economic crisis in the EITs. The world other than the EITs continued its long-term trend (1971-1995) of annual energy growth in the 2.8% to 2.9% range.

The average annual increase in urban population was nearly 4.0% per year in Asia and Rest of World regions. This increased urbanization led to increased use of commercial fuels, such as kerosene and liquefied petroleum gas (LPG), for cooking instead of traditional biomass fuels. In general, higher levels of urbanization are associated with higher incomes and increased household energy use, including significantly increased purchase and use of a variety of household appliances (Sathaye *et al*., 1989; Nadel *et al*., 1997, Sathaye and Ketoff, 1991). Wealthier populaces in developing countries exhibit consumption patterns similar to those in developed countries, where purchases of appliances and other energy-using equipment increase with gains in disposable income (WEC, 1995a).

Between 1971 and 1990, global primary energy use per capita in the buildings sector grew from 16.5GJ/capita to 20GJ/capita. Per capita energy use in buildings varied widely by region, with the developed and EIT regions dominating globally. Energy use per capita is higher in the residential sector than in the commercial sector in all regions, although average annual growth in commercial energy use per capita was higher during the period, averaging 1.7% per year globally compared to 0.6% per year for the residential sector.

Energy consumption in residential buildings is strongly correlated with household income levels. Between 1973 and 1993, increases in total private consumption translated into larger homes, more appliances, and an increased use of energy services (water heating, space heating) in most developed countries (IEA, 1997d). In developed countries, household floor area increased but household size dropped from an average of 3.5 persons per household in 1970 to 2.8 persons per household in 1990. These trends led to a decline in energy use per household but increased residential energy use per capita (IEA, 1997d).

In the commercial sector, the ratio of primary energy use to total GDP as well as commercial sector GDP fell in a number of developed countries between 1970 and the early 1990s. This decrease, primarily a result of increases in energy efficiency, occurred despite large growth in energy-using equipment in commercial buildings, almost certainly the result of improved equipment efficiencies. Growth in electricity use in the commercial sector shows a relatively strong correlation with the commercial sector GDP (IEA, 1997d).

Space heating is the largest end-use in the developed countries as a whole and in the EIT region (Nadel *et al*., 1997), although not as important in some developed countries with a warm climate. The penetration of central heating doubled from about 40% of dwellings to almost 80% of dwellings in many developed countries between 1970 and 1992 (IEA, 1997d). District heating systems are common in some areas of Europe and in the EIT region. Space heating is not common in most developing countries, with the exception of the northern half of China, Korea, Argentina, and a few other South American countries (Sathaye *et al*., 1989). Residential space heating energy intensities declined in most developed countries (except Japan) between 1970 and 1992 because of reduced heat losses in buildings, lowered indoor temperatures, more careful heating practices, and improvements in energy efficiency of heating equipment (IEA, 1997d; Schipper *et al*., 1996).

Water heating, refrigeration, space cooling, and lighting are the next largest residential energy uses, respectively, in most developed countries (IEA, 1997d). In developing countries, cooking and water heating dominate, followed by lighting, small appliances, and refrigerators (Sathaye and Ketoff, 1991). Appliance penetration rates increased in all regions between 1970 and 1990. The energy intensity of new appliances declined over the past two decades; for example, new refrigerators in the US were 65% less energy-intensive in 1993 than in 1972, accounting for differences in size or performance (IEA, 1997d; Schipper *et al*., 1996). Electricity use and intensity (MJ/m^2) increased rapidly in the commercial buildings sector as the use of lighting, air conditioning, computers, and other office equipment has grown. Fuel intensity (PJ/m^2) declined rapidly in developed countries as the share of energy used for space heating in commercial buildings dropped as a result of thermal improvements in buildings (Krackeler *et al*., 1998). Fuel use declined faster than electricity consumption increased, with the result that primary energy use per square meter of commercial sector floor area gradually declined in most developed countries.

The carbon intensity of the residential sector declined in most developed countries between 1970 and the early 1990s (IEA, 1997d). In the service sector, carbon dioxide emissions per square meter of commercial floor area also dropped in most developed countries during this period in spite of increasing carbon intensity of electricity production in many countries (Krackeler *et al*., 1998). In developing countries, carbon intensity of both the residential and commercial sector is expected to continue to increase, both as a result of increased demand for energy services and the continuing replacement of biomass fuels with commercial fuels (IEA, 1995).

3.3.6 Technological and Economic Potential

An estimate of the technological and economic potential of energy efficiency measures was recently prepared for the IPCC (Acosta Moreno *et al*., 1996).[11] This analysis provides an estimate of energy efficiency potential for buildings on a global basis. Using the B2 Message marker scenario (Nakicenovic *et al*., 2000) as the base case,[12] the analysis indicates an overall technical and economic potential for reducing energy-related CO_2 emissions in the buildings sector of 715MtC/yr in 2010 for a base case with carbon emissions of 2,600MtC/yr (27%), of 950MtC/yr in 2020 for a base case with carbon emissions of 3,000MtC/yr (31%), and of 2,025MtC/yr in 2050 for a base case with carbon emissions of 3,900MtC/yr (52%) (see Table 3.5).[13] It is important to note that the availability of technologies to achieve such savings cost-effectively depends critically on significant R&D efforts.

Estimates of the ranges of costs of carbon reductions are based on a synthesis of recent studies of costs (Brown *et al*., 1998); these estimates are similar to those provided in an International Energy Agency Workshop on Technologies to Reduce Greenhouse Gas Emissions (IEA, 1999a). The qualitative rankings for the reductions in carbon emissions follow the results of the IPCC Technical Paper (Acosta Moreno *et al*., 1996). In general, it is assumed that costs are initially somewhat higher in developing countries because of the reduced availability of advanced technology and the lack of a sufficient delivery infra-

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[11] The review of more recent information bearing on the technical and economic potential of energy efficiency measures gives no reason to change the earlier estimate in the IPCC technical paper (see, for example, Brown *et al*., 1998; de Almeida and Fonseca, 1999; Jochem, 1999; Kainuma *et al*., 1999a; Lenstra, 1999; Levine *et al*, 1996; Schaeffer and Almeida, 1999; Sheinbaum *et al*., 1998; Urge-Vorsatz and Szesler, 1999; Zhou, 1999).

[12] The original analysis was based on the IS92a scenario. From the set of IPCC SRES scenarios, for the period covered in this chapter (up to 2020), scenario B2 most resembles baseline scenarios with the low levels of technology introduction used in the literature assessed here.

[13] Of the efficiency measures that are technically and economically feasible, the IPCC report estimated that between 35% and 60% could be adopted in the market through known and established policy approaches.

Table 3.5: *Technical and economic potential for reducing energy-related carbon dioxide emissions from the buildings sector* (Acosta Moreno *et al*., 1996).

	Projected emissions reductions (MtC)			**Share of projected total emissions**		
	2010	**2020**	**2050**	**2010**	**2020**	**2050**
Developed Countries + EIT Region						
Residential	325	420	660	30%	35%	54%
Commercial	185	245	450	32%	38%	68%
Total	510	665	1110	31%	36%	59%
Developing Countries						
Residential	125	170	515	20%	21%	39%
Commercial	80	115	400	24%	26%	57%
Total	205	285	915	21%	23%	45%
World	715	950	2025	27%	31%	52%

Note: Projected total emissions based on B2 Message marker scenario (standardized) (Nakicenovic *et al*., 2000).

structure. However, depending upon conditions in the country or region, these high costs could be offset by the fact that there are many more low-cost opportunities to improve energy efficiency in most developing countries.

These studies show that with aggressive implementation of energy-efficient technologies and measures, CO_2 emissions from residential buildings in 2010 can be reduced by 325MtC in developed countries and the EIT region at costs ranging from –US$250 to –US$150/tC saved and by 125MtC in developing countries at costs of –US$200 to US$50/tC saved. Similarly, CO_2 emissions from commercial buildings in 2010 can be reduced by 185MtC in developed countries and the EIT region at costs ranging from –US$400 to –US$250/tC saved and by 80MtC in developing countries at costs ranging from -US$400 to US$0/tC saved.

3.3.7 Conclusions

Energy demand in buildings worldwide grew almost 3% per year from 1971 to 1990, dropping slightly after that as a consequence of the significant decrease in energy use in the EIT region. Growth in buildings energy use in all other regions of the world continued at an average rate of 2.5% per year since 1990. This growth has been driven by a wide variety of social, economic, and demographic factors. Although there is no assurance that these factors will continue as they have in the past, there is also no apparent means to modify most of the fundamental drivers of energy demand in residential and commercial buildings. However, there is considerable promise for improving the energy efficiency of appliances and equipment used in buildings, improving building thermal integrity, reducing the carbon intensity of fuels used in buildings, reducing the emissions of HFCs, and limiting the use of HFCs to those areas where appropriate. There are many cost-effective technologies and measures that have the potential to significantly reduce the growth in GHG emissions from buildings in both developing and developed countries by improving the energy performance of whole buildings, as well as reducing GHG emissions from appliances and equipment within the buildings.

3.4 Transport and Mobility

3.4.1 Introduction

This section addresses recent patterns and trends in greenhouse gas (GHG) emissions by the transport sector, and the technological and economic potential to reduce GHG emissions. The chapter focuses on areas where important developments have occurred since the SAR. It does not attempt to comprehensively present mitigation options for transport, as was done there (Michaelis *et al*., 1996). For a discussion of barriers and market potential with respect to advanced transportation technologies, the reader is referred to Chapter 5, especially Section 5.4.2. For a discussion of policies, measures and options, including behavioural strategies, the reader is referred to Chapter 6.

Recent successes with key future technologies for motor vehicles such as fuel cell power trains and advanced controls for air pollutants (carbon monoxide, hydrocarbons, oxides of nitrogen, and particulate matter) seem to promise dramatic changes in the way the transport sector uses energy and in its impacts on the environment. At the same time, the rapid motorization of transport around the world, the continued availability of low-cost liquid fossil fuels, and the recent trend of essentially constant fuel economy levels caused by demand for larger, more powerful vehicles, all point towards steadily increasing GHG emissions from transport in the near future (e.g., WEC, 1998a; Ogawa *et al*., 1998). These are challenges that must be met by the evolution of policies and institutions capable of managing environmentally beneficial change in an increasingly global economy.

3.4.2 Summary of the Second Assessment Report

The SAR's chapter 21, Mitigation Options in the Transportation Sector (Michaelis *et al*., 1996), provides an overview of global trends in transportation activity, energy intensities, and GHG emissions, along with a comprehensive review of economic, behavioural, and technological options for curtailing GHG emissions from the global transport sector. It concludes with an assessment of transport policies and their effects on GHG emissions. Its review of mitigation options for transportation demand management, modal structure, and alternative fuels, and its analysis of transport policies are still essentially up to date and are not repeated in this section.

Historically, transportation energy use and GHG emissions have increased because reductions in energy intensities have not kept pace with increasing transport activity. The world's motor vehicle fleet grew at an average annual rate of 4.5% from 1970 to 1990. Over the same period, light-duty vehicle fuel economy improved by 2% per year or less. Increases in vehicular fuel economy have also been accompanied by declining vehicle occupancy rates. It is noted below that the fuel economy of road passenger transport vehicles has levelled off since the publication of the SAR, and no longer appears to be improving. Air travel and truck freight activity have also grown more rapidly than energy intensities (energy use per passenger km) have declined. Since 1970, transport energy use and GHG emissions have grown at an average annual rate of 2.4%.

The SAR concluded that by 2010 it might be technically feasible to reduce energy intensities for new transport vehicles by 25% to 50% without reduction of performance or quality, by adopting a variety of fuel economy technologies. It noted that the economic potential would likely be smaller. The adoption of energy efficiency improvements throughout the sector was estimated to be able to reduce transportation energy use in 2025 by one-third versus projected levels.

The SAR also extensively reviewed the life cycle GHG emissions from alternative fuels and concluded that only fuels derived from biomass or electricity generated from substantially non-fossil sources could reduce life cycle GHG emissions by more than 20% versus conventional gasoline internal combustion engine vehicles. Compressed or liquefied natural gas and liquefied petroleum gases are capable of reducing full fuel cycle GHG emissions by 10% to 20% over gasoline-powered light-duty vehicles, but emissions would actually increase if these fuels were used to replace diesel engines in heavy-duty vehicles.

3.4.3 Historic and Future Trends

Since the publication of the SAR, important advances have been achieved in several areas of automotive technology. Among the most significant are: (1) two global automotive manufacturers are now selling hybrid automobiles 5-10 years ahead of what was anticipated just 5 years ago; (2) dramatic reductions have been made in fuel cell cost and size, such that several manufacturers have announced that they will introduce fuel cell vehicles by 2005, 10-20 years ahead of what was previously anticipated; and (3) improvements in fuels, engine controls, and emissions after-treatment led to the production of a gasoline internal combustion engine vehicle with virtually zero emissions of urban air pollutants. This achievement, combined with regulations requiring low-sulphur fuels, may foreshadow the development of acceptable emissions control systems for more energy efficient direct injection engines, although significant hurdles remain. It may also reduce the incentive for adopting alternative fuel vehicles, such as battery electric and natural gas vehicles, which can also have lower greenhouse gas emissions. These developments could have profound effects on future GHG emissions from road, rail, marine, and pipeline transport. Also, since the publication of the SAR, the IPCC has released a comprehensive report on the impacts of aviation on the global atmosphere (Penner *et al*., 1999) that includes a projection of expected progress in reducing energy intensity and GHG emissions from commercial air transport, and adds greatly to the information about aviation's effects on climate.

Worldwide, transport produces roughly 20% of carbon emissions and smaller shares of the other five greenhouse gasses covered under the Kyoto Protocol. According to IEA statistics, the transport sector's share of world GHG emissions increased from about 19% in 1971 to 22% in 1995 (Price *et al*., 1998) and 23% in 1997 (IEA, 1999c, p. II.67). Excluding emissions from vehicle air conditioners (described in the Appendix), CO_2 from combustion of fossil fuels is the predominant GHG

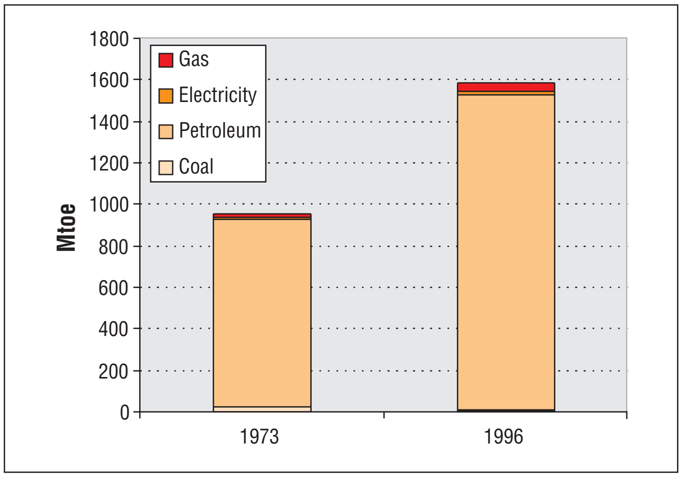

Figure 3.5: *World transportation energy use, 1973 and 1996.*

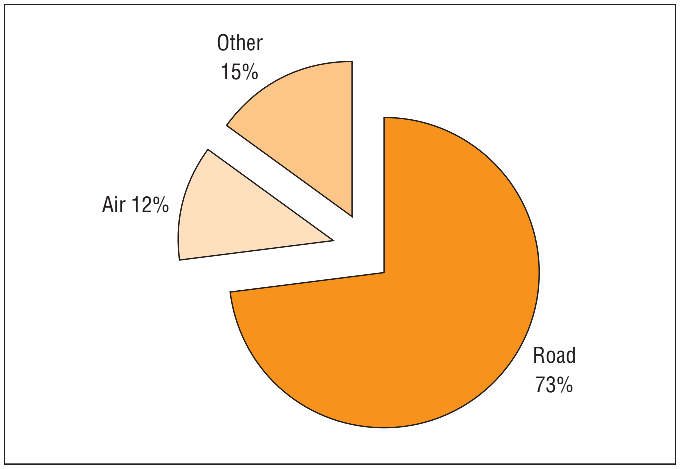

Figure 3.6: *World transport energy by mode, 1996.*

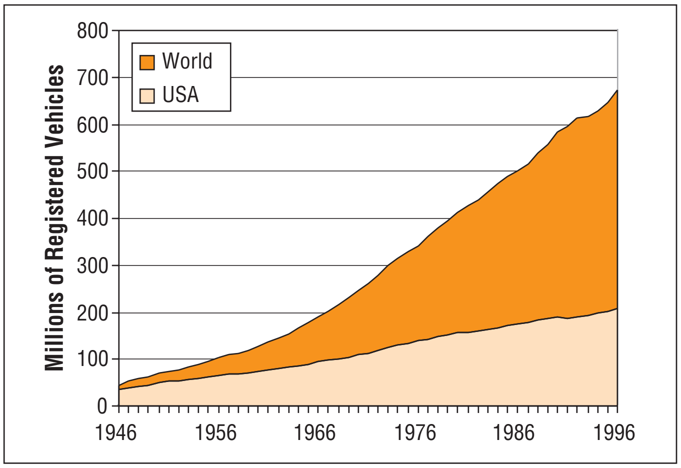

Figure 3.7: *Growth of world motor vehicle population, 1946-1996.*

produced by transport, accounting for over 95% of the annual global warming potential produced by the sector. Nitrous oxide produced by vehicles equipped with catalytic converters, and methane emitted by internal combustion engines account for nearly all the remainder. Almost all of the carbon comes from petroleum fuels. Between 1973 and 1996, world transportation energy use, of which petroleum-derived fuels comprise over 95%, increased by 66% (*Figure 3.5*). Alternative energy sources have not played a significant role in the world's transport systems. Despite two decades of price upheavals in world oil markets, considerable research and development of alternative fuel technologies, and notable attempts to promote alternative fuels through tax subsidies and other policies, petroleum's share of transport energy use has not decreased (94.7% in 1973 and 96.0% in 1996) according to IEA statistics (IEA, 1999c).

On a modal basis, road transport accounts for almost 80% of transport energy use (*Figure 3.6*). Light-duty vehicles alone comprise about 50%. Air transport is the second largest, and most rapidly growing mode, with about 12% of current transport energy use according to International Energy Agency estimates (IEA, 1999c).

The growth of transport energy use, its continued reliance on petroleum and the consequent increases in carbon emissions are driven by the long-term trends of increasing motorization of world transport systems and ever-growing demand for mobility. Immediately after World War II, the world's motor vehicle fleet numbered 46 million vehicles, and 75% of the world's cars and trucks were in the USA. In 1996, there were 671 million highway vehicles worldwide, and the US share stood at just over 30% (*Figure 3.7*). Since 1970, the US motor vehicle population has been growing at an average rate of 2.5% per year, but the population of vehicles in the rest of the world has been increasing almost twice as rapidly at 4.8% per year (AAMA, 1998, p. 8). The same patterns of growth are discernible in statistics on vehicle stocks (ECMT, 1998).

Transport achieved major energy efficiency gains in the 1970s and 1980s, partly because of an economic response to the oil price increases of 1973 to 1974 and 1979 to 1980, and partly as a result of government policies inspired by the oil price shocks. Driven principally by mandatory standards, the average fuel economy of new passenger cars doubled in the USA between 1974 and 1984 (e.g., Greene, 1998). In Europe, similar improvements were achieved by a combination of voluntary efficiency agreements and higher taxes on motor fuels. From 1980 to 1995 the average sales-weighted fuel consumption rates of passenger cars sold in Europe and Japan fell by 12%, from 8.3 l/100km to 7.3 l/100km (Perkins, 1998). All of the decrease, however, occurred between 1980 and 1985 (*Figure 3.8*). Since 1985, the fuel economies of light-duty vehicles sold in the USA and Europe have remained essentially constant.

Energy efficiency improvements in other modes have also slowed or stagnated over the past 10-15 years. Average energy

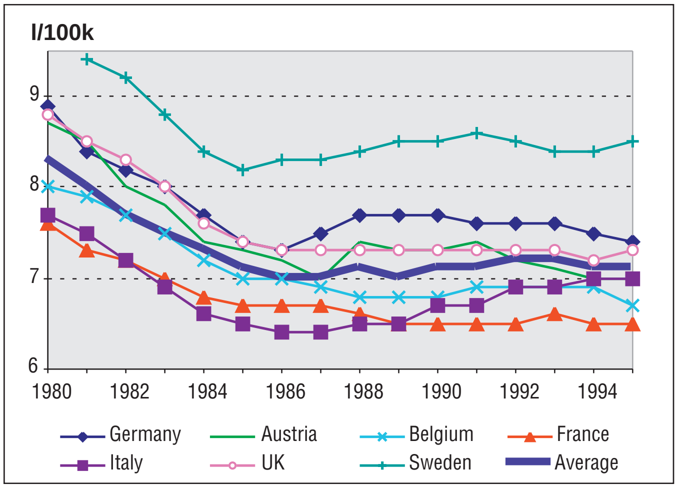

Figure 3.8: *Weighted average fuel consumption of new passenger cars.*

***Table 3.6:** Modal energy intensities, 1973 to 1994*
(IEA, 1997d, Table 3.1).

Energy intensity MJ per pass-km	**Europe-8** 1973	**Europe-8** 1993	**USA** 1973	**USA** 1994	**Japan** 1973	**Japan** 1994
Average, all modes	1.46	1.56	3.10	2.52	1.22	1.67
Car	1.65	1.73	3.10	2.59	2.20	2.46
Bus	0.58	0.71	0.79	1.03	0.54	0.73
Rail	0.58	0.48	1.81	2.15	0.17	0.19
Air	4.55	2.78	4.92	2.46	3.49	2.13

use per passenger-kilometre in Europe and Japan actually increased between 1973 and 1993/4, but declined by almost 20% in the USA (*Table 3.6*). Bus and rail modal energy intensities generally increased, with the exception of rail travel in Europe. The energy intensity of commercial air travel, however, has declined consistently, achieving a 40%-50% reduction over the last 25 years.

On the freight side, trucking's share of tonne km increased in every OECD country, included in a recent analysis of energy trends by the IEA (1997d, *Figure 4.6*), leading to an overall increase in the energy intensity (MJ/t-km) of freight movements. Unlike passenger modes, for freight, changes in modal structure tend to dominate changes in modal energy intensities in determining overall energy intensity (IEA, 1997d, p. 127).

The slowing of energy efficiency improvements in recent years has occurred despite the fact that new technologies with the potential to increase energy efficiency continue to be adopted. In Europe, the market share of diesel cars increased from 7% in 1980 to 17% in 1985 and 23% in 1995, due in part to lower diesel fuel taxes (Perkins, 1998). In the USA, emissions and fuel economy standards increased the use of multipoint fuel injection from 16% of new light-duty vehicles in 1985 to 100% in 1999, and installation of 4- and 5-valve engines increased from zero to 40% over the same period (Heavenrich and Hellman, 1999, *Table 4*). Manufacturers also continued to substitute lighter weight materials such as high-strength steel and aluminium, and to reduce aerodynamic drag and tyre rolling resistance. Yet fuel economy stagnated because vehicles were made larger and much more powerful. Between 1988 and 1999, the average mass of a new US light-duty vehicle increased from 1381 kg to 1534 kg. At the same time, power per kg increased 29% (Heavenrich and Hellman, 1999). In Europe, the average power per car increased by 27% between 1980 and 1995, from 51 to 65 kW (Perkins, 1998).

Because of the slowing down of energy efficiency gains, world transportation energy use is now increasing at just slightly less than the rate of growth in transportation activity. Given the relatively close correlation between economic growth and the demand for transport (*Table 3.7*; see WEC, 1995b, Ch. 3.2 for further details), it is reasonable to expect continued strong growth of transport energy use and carbon emissions, unless significant, new policy initiatives are undertaken. The following paragraphs review several studies of future transportation demand and energy use. A common theme of these and many others is strong growth in transport energy use and the challenges it poses to reducing greenhouse gas emissions from the sector.

Projections of future transport energy use under baseline assumptions reflect an expectation of robust growth in transport activity, energy demand, and carbon emissions through 2020. The World Energy Council (WEC, 1995b) considered three alternative scenarios for transport energy demand through 2020: (1) "markets rule", (2) "muddling through", and (3) "green drivers". Of these, markets rule reflects a high-growth baseline future (2.8%/yr in the OECD, 5.2% in the rest of the world), muddling through a lower growth one (2.2%/year in OECD, 4.2% elsewhere). In the markets rule scenario, world transport energy consumption grows 200% in the quarter century from 1995 to 2020. In the muddling through scenario, transport energy use grows by 100% by

***Table 3.7:** Annual growth in GDP and transport in OECD countries, 1975-1990*
(WEC, 1995b, Table 3.2.1).

	GDP	**Freight traffic**	**Passenger traffic**
OECD Europe	2.6%	2.8%	2.8%
USA	2.8%	2.6%	2.3%
Japan	4.2%	3.6%	2.6%

Table 3.8: *Energy information administration projections of global transport energy use to 2020*
(US DOE/EIA, 1999b, Tables E1, E7, E8, E9).

	1996	**2010** **Millions of barrels per day**	**2020**	**Average annual percent change**
Road	25.5	37.4	45.2	2.4
Air	4.0	6.6	9.6	3.7
Other	5.1	5.8	6.5	1.0
TOTAL	34.6	49.9	61.3	2.4

2020, with most of the shortfall from the markets rule scenario occurring after 2010. In the green drivers scenario, transport energy use is nearly constant as a result of much higher energy taxes and comprehensive environmental regulation. In all three scenarios, growth in freight transport and air travel far outpace the growth of passenger vehicle travel, so that the passenger car's share of total transport energy use falls from about 50% in 1995 to 30% by 2020.

A more recent WEC (1998a) report foresaw considerably slower growth in transport energy use through 2020: 55% in a base case with an 85% increase in a higher economic growth case. In both cases, light-duty vehicles continued to dominate through 2020, accounting for 44% of global transport energy demand in the base case. Still road freight and air travel gained on highway passenger vehicles. Road freight increased from 30% of transport energy demand in 1995 to 33% in 2020. Air transport's share grew from 8% to almost 13%. Global carbon emissions from transport were expected to grow by 56% in the base case, from 1.6GtC in 1995 to 2.5GtC in 2020.

The US DOE and US Energy Information Administration's (EIA's) International Energy Outlook (1999b, p.115) foresees transportation's share of world oil consumption climbing from 48% in 1996 to 53% by 2010 and 56% by 2020. The EIA expects a 77% increase in total world transport energy use by 2020, an average annual global growth rate of 2.4% (*Table 3.8*). Road dominance of energy use is maintained by the rapid increase in vehicle stocks outside of the OECD. The world motor vehicle population is projected to surpass 1.1 billion vehicles in 2020. The SAR (Michaelis *et al*., 1996, *Table 21-3*) presented projections of future global vehicle stocks ranging from 1.2 to 1.6 billion by 2030, rising to 1.6 to 5.0 billion by 2100.

Projections of passenger travel, energy use, and CO_2 emissions to 2050 by Schafer and Victor (1999) show carbon emissions rising from 0.8GtC in 1990 to 2.7GtC in 2050, driven by an increase in travel demand from 23 trillion passenger-kilometres in 1990 to 105 trillion p-km in 2050. The model used is based on constant travel budgets for time and money, so that as incomes and travel demand grow, passenger travel must shift to faster modes in order to stay within time budget limits. As a result, automobile travel first increases, and then eventually declines as travel shifts to high-speed rail and air. The projections assume that car, bus and conventional rail systems maintain their energy intensities at approximately 1990 levels through 2050. Energy intensity of the air mode (which by the authors' definition includes high-speed rail) is assumed to decrease by 70% by 2050, substantially more than the Penner *et al*. (1999)-report estimates. No change in the average carbon content of transportation fuels is assumed.

Projections such as these suggest that it will be very difficult to attain a goal such as holding transport's carbon emissions below 1990 levels by 2010. Lead times for introducing significant new technologies, combined with the normal lifetimes for transportation equipment on the order of 15 years, imply that sudden, massive changes in the trends and outlooks described above can be achieved only with determined effort. At the same time, dramatic advances in transport energy technology have been achieved over just the past 5 years, and the potential for further advances is very promising. By 2020 and beyond the world may see revolutionary changes in energy sources and power plants for new transport equipment, provided that appropriate policies are implemented to accelerate and direct technological changes towards global environmental goals.

3.4.4 New Technology and Other Options

Significant energy efficiency technologies that less than ten years ago were thought too "long-term" to be considered in an assessment of fuel economy potential through 2005 (NRC, 1992), are now available for purchase in at least some OECD countries. The US Partnership for a New Generation of Vehicles (PNGV), the European "Car of Tomorrow" and Japanese Advanced Clean Energy Vehicle programmes have helped achieve these striking successes. In December 1997, a commercial hybrid electric vehicle was introduced in Japan, demonstrating a near doubling of fuel economy over the Japanese driving cycle for measuring fuel economy and emissions. In 1998, a practical, near zero-emission (considering urban air pollutants) gasoline-powered passenger car was developed, and demonstrated. This achievement established the possibility that modern emissions control technology, combined with scientific fuel reformulation, might be able to achieve virtually any desired level of tailpipe emissions at reasonable cost using conventional fossil fuel resources. Emissions problems now limit the application of lean-burn fuel economy technologies such as the automotive diesel engine. Advanced technologies and cleaner fuels may achieve similar results for lean-burn gasoline and diesel engines in the near future. Such advances in urban air pollutant emissions controls for fossil fuel burning engines reduce the environmental incentives for curbing fossil fuel use by road vehicles. Automotive fuel cells also realized order of magnitude reductions in size and cost, and dramatic improvements in power density. The status of these key technologies is reviewed below.

3.4.4.1 Hybrid Electric Vehicles

A hybrid electric vehicle combines an internal combustion engine or other fuelled power source with an electric drivetrain and battery (or other electrical storage device, e.g., an ultracapacitor). Potential efficiency gains involve: (1) recapture of braking energy (with the motor used as generator and captured electricity stored in the battery); (2) potential to downsize the engine, using the motor/battery as power booster; (3) potential to avoid idling losses by turning off the engine or storing unused power in the battery; and (4) increasing average engine efficiency by using the storage and power capacity of the electric drivetrain to keep engine operation away from low efficiency modes. Toyota recently introduced a sophisticated hybrid subcompact auto, the Prius, in Japan and has since introduced a version into the US market. Honda also began selling in model year 2000 its Insight hybrid, a two seater. Ford, GM, Daimler/Chrysler and several others have hybrids in advanced development. The most fuel-efficient hybrid designs can boost fuel economy by as much as 50% at near-constant performance under average driving conditions. The added complexity of the dual powertrain adds significantly to the cost of hybrids, and this could hinder their initial market penetration in countries with low fuel prices, unless policies are adopted to promote them.

Hybrids attain their greatest efficiency advantage—potentially greater than 100%—over conventional vehicles in slow stop-and-go traffic, so that their first applications might be urban taxicabs, transit buses, and service vehicles such as garbage trucks. An assessment of the potential for hybridization to reduce energy consumption by medium-sized trucks in urban operations concluded that reductions in l/100km of 23% to 63% could be attained, depending on truck configuration and duty cycle (An *et al*., 2000).

Testing the Toyota Prius under a variety of driving conditions in Japan, Ishitani *et al*.,(2000) found that the hybrid electric design gave 40%–50% better fuel economy at average speeds above 40 km/h, 70%–90% better in city driving at average speeds between 15 and 30 km/h and 100%–140% better fuel economy under highly congested conditions with average speeds below 10 km/h. Actual efficiency improvements achieved by hybrids will depend on both design of the vehicle and driving conditions. Much of the efficiency benefit of hybrids is lost in long-distance, constant high-speed driving.

3.4.4.2 Lower Weight Structural Materials

Mass reduction via materials substitution is a potentially important strategy for improving light-duty vehicle fuel economy, because it permits synergistic reductions in engine size without loss of performance. The use of alternative materials to reduce weight has been historically restrained by cost considerations, manufacturing process technology barriers, and difficulty in meeting automotive requirements for surface finish quality, predictable behaviour during crash tests, or repairability. The past few years have seen significant developments in space frame structures, advanced new manufacturing technology for plastics and aluminium, and improved modelling techniques for evaluating deformability and crash properties. Ford has displayed an advanced lightweight prototype that is a mid-size car with a weight of only 900 kg, as compared to vehicles weighing 1450 kg today. Even if some of the more exotic weight-saving materials from Ford's prototype were discarded, a weight reduction of 30% or more appears possible. With engine downsizing to maintain a constant ratio of kW/kg, this should produce a 20% fuel economy improvement. Some aluminium-intensive luxury cars have already been introduced (for example, the Audi A8 and the new Volkswagen Lupo with 3l/100km consumption), and Ford is known to be considering the introduction of such a vehicle in the mass market.

According to Bouwman and Moll (1999), 85% of life cycle vehicle energy use occurs in the vehicle use phase, with about 15% accounted for in vehicle production and about 3% recovered in recycling. Mass reductions of 30% to 40% via extensive substitution of aluminium for steel have been incorporated in the designs of advanced, high fuel economy prototypes, improving fuel economy by 20% to 25%. Because the production of aluminium requires more energy than production of steel, and the recycling of aluminium auto bodies is more difficult given current recycling technology, the benefits of substituting aluminium for steel must be assessed by a life cycle analysis of greenhouse gas emissions (efforts are being made to improve aluminium recycling technology, however). Analyses have shown that accounting for life cycle impacts diminishes, but does not eliminate GHG emission reductions caused by the use of aluminium for mass reduction in motor vehicles (*Figure 3.9*). The amount of reduction, however, is sensitive to several key assumptions. Considering the total life cycle emissions for a typical passenger car in the USA, Das (2000) concluded that higher net emissions in the production plus recycling stages would reduce the potential GHG benefits of aluminium in the vehicle use stage by 6.5% versus conventional steel auto bodies, but by 15.8% versus advanced, ultra-light steel body (ULSAB) designs.

Because the increased emissions come first in the production stage, there is a "recovery" period before net emissions reductions are realized. Das (2000) found a recovery period of four

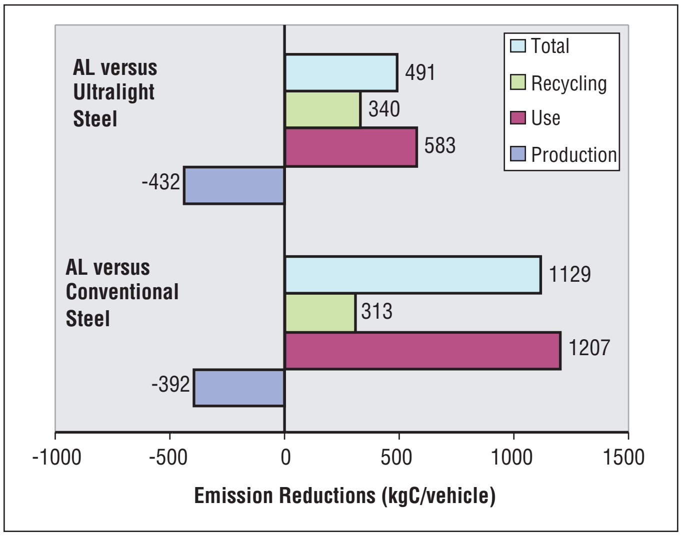

Figure 3.9: *Life cycle CO_2-equivalent greenhouse gas emission estimates for automobile body materials.*

years versus steel but 10 years versus ultra-light steel auto-bodies (ULSAB) for an aluminium-intensive vehicle. An analysis by Clark (1999) of aluminium versus conventional steel, assuming fewer lifetime kilometres, found a cross-over point at approximately eight years for a single vehicle, but at 15 years for an expanding fleet of aluminium-intensive vehicles. In comparison to ULSAB, the car fleet crossover point was found to be at 33 years. In other OECD countries where lifetime vehicle kilometres may be one-half, or less, the levels of the USA, the cross-over points would be even farther in the future. Sensitivity analyses have shown that the results depend strongly on key assumptions, especially the sources of energy for aluminium production and lifetime vehicle miles.

Bouwman and Moll (1999) obtained similar results in scenarios based on the growing Dutch passenger car fleet. A scenario in which aluminium vehicles were introduced in 2000achieved lower energy use than a steel scenario after 2010. By 2050, the aluminium scenario energy use was 17% below that of the all steel scenario.

3.4.4.3 Direct Injection Gasoline and Diesel Engines

Direct injection lean-burn gasoline engines have already been introduced in Japan and Europe, but have been restricted in North America by a combination of tight emission standards and high sulphur content in gasoline. Fuel sulphur levels will be drastically reduced in Europe and North America over the next 10 years. The US EPA, for example, has proposed regulations that would set caps on sulphur content of 30 ppm for gasoline and 15 ppm for diesel fuel (Walsh, 2000). While planned reductions in the sulphur content of fuels to the range of 10 to 30 ppm will allow direct injection gasoline engines to be introduced, it is not yet clear that the full fuel efficiency benefits can be retained at lower NO_X levels. Preliminary evaluations suggest that benefits may be in the 12% to 15% range rather than the 16% to 20% range available in Japan and Europe, but even this assumes some advances in after treatment technology. Engine costs, however, seem quite moderate, in the range of US$200 to US$300 more than a conventional engine.

Direct injection (DI) diesel engines have long been available for heavy trucks, but recently have become more competitive for automobiles and light trucks as noise and emission problems have been resolved. These new engines attain about 35% greater fuel economy than conventional gasoline engines and produce about 25% less carbon emissions over the fuel cycle. In light-duty applications, DI diesels may cost US$500 to US$1000 more than a comparable gasoline engine. Tightening of NO_x and particulate emissions standards presents a challenge to the viability of both diesel and gasoline lean-burn engines, but one that it may be possible to overcome with advanced emissions controls and cleaner fuels (e.g., Martin *et al.*, 1997; Gerini and Montagne, 1997; Mark and Morey, 1999; Greene, 1999). Further improvements in diesel technology also offer substantial promise in heavy-duty applications, especially heavy trucks but also including marine and rail applications. Current research programmes are aiming to achieve maximum thermal efficiencies of 55% in heavy-duty diesels (compared to current peak efficiencies of about 40%-45%), with low emissions.

3.4.4.4 Automotive Fuel Cells

Fuel cells, which have the potential to achieve twice the energy conversion efficiency of conventional internal combustion engines with essentially zero pollutant emissions, have received considerable attention recently, with most major manufacturers announcing their intentions to introduce such vehicles by the 2005 model year. The recent optimism about the fuel cell has been driven by strong advances in technology performance, including rapid increases in specific power that now allow a fuel cell powertrain to fit into a conventional vehicle without sacrificing its passenger or cargo capacities. While fuel cell costs have been reduced by approximately an order of magnitude, they are still nearly 10 times as expensive per kW as spark ignition engines. Recent analyses project that costs below US$40/kW for complete fuel cell drivetrains powered by hydrogen can be achieved over the next ten years (Thomas *et al.*, 1998). Hydrogen is clearly the cleanest and most efficient fuel choice for fuel cells, but there is no hydrogen infrastructure and on-board storage still presents technical and economic challenges. Gasoline, methanol or ethanol are possible alternatives, but require on-board reforming with consequent cost and efficiency penalties. Mid-size fuel cell passenger cars using hydrogen could achieve fuel consumption rates of 2.5 gasoline equivalent l/100 km in vehicles with lightweight, low drag bodies; comparable estimates for methanol or gasoline-powered fuel cell vehicles would be 3.2 and 4.0 l/100 km (gasoline equivalent), respectively. While gasoline is relatively more difficult to reform, it has the benefit of an in-place refuelling infrastructure, and progress has been made in reformer technology (NRC, 1999a).

The fuel economy of hydrogen fuel cell vehicles is projected to be 75% to 250% greater than that of conventional gasoline internal combusiton engine (ICE) vehicles, depending on the drive cycle (Thomas *et al*., 1998). Primarily as a result of energy losses in reforming, comparable estimates of the fuel economy benefit of methanol-powered fuel cells range from 25% to 125%. The GHG reduction potential of hydrogen or methanol fuel cells, however, requires a "well-to-wheels" analysis to measure the full fuel cycle impacts. Both sources cited here include emissions of all significant greenhouse gases produced in the respective processes. Assuming hydrogen produced by local reforming of natural gas, Thomas *et al*. (1998, *Figure 8*) estimated roughly a 40% reduction in well-to-wheels GHG emissions for a direct hydrogen fuel cell vehicle versus a conventional gasoline ICE vehicle getting 7.8 l/100km (about 150 g CO_2 equivalent per km, versus 250). Wang (1999a, p. 4) concluded that direct hydrogen fuel cell vehicles, with hydrogen produced at the refuelling station by reforming natural gas, would reduce full fuel cycle GHG emissions by 55% to 60% versus a comparably sized 9.8 l/100km gasoline vehicle. Hydrogen could also be produced from methane in large-scale centralized facilities. This could create opportunities for sequestering carbon but would also require an infrastructure for hydrogen transport. Hydrogen produced via electrolysis was estimated to produce 50% to 100% *more* full fuel cycle GHG emissions, depending on the energy sources used to generate electricity. Methanol produced from natural gas was estimated to give a 50% reduction in full fuel cycle GHG emissions. Wang (1999b, *Table 4.4*) projected direct hydrogen fuel cell vehicles to be 180% to 215% more energy efficient, and methanol fuel cell vehicles to be 110% to 150% more efficient. These analyses attempt to hold other vehicle characteristics constant but, of course, that is never entirely possible.

3.4.4.5 Fuel Cycle Emissions

In considering the impacts of advanced technologies and alternative fuels on emissions of greenhouse gases, it is important to include the full fuel cycle, since emissions in feedstock and fuel production can vary substantially. The same fuel can be produced from several feedstocks, and this too has important implications for greenhouse gas emissions. Finally, as Ishitani *et al*. (2000) have demonstrated, the use of different drive cycles as a basis for comparison can also change the ranking of various advanced technologies. Hybrid vehicles, for example, will perform relatively better under congested, low-speed driving conditions. *Table 3.9* shows a sample of results obtained by Wang (1999a) based on US assumptions for passenger car technologies expected to be available in the year 2010. In all cases, carbon dioxide is the predominant GWP-weighted

Table 3.9: *GHG emissions from advanced automotive technologies and alternative fuels*
(Wang, 1999, App. B-II).

	CO_2-equivalent grams per km						
	Fuel cycle stage			**Greenhouse gas**			
	Feedstock	**Fuel**	**Operation**	**CO_2**	**N_2O**	**CH_4**	**Total**
Gasoline (reformulated)	15.6	52.7	228.9	282.2	5.7	9.4	295.6
Gasoline direct injection (DI)	12.6	42.1	184.3	225.6	5.7	7.7	237.6
Propane (from natural gas)	19.0	13.6	197.6	217.5	5.5	7.3	228.9
Compressed natural gas (CNG)	30.7	21.3	174.6	206.2	3.1	17.3	225.3
Diesel DI	10.6	27.2	161.6	191.7	3.3	4.5	198.4
20% biodiesel DI	11.7	32.7	132.7	169.1	3.7	4.3	176.1
Grid-Hybrid (RFG)	9.8	63.5	88.8	152.7	4.1	5.3	161.2
Hybrid (RFG)	8.6	27.5	123.3	148.3	5.7	5.4	158.5
Electric vehicle (EV, US mix)	12.3	145.2	0.0	152.1	0.6	4.8	156.6
Fuel Cell (Gasoline)	7.8	26.1	112.6	140.8	1.4	4.4	145.7
Hybrid. CNG	19.1	13.2	110.5	127.6	2.7	12.5	142.0
Fuel cell (methanol. NG)	8.1	17.9	83.1	105.0	1.2	3.0	108.5
Fuel cell (H_2 from CH_4))	11.0	97.3	0.0	103.1	0.2	5.0	107.62
EV (CA mix)	10.4	51.1	0.0	58.5	0.2	2.8	61.1
Fuel cell (solar)	0.0	20.3	0.0	18.9	0.2	1.2	20,2

	100-year global warming potentials		
	CO_2	**N_2O**	**CH_4**
	1	310	21

greenhouse gas. Advanced direct injection gasoline engines appear to achieve nearly the same greenhouse gas emissions reductions as spark-ignition engine vehicles fuelled by propane or compressed natural gas. Direct-injection diesel vehicles show a reduction of one-third over advanced gasoline vehicles. The gasoline hybrid achieves almost a 50% reduction, while the grid-connected hybrid does no better because of the large share of coal in the US electricity generation mix. The dependence of electric vehicle (EV) emissions on the power generation sector is illustrated by the very large difference between EVs using California versus US average electricity. Fuel cell vehicles using gasoline are estimated by Wang (1999a) to achieve a 50% reduction in emissions, but hybrid vehicles fuelled by compressed natural gas (CNG) do slightly better. Fuel cells powered by hydrogen produced by reforming natural gas locally at refuelling outlets are estimated to reduce fuel cycle greenhouse gas emissions by almost two thirds, while those using hydrogen produced from solar energy achieve more than a 90% reduction. Clearly, Wang's (1999b) estimates differ substantially from those of Thomas *et al*. (1998) as noted above. Such differences are common, as a result of differences in the many assumptions that must be made in fuel cycle analyses.

3.4.4.6 Use of Biofuels

Liquid and gaseous transport fuels derived from a range of biomass sources are technically feasible (see Section 3.8.4.3.2). They include methanol, ethanol, di-methyl esters, pyrolytic oil, Fischer-Tropsch gasoline and distillate, and biodiesel from vegetable oil crops (Section 3.6.4.3). Ethanol is commercially produced from sugar cane in Brazil and from maize in the USA where it has been sold neat or blended for more than a decade. Ethanol is blended with gasoline at concentrations of 5-15%, thereby replacing oxygenates more typically used in North America such as methyl-t-butylether (MTBE) and ethyl-t-butylether (ETBE) additives. ETBE production from bio-ethanol is also a promising market in Europe but the production costs by hydrolysis and fermentation from cereals or sweet sorghum crops remain high (Grassi, 1998).

In Brazil the production of ethanol-fuelled cars achieved 96% market share in 1985 but declined to 3.1% in 1995 and 0.1% in 1998. Since the government approved a higher blend level (26%) of ethanol in gasoline the production of ethanol has continued to increase achieving a peak of 15,307m^3 in the 1997/98 harvesting season. This represented 42.73% of the total fuel consumption in all Otto cycle engines giving an annual net carbon emission abatement of 11% of the national total from the use of fossil fuels (IPCC, 2000).

National fuel standards are in place in Germany for biodiesel and many engine manufacturers such as Volkswagen now maintain warranties (Schindlbauer, 1995). However, energy yields (litres oil per hectare) are low and full fuel cycle emissions and production costs are high (see Section 3.8.4.3.2).

3.4.4.7 Aircraft Technology

Several major technologies offer the opportunity to improve the energy efficiency of commercial aircraft by 40% or more (*Table 3.10*). The Aeronautics and Space Engineering Board of the National Research Council (NRC, 1992, p. 49) concluded that it was feasible to reduce fuel consumption per seat mile for new commercial aircraft by 40% by about 2020. Of the 40%, 25% was expected to come from improved engine performance, and 15% from improved aerodynamics and weight. A reasonable preliminary goal for reductions in NO_x emissions was estimated to be 20%–30%.

An assessment of breakthrough technologies by the US National Research Council (1998) estimated that the blended wing body concept alone could reduce fuel consumption by 27% compared to conventional aircraft, assuming equal engine efficiency. The NRC report also identified a number of breakthrough technologies in the areas of advanced propulsion systems, structures and materials, sensors and controls, and alternative fuels that could have major impacts on aircraft energy use and GHG emissions over the next 50 years.

Noting that the energy efficiency of new production aircraft has improved at an average rate of 1-2% per year since the dawn of the jet era, the IPCC Special Report on *Aviation and the Global Atmosphere* concluded that the fuel efficiency of new production aircraft could improve by 20% from 1997 to 2015 (*Table 3.11*), as a result of a combination of reductions in aerodynamic drag and airframe weight, greater use of high-bypass engines with improved nacelle designs, and advanced, "fly-by-light" fibre optic control systems (Penner *et al*., 1999, Ch. 7). Advanced future aircraft technologies including laminar flow concepts, lightweight materials, blended wing body designs, and subsystems improvements were judged to offer 30%-40% to 40%-50% efficiency improvements by 2050, with the lower range more likely if reducing NO_X emissions is a high priority. The purpose of these scenarios was not to describe the technological or economic potential for efficiency improvement and emissions reductions, but rather to provide a "best judgement" scenario for use in assessing the impacts of aviation on the global atmosphere through 2050. A

Table 3.10: *Energy information administration aircraft technology estimates*

Technology	**Year of introduction**	**% gain in seat-km per kg**
Ultra-high bypass engine	1995	10
Propfan engine	2000	23
Hybrid laminar flow	2020	15
Advanced aerodynamics	2000	18
Material substitution	2000	15
Engine thermodynamics	2010	20

Table 3.11: *Historical and future improvements in new production aircraft energy efficiency (%)* (Lewis and Niedzwiecki, 1999, Table 7.1).

Time period	Airframe	Propulsion	Total	percent per year
1950 to 1997	30	40	70	1.13
1997 to 2015	10	10	20	1.02
1997 to 2050	25	20	45	0.70

number of alternatives to kerosene jet fuel were considered. None were considered likely to be competitive with jet fuel without significant technological breakthroughs. On a fuel cycle basis, only liquid methane and hydrogen produced from nuclear or renewable energy sources were estimated to reduce greenhouse gas emissions relative to jet fuel derived from crude oil.

In operation, aircraft seat-km per kg is also influenced by aircraft size, and overall passenger-km per kg efficiencies depend on load factors as well. Industry analysts (Henderson, 1999) have forecasted an increase in global load factors to 73% by 2018, but foresee only a small potential for increasing aircraft size, however, since most additional capacity is expected to be supplied by increased flight frequencies. If average aircraft size could be increased, perhaps as a strategy for reducing airport congestion, further reductions in energy intensity could be achieved.

3.4.4.8 Waterborne Transport

Opportunities for reducing energy use and GHG emissions from waterborne transport were not covered in the SAR. The predominant propulsion system for waterborne transport is the diesel engine. Worldwide, 98% of freighters are powered by diesels. Although the 2% powered by steam electric drive tend to be the largest ships and account for 17% of gross tonnage, most are likely to be replaced by diesels within the next 10 years (Michaelis, 1997). Still, diesel fuel accounted for only 21% of international marine bunker fuel consumed in 1995 (Olivier and Peters, 1999). Modern marine diesel engines are capable of average operating efficiencies of 42% from fuel to propeller, making them already one of the most efficient propulsion systems. The best modern low-speed diesels can realize efficiencies exceeding 50% (Farrell *et al*., 2000).

Fuel cells might be even more efficient, however, and might possibly be operated on fuels containing less carbon (Interlaboratory Working Group, Appendix C, 1999). Design studies suggest that molten carbonate fuel cell systems might achieve energy conversion efficiencies of 54%, and possibly 64% by adding a steam turbine bottoming cycle. These studies do not consider full fuel cycle emissions, however. Farrell *et al*. (2000) estimated the cost of eliminating carbon emissions from marine freight by producing hydrogen from fossil fuel, sequestering the carbon, and powering ships by solid oxide or molten carbonate fuel cells at US$218/tC, though there is much uncertainty about costs at this time.

A number of improvements can be made to conventional diesel vessels in, (1) the thermal efficiency of marine propulsion (5%–10%); (2) propeller design and maintenance (2%–8%); (3) hydraulic drag reduction (10%); (4) ship size; (5) speed (energy use increases to the third power of speed); (6) increased load factors; and (7) new propulsion systems, such as underwater foils or wings to harness wave energy (12%–64%) (CAE, 1996). More intelligent weather routing and adaptive autopilot control systems might save another 4%–7% (Interlaboratory Working Group, Appendix C, 1999).

3.4.4.9 Truck Freight

Modern heavy trucks are equipped with turbo-charged direct-injection diesel engines. The best of these engines achieve 45% thermal efficiency, versus 24% for spark-ignited gasoline engines (Interlaboratory Working Group, 1997). Still, there are opportunities for energy efficiency improvements and also for lower carbon alternative fuels, such as compressed or liquified natural gas in certain applications. By a combination of strategies, increased peak pressure, insulation of combustion chambers, recovery of waste heat, and friction reduction, thermal efficiencies of 55% might be achievable, though there are unresolved questions about nitrogen oxide emissions (US DOE/OHT, 1996). For medium-heavy trucks used in short distance operations, hybridization may be an attractive option. Fuel economy improvements of 60%-75% have been estimated for smaller trucks with 5-7 litre engines (An *et al*., 1999). With drag coefficients of 0.6 to 0.9, heavy trucks are much less aerodynamic than light-duty vehicles with typical drag coefficients of 0.2 to 0.4. Other potential sources of fuel economy improvement include lower rolling resistance tyres and reduced tare weight. The sum total of all such improvements has been estimated to have the potential to improve heavy truck fuel economy by 60% over current levels (Interlaboratory Working Group, 2000).

3.4.4.10 Systems Approaches to Sustainability

Recognizing the growing levels of external costs produced by the continuing growth of motorized transport, cities and nations around the world have begun to develop plans for achieving sustainable transport. A recent report by the ECMT

(1995) presents three policy "strands", describing a progression of scenarios intended to lead from the status quo to sustainability. The first strand represents "best practice" in urban transport policy, combining land-use management strategies (such as zoning restrictions on low-density development and parking area controls) with advanced road traffic management strategies, environmental protection strategies (such as tighter pollutant emissions regulations and fuel economy standards), and pricing mechanisms (such as motor fuel taxes, parking charges, and road tolls). Even with these practices, transport-related CO_2 emissions were projected to increase by about one-third in OECD countries over the next 20 years and by twice that amount over the next 30 to 40 years. A second strand added significant investment in transit, pedestrian, and bicycle infrastructure to shape land use along with stricter controls on development, limits on road construction plus city-wide traffic calming, promotion of clean fuels and the setting of air quality goals for cities, as well as congestion pricing for roads and user subsidies for transit. The addition of this strand was projected to reduce the growth in CO_2 emissions from transport to a 20% increase over the next 20 years. The third strand added steep year-by-year increases in the price of fuel, full-cost externality pricing for motor vehicles (estimated at 5% of GDP in OECD countries), and ensuring the use of high-efficiency, low-weight, low-polluting cars, vans, lorries, and buses in cities. Addition of the third strand was projected to reduce fuel use by 40% from 1995 to 2015.

3.4.5 Regional Differences

Technical and economic potentials for reducing greenhouse gas emissions will vary by region according to differences in geography, existing transportation infrastructure, technological status of existing transport equipment, the intensity of vehicle use, prevailing fuel and vehicle fiscal policies, the availability of capital, and other factors. Differences in spatial structure, existing infrastructure, and cultural preferences also influence the modal structure and level of transport demand.

Many developing countries and countries with economies in transition are experiencing rapid motorization of their transport systems but are not yet locked into a road-dominated spatial structure. In addressing the transport problems of these economies, the World Bank (1996) has emphasized the importance of combining efficient pricing of road use (including external costs) with co-ordinated land use and infrastructure investment policies to promote efficient levels of transport demand and modal choice. Without providing specific GHG emission reduction estimates, the World Bank study notes that non-highway modes such as rail can reduce energy requirements by two-thirds versus automobiles and 90% versus aircraft, in situations where the modes provide competitive services.

Studies of transport mitigation options in Africa and Asia have emphasized behavioural, operational, and infrastructure measures in addition to technology. In Africa, in particular, options that have been examined include: the reduction of energy intensity through expanding mass transit systems (e.g., modal shifts from road to rail), vehicle efficiency improvement through maintenance and inspection programmes, improved traffic management, paving roads, and the installation of fuel pipelines (e.g., modal shift from road or rail to pipeline), provision of infrastructure for non-motorized transport, and decarbonization of fuels through increased use of compressed natural gas or biomass ethanol (Baguant and Teferra, 1996; Zhou, 1999). Mass movements of goods, passengers, and fuel become more cost-effective as the volumes and load factors increase, and for most African countries this is likely to be achievable only after 2010 (Zhou, 1999). In studies conducted for East and Southern Africa, these options were found to be implementable at little or no cost per tC (*Table 3.12*). Zhou (1999) has estimated that investments in paving roads, rail freight systems and pipelines could reduce greenhouse gas emissions in Botswana at negative cost (*Table 3.12*). Vehicle inspection programmes, as well as fuel decarbonization by use of compressed natural gas and biomass ethanol were all estimated to be no cost to low-cost options. Bose (1999a) notes that in developing countries mass transport modes and demand management strategies are an essential complement to technological solutions because of three factors: (1) lack of leverage in global vehicle markets to influence the development of appropriate transport technologies; (2) the relatively greater importance of older, more polluting vehicles combined with slower stock turnover; and (3) the inability to keep pace with rapid motorization in the provision of infrastructure.

Table 3.12: *Estimated costs of greenhouse gas mitigation options in Southern Africa*
(Zhou, 1999; UNEP/Southern Centre, 1993).

Measure	Cost (US$/tC)
Paved roads	–41.42
Road freight to rail	–31.47
Petroleum and product pipelines	–18.91
Fuel pricing policies	0.00
Vehicle inspections	0.20
Rail electrification	111.94
Compressed natural gas	1.37
Ethanol	–186.5

3.4.6 Technological and Economic Potential

This section addresses the technological potential to cost-effectively increase energy efficiency in transport and thereby reduce GHG emissions. Most studies concentrate on light-duty vehicles because of their 50% share of energy use and GHG emissions, and on technology or fuel pricing policies. Technical efficiency improvements, in the absence of complementary fiscal policies, are subject to a "rebound effect" in that they reduce the fuel cost of travel. Rebound effects in the USA amount to about 20% of the potential GHG reductions (Greene, 1999). In Europe, where fuel prices are higher, rebound effects may be as large as 40% (Michaelis, 1997). Most assessments take the rebound effect into account when estimating technical efficiency impacts. Fewer studies address policies such as land use planning, investment in or subsidy of particular transport modes, or information.

An Asian four-country study of the technological and economic potential to reduce GHG emissions considered five types of options for GHG mitigation in transport: (1) improving fuel efficiency, (2) improving transportation system efficiency, (3) behavioural change, (4) modal split changes, and (5) technological change (Bose, 1999b). The Indian study concluded that abatement costs for transport were high relative to options available in other sectors, and projected little change in transport for emissions constraints less than a 20% reduction from the baseline. The Bangladesh study, using a different methodology, concluded that a wide array of near-term technology options had no net cost, but that the cost of 4-stroke engines for 3-wheeled vehicles fell between US$48 and US$334/tC reduced, depending on the application. The Thailand study found that lean-burn engines would improve efficiency by 20% at a negative net cost of US$509/tC. The Korean study also concluded that several "no regrets" options were available, including use of continuously variable transmissions, lean-burn engines, and exclusive bus lanes.

Recognizing that transportation energy consumption and CO_2 emissions increased by 16% from 1990 to 1995, and that carbon emissions may be 40% higher in 2010 than in 1990 if measures are not taken, the government of Japan has strengthened energy efficiency standards based on a "Front Runners" approach, which sets standards to meet or exceed the highest energy efficiency achieved among products currently commercialized (MITI/ANRE, 1999). These require a 22.8% improvement over 1995 new gasoline car fuel economy in 1/km by 2010, and a 13.2% improvement for gasoline light-duty freight vehicles (Minato, 1998). For diesel-fuelled vehicles the corresponding requirements are 14.9% and 6.5% by 2005. Technological improvements in other modes are expected to produce efficiency improvements of 7% for railways, 3% for ships, and 7% for airlines over the same period (Minato, 1998). Cost-effective technical potentials have also been reported by Kashiwagi *et al.* (1999), who cite 27.7 PJ of energy savings in Japan's transport sector achievable at US$0.044/kWh, or less.

There are significant barriers to the kinds of fuel economy improvements described above, and substantial policy initiatives will be needed to overcome them. In Europe, for example, the European automobile manufacturers' association, ACEA, and the European Union have agreed to voluntary standards to reduce carbon emissions from new passenger cars by 25% over the next 10 years. The European standards will require reducing average fuel consumption of new cars from 7.7 to 5.8 l/100 km, creating a strong incentive to adopt advanced fuel economy technologies. A survey of 28 European countries identified 334 separate measures countries were taking to reduce CO_2 emissions from transport (Perkins, 1998).

At least nine recent studies have assessed the economic potential for technology to improve light-duty vehicle fuel economy (Weiss *et al.*, 2000; Greene and DeCicco, 1999; Michaelis, 1997). The conclusions of eight of the studies are summarized in the form of quadratic fuel economy cost curves describing incremental purchase cost versus the improvement in fuel economy over a typical 8.4 l/100 km passenger car (*Figure 3.10*). Most of the technology potential curves reflect a short-

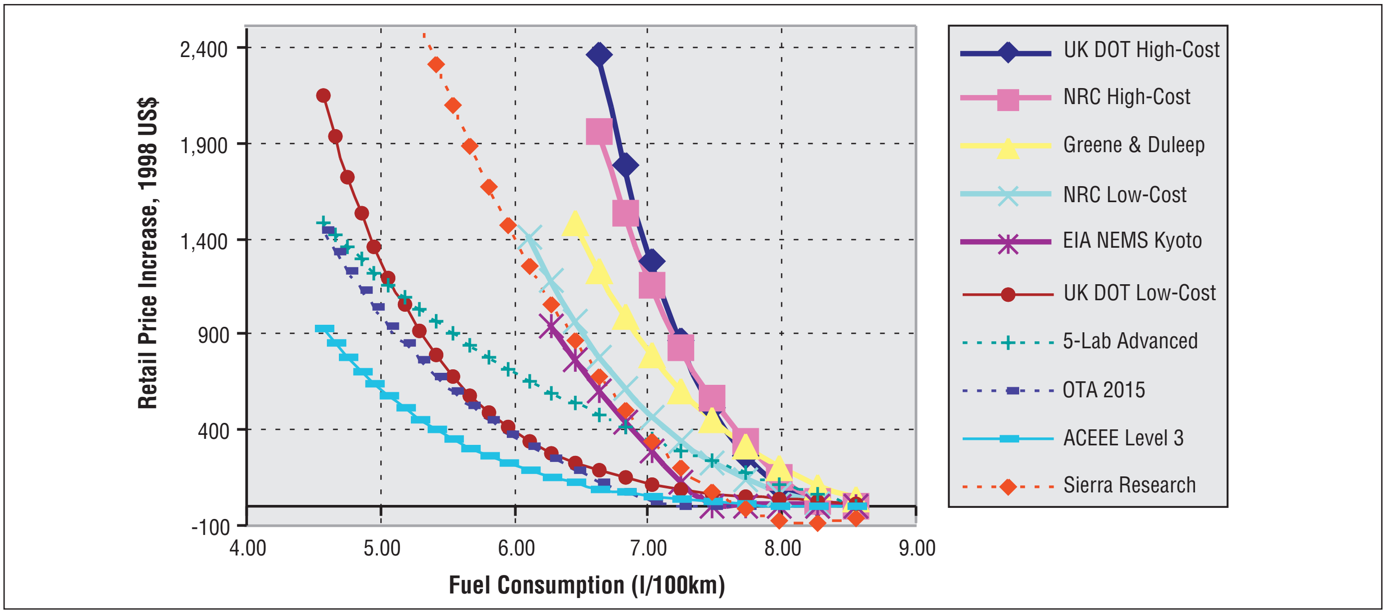

Figure 3.10: *Passenger car fuel economy cost curves.*

Table 3.13: *Estimated technological potential for carbon emissions reductions in the US transportation sector*
(Brown *et al*., 1998).

	1990	**2010**	**2020**	**2030**
Business as usual (MtC)	432	598	665	741
Technology potential (%)		7–12	15–17	27–40

	1990	**2010**		
		Baseline	**Efficiency**	**High efficiency**[a]
Transport emissions (MtC)	432	616	543	513
Reduction (%)			12	17

[a] Includes US$50/tC permit cost.

run perspective, considering what can be achieved using only proven technologies over a 10-year period. The two most pessimistic (which reflect a 1990 industry view of short-term technology potential) indicate that even a reduction from 8.4 to 6.5 l/100 km would cost nearly US$2000. The curves labelled "ACEEE Level 3" and "UK DOT Low-Cost" are limited to proven technologies, but allow substantial trade-offs in performance, transmission-management and other features that may affect customer satisfaction. The curves labelled "5-lab" and "OTA 2015" include the benefits of technologies in development, but not yet commercialized (NRC, 1992; DeCicco and Ross, 1993; US DOE/EIA, 1998). The most optimistic of these suggest that an improvement to less than 5.9 l/100 km is possible at an incremental cost of less than US$1000 per vehicle (1998 US$). The Sierra Research (Austin *et al*., 1999) curve is intended to pertain to the year 2020, but reflects industry views about technology performance, and excludes certain key technologies such as hybrids and fuel cell vehicles that could have dramatic impacts over the next 20 years.

Three of the studies (OTA, 1995b; DeCicco and Ross, 1993; National Laboratory Directors, 1997) considered more advanced technologies such as those described above (e.g., direct-injection engines, aluminium-intensive designs, hybrid vehicles, fuel cells). These concluded that by 2015, consumption rates below 4.7 l/100 km could be attained at costs ranging from under US$1000 to US$1500 per vehicle. These long-run curves span a range similar to fuel consumption/cost curves for European passenger cars reported by Denis and Koopman (1998, *Figure 3*), except that the base fuel consumption rate is 7 l/100 km as opposed to 8.5 in the USA, and improvements to the range of 4 to 5 l/100 km were judged achievable at incremental costs of 2000 to 700 ECU, respectively (1990 ECU).

A lifecycle analysis of the greenhouse gas impacts of nine hybrid electric and fuel cell vehicles was compared to a 1996 vehicle and an "evolved 2020" baseline vehicle for the year 2020 by Weiss *et al*. (2000). The study concluded that a hybrid vehicle fuelled by compressed natural gas could reduce GHG emissions by almost two-thirds relative to the 1996 reference vehicle, and by 50% compared with an advanced 2020 internal combustion engine vehicle. Other technologies capable of 50%, or greater lifecycle GHG reductions versus the 1996 reference vehicle included: gasoline and diesel hybrids, battery-electric, and hydrogen fuel cell vehicles.

A recent study by five of the US Department of Energy's (DOE's) National Laboratories (Interlaboratory Working Group, 1997) assessed the economic market potential for carbon reductions, using the EIA's National Energy Modelling System. Transport carbon emissions were projected to rise from 487 MtC in 1997 to 616 MtC by 2010 in the baseline case. In comparison to the baseline case, use of cost-effective technologies reduced carbon emissions by 12% in 2010 in an "Efficiency" case (*Table 3.13*). More optimistic assumptions about the success of R&D produced a reduction of 17% by 2010. The authors noted that lead times for cost-effectively expanding manufacturing capacity for new technologies and the normal turnover of the stock of transport equipment significantly limited what could be achieved by 2010. Efficiency improvements in 2010 for new transportation equipment were substantially greater (*Table 3.14*). New passenger car efficiency increased by 36% in the "Efficiency" case and by 57% in the more optimistic case (Brown *et al*., 1998).

Eleven of the US DOE's National Laboratories completed a comprehensive assessment of the technological potential to reduce GHG emissions from all sectors of the US economy (National Laboratory Directors, 1997). This study intentionally made optimistic assumptions about R&D success, and did not explicitly consider costs or other market factors. The study concluded that the technological potential for carbon emissions reductions from the US transport sector was 40–70 million metric tons of carbon (MtC) by 2010, 100–180MtC by 2020 and 200–300MtC by 2030. These compare to total US transportation carbon emissions of 473MtC in 1997 (note that this

Table 3.14: *Projected transportation efficiencies of 5-Laboratory Study* (Interlaboratory Working Group, 1997).

		2010		
Determinants	**1997**	**Baseline**	**Efficiency**	**HE/LC**[a]
New passenger car l/100 km	8.6	8.5	6.3	5.5
New light truck l/100 km	11.5	11.4	8.7	7.6
Light-duty fleet l/100 km[b]	12.0	12.1	10.9	10.1
Aircraft efficiency (seat-l/100 km)	4.5	4.0	3.8	3.6
Freight truck fleet l/100 km	42.0	39.2	34.6	33.6
Rail efficiency (tonne-km/MJ)	4.2	4.6	5.5	6.2

[a] HE/LC, high-energy/low-carbon.

[b] Includes existing passenger cars and light trucks

Table 3.15: *Assumptions and results of three European studies*

	Dutch	**Hanover**	**EU**
Base and target years (length of scenario in years)	1995, 2020 (25 years)	1990, 2010 (20 years)	1990, 2000 (10 years)
CO_2 emissions in target year: baseline (Mt)	36.6–43.3	1.9	649.8
Annual percentage growth in baseline emissions (Mt)	0.4% to 1.4% per year	0.6% per year	1.7% per year
Solution scenario	(I) Best technical means, (II) Intensifying current policy, (III) Non-conventional local transport technologies	(A) Local/regional, (B) National	(R) Reasonable restrictive, (T) Target orientation
Base and target years (length of scenario, in years)	1995, 2020 (25 years)	1990, 2010 (20 years)	1990, 2000 (10 years)
CO_2 emission reduction (transport sector - Mt)	(I) 11–13, (II) 3–11, (III) 18	(A) 0.16 and B) 0.34	(R) 84 and (T) 177
Reduction of total transport emissions (including non-road transport) relative to baseline in target year	(I) 30%, (II) 8%–25%, (III) 42%	(A) 8% and B) 18%	(R) 13% and (T) 25%
Economic evaluation			
Net annual costs	Not quantified, though asserted to be <€0 /tC	Not quantified	Not quantified

base year estimate differs from that for the Interlaboratory Working Group). The report suggested the following technological potentials for carbon emissions reductions by mode of transport over the next 25 years: (1) light-duty vehicles with fuel cells, 50%–100%; (2) heavy trucks via fuel economy improvements, 20%–33%; and (3) air transport, 50%. It is difficult to interpret the practical implications of these conclusions, however, since no attempt was made by this study to estimate achievable market potentials.

Three European studies of the technical-economic potential for energy savings and CO_2 reduction were reviewed by van Wee and Annema (1999). Generally, the studies focused on technological options, such as improving the fuel efficiencies of conventional cars and trucks, promotion of hybrid vehicles, switching trucks and buses to natural gas, and electrifying buses, delivery trucks, and mopeds. Only the study for Hanover included investment in improved public transport as a major policy option. The results, summarized in *Table 3.15*, suggest that emissions reductions of 8% to as much as 42% over business-as-usual projections may be possible.

The effects of a variety of fiscal and regulatory policies on CO_2 emissions from road passenger vehicles have been estimated for Europe over a 15-year forecast horizon (Jansen and Denis, 1999; Denis and Koopman, 1998). These studies, both using the EUCARS model developed for the European Commission, concluded that CO_2 reductions on the order of 15% over a baseline case could be achieved in the 2011 to 2015 time period at essentially zero welfare loss. Among the more effective policies were fuel taxes based on carbon content, fuel consumption standards requiring proportional increases for all cars, and the combination of fuel-consumption based vehicle sales taxes with a fuel tax. When reductions in external costs and the benefit of raising public revenues are included in the calculation of social welfare impacts, the feebate (a policy combining subsidies for fuel efficient vehicles and taxes on inefficient ones) and fuel tax policy combination was able to achieve CO_2 reductions of 20% to 25% in the 2011 to 2015 time period at zero social cost (Jansen and Denis, 1999).

3.4.7 Conclusions

Over the past 25 years, transport activity has grown at approximately twice the rate of energy efficiency improvements. Because the world's transportation system continued to rely overwhelmingly on petroleum as an energy source, transport energy use and GHG emissions grew in excess of 2% per year. Projections to 2010 and beyond reviewed above reflect the belief that transport growth will continue to outpace efficiency improvements and that without significant policy interventions, global transport GHG emissions will be 50%–100% greater in 2020 than in 1995. Largely as a result of this anticipated growth, studies of the technical and economic potential for reducing GHG emissions from transport generally conclude that while significant reductions from business-as-usual projections are attainable, it is probably not practical to reduce transport emissions below 1990 levels by the 2010–2015 time period. On the other hand, the studies reviewed generally indicate that cost-effective reductions on the order of 10%–20% versus baseline appear to be achievable. In addition, more rapid than expected advances in key technologies such as hybrid and fuel cell vehicles, should they continue, hold out the prospect of dramatic reductions in GHG emission from road passenger vehicles beyond 2020. Most analyses project slower rates of GHG reductions for freight and air passenger modes, to a large extent reflecting expectations of faster rates of growth in activity.

Assessing the total global potential for reducing GHG emissions from transportation is hindered by the relatively small number of studies (especially for non-OECD countries) and by the lack of consistency in methods and conventions across studies. Not all studies shown in Table 3.16 cover the entire transportation sector, even of the countries included in the study. Most consider a limited set of policy options, (e.g., only motor vehicle fuel economy improvement). In general, the studies do not report marginal costs of GHG mitigation, but rather average costs versus a base case. Keeping all of these limitations in mind, *Table 3.16* summarizes the findings of several major studies. For 2010, the average low GHG reduction estimate is just under 7% of baseline total transport sector emissions in 2010, with the higher estimates averaging a 17% reduction. There is, however, considerable dispersion around both numbers, indicative both of uncertainty and differences in methodology and assumptions. For studies looking ahead to 2020, the average low estimate is 15% and the average high estimate is 34% of baseline 2020 transport sector emissions. Estimated (average rather than marginal) costs are generally negative (as much as -US$200/tC), indicating that fuel savings are expected to outweigh incremental costs. There are some positive cost estimates as high as US$200/tC, however. The majority of the studies cited in *Table 3.16* are based on engineering-economic analyses. Some argue that this method tends to underestimate welfare costs because trade-offs between CO_2 mitigation and non-price attributes (e.g., performance, comfort, reliability) are rarely explicitly considered (Sierra Research, Inc., 1999).

3.5 Manufacturing Industry

3.5.1 Introduction

This section deals with greenhouse gas emissions and greenhouse gas emission reduction options from the sector *manufacturing industry*[14]. Important are the energy intensive (or heavy) industries, including the production of metals (especially iron and steel, and aluminium), refineries, pulp and

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[14] NACE codes 15 to 37.

Table 3.16: *Estimates of the costs of reducing carbon emissions from transport based on various studies, 2010-2030* (Brown *et al*., 1998; ECMT, 1997; US DOE/EIA, 1998; DeCicco and Mark, 1998; Worrell *et al*., 1997b; Michaelis, 1997; Denis and Koopman, 1998)

						Quantity		**Reduction**		**Cost in US$/MtC**	
Study	**Year of publication**	**Application**	**Year of scenario**	**Years in future**	**Country**	**Low (MtC)**	**High (MtC)**	**Low (%)**	**High (%)**	**Low**	**High**
OECD Working Paper 1	1997	Light-duty road vehicle efficiency	2010	13	OECD	50	150	2.5	7.5	US$0	US$0
US National Academy of Sciences	1992	Vehicle efficiency	2010	18	USA	20	79	3.2	12.7	-US$275	-US$77
	1992	System efficiency	2010	18	USA	3	13	0.5	2.1	-US$183	US$18
US DOE 5-Lab Study	1997	Transport sector	2010	13	USA	82	103	13.2	16.6	-US$157	US$6
US Energy Information Administration	1998	Transportation sector	2010	12	USA	41	55	6.6	8.9	-US$121	US$163
Tellus Institute	1997	Transportation efficiency	2010	13	USA	90	90	14.5	14.5	-US$465	-US$465
	1997	Transportation demand reduction	2010	13	USA	61	61	9.8	9.8	US$0	US$0
ACEEE	1998	Transport sector	2010	12	USA		125		22.6	-US$139	
US DOE, Clean Energy Futures	2000	Transport sector	2010	10	USA	20	66	3.2	10.5	-US$280	-US$144
European Council of Ministers of Transport	1997	Transport sector	2010	13	Austria	2			8.3		
	1997	Transport sector	2010	13	Belgium	4			13.3		
	1997	Transport sector	2010	13	Czech R.	6			57.1		
	1997	Transport sector	2010	13	Netherlands	11			37.2		
	1997	Transport sector	2010	13	Poland	5			12.8		
	1997	Transport sector	2010	13	Slovak R.	1			16.3		
	1997	Transport sector	2010	13	Sweden	4			23.2		
	1997	Transport sector	2010	13	UK	22			14.3		
Summary for 2010					**Minimum/maximum**			**0.5**	**57.1**	**-US$465**	**US$163**
					average			**6.7**	**16.9**	**-US$153**	**-US$62**
Denis and Koopman	1998	Road pricing	2015	17	EU				25.0		
	1998	CO_2 tax	2015	17	EU				13.0		
	1998	Purchase subsidy + CO_2 tax	2015	17	EU				14.0	US$0	US$0
US Congress OTA	1991	Transportation efficiency	2015	24	USA		195		29.2	-US$180	US$195
Summary for 2015					**Minimum/maximum**			**13.0**	**29.2**	**-US$180**	**US$195**
					average				**20.3**		
US DOE, Clean Energy Futures	2000	Transport sector	2020	20	USA	58	163	8.3	23.4	-US$234	-US$153
ACEEE	1998	Transport sector	2020	22	USA		260		42.4	-US$164	
United Nations	1997	Transport sector	2020	23	Industrialized	153	423	14.9	41.2		
	1997	Transport sector	2020	23	Transitional	72	126	18.2	31.8		
	1997	Transport sector	2020	23	Developing	297	450	28.4	43.1		
OECD Working Paper 1	1997	Light-duty road vehicle efficiency	2020	23	OECD	100	500	4.3	21.7	US$0	US$0
Summary for 2020					**Minimum/maximum**			**4.3**	**43.1**	**-US$234**	
					average			**14.8**	**34.0**		
ACEEE	1998		2030	32	USA		401		58.8	-US$192	

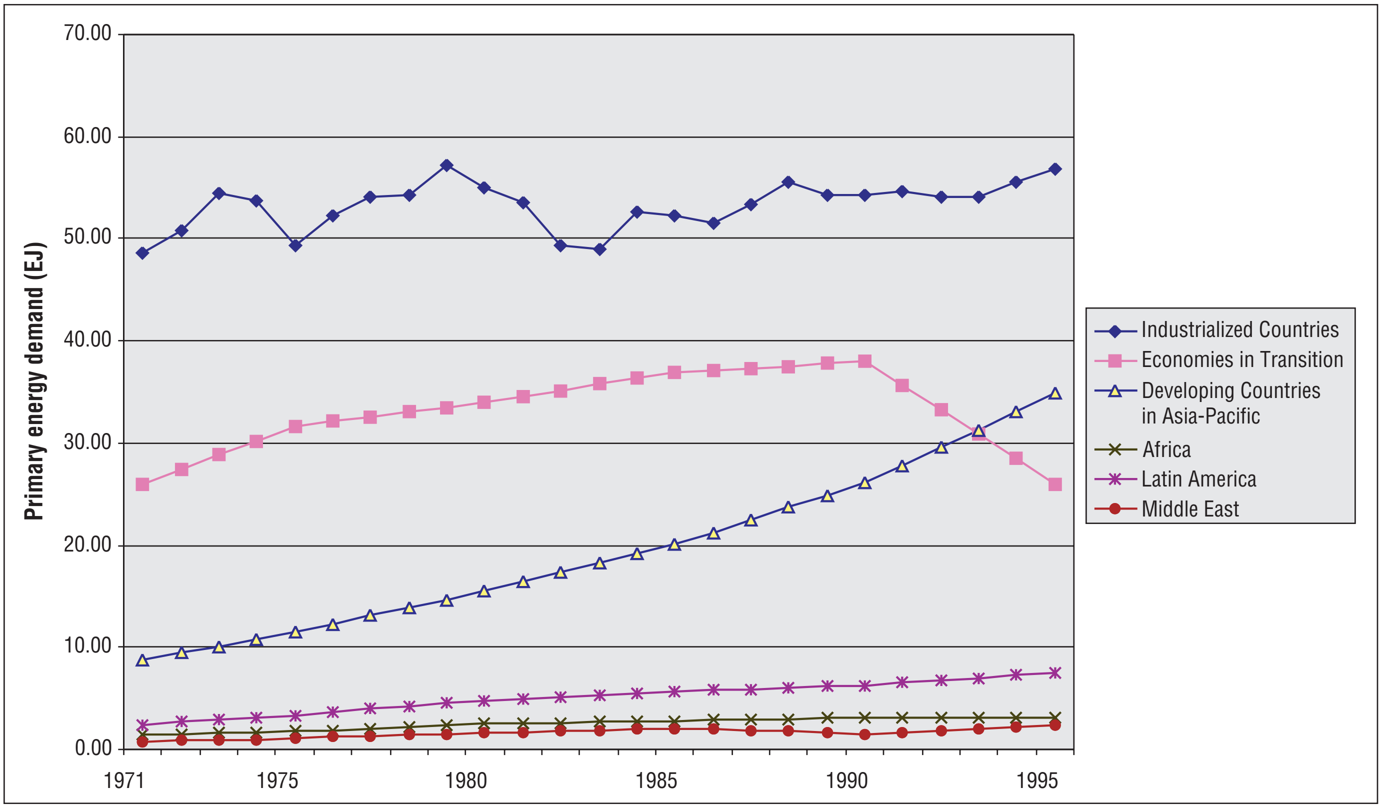

Figure 3.11: *Development of industrial energy use in terms of primary energy (direct fuel use and indirect fuel use in power plants) in the different world regions. Data from Price at al, 1998, 1999.*

paper, basic chemicals (important ones are nitrogen fertilizers, petrochemicals, and chlorine), and non-metallic minerals (especially cement). The less energy intensive sectors, also called *light industry*, are among others, the manufacture of food, beverages, and tobacco; manufacturing of textiles; wood and wood products; printing and publishing; production of fine chemicals; and the metal processing industry (including automobiles, appliances, and electronics). In many cases these industries each produce a wide variety of final products. Non-CO_2 gases emitted from the manufacturing sector include nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Adipic acid, nitric acid, HCFC-22 and aluminium production processes emit these gases as unintended by-products. A number of other highly diverse industries, including a few sectors replacing ozone- depleting substances, use these chemicals in manufacturing processes[15].

All direct emissions from manufacturing are taken into account, plus emissions in the electricity production sector, as far as they are caused by electricity consumption by manufacturing industry firms.

Kashiwagi *et al*. (1996) dealt with industry emission reduction options in IPCC (1996). In that chapter, processes, energy consumption, and a range of emission reduction options (mainly for CO_2) have been described on a sector-by-sector basis. For the TAR, these options are summarized (see Section 3.5.3) and estimates of potentials and costs for emission reduction are quantified. The scope of TAR has been expanded to also include greater detail on non-CO_2 greenhouse gases and the differences in regional emission profiles and emission reduction opportunities.

3.5.2 *Energy and GHG Emissions*

Emissions of carbon dioxide are still the most dominant contribution of manufacturing industry to total greenhouse gas emission. These emissions are mainly connected to the use of energy. In *Figure 3.11* an overview is given of the energy consumption of the manufacturing industry (see also *Table 3.1*). Energy use is growing in all regions except in the economies in transition, where energy consumption declined by 30% in the period 1990 to 1995. This effect is so strong that it nearly offsets growth in all other regions. In industrialized countries energy use is still growing at a moderate rate; electricity consumption grows faster than fuel consumption. The strongest growth rates occur in the developing countries in the Asia-Pacific region. All developing countries together account for 36% of industrial energy use. However, industry in industrial-

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[15] Chapter 3 Appendix *Options to Reduce Global Warming Contributions from Substitutes for Ozone Depleting Substances* elaborates on the sectors that would be affected by both the Montreal Protocol and the Kyoto Protocol.

Table 3.17: *Overview of greenhouse gas emissions by manufacturing industry (in* MtC_{eq}*) in 1990 (1995 for the fluorinated gases). Note that the accuracy is much less than 1* MtC_{eq}
Sources: see notes.

Source	**OECD**	**EIT**	**Asia-Pacific DCs**	**Other DCs**	**Total**	**Trends after 1990 (% per year)**
Fuel CO_2[f]	546	454	461	105	1567	Stable (90-95)
Electricity CO_2[f]	341	167	170	66	726	+1.2% (90-95)
CO_2 from cement[a]	51	25	60	19	155	
CH_4[a]					8	
N_2O[b]	34	13	13	4	65	
HFC-23[c]	19	~1	~2	~1	22	+2% (90-97)
PFCs[d]	>11	>4	>4		31	Decreasing
SF_6[e]	26	6	7		40	+4% (90-96)
Total					2614	

[a] Olivier *et al*., 1996.

[b] Total N_2O emissions are estimated to be 489 ktonnes (65MtC_{eq}) (Olivier *et al*., 1999). Main industrial process that lead to emissions of N_2O are the production of adipic acid (38 MtC_{eq}) and nitric acid (23 MtC_{eq}).

[c] At present, the main HFC source from industrial processes is the emission of HFC-23 (trifluoromethane, with an estimated GWP of 11,700) as an unintended by-product of HCFC-22 (chlorodifluoromethane) production. The weight percentage by-product is estimated to be 4%, 3%-5% (March Consulting, 1998) or 1.5%–3% (Branscome and Irving, 1999) of the HCFC-22 production. Some abatement takes place, but the fraction for 1995 is not known. Atmospheric measurements of HFC-23 suggest an *emitted* by-product fraction of 2.1% (Oram *et al*., 1998). This leads to the reported 22MtC_{eq} These are not inconsistent with reported US -23 emissions of 9.5MtC_{eq} in 1990 and 7.4 MtC_{eq} in 1995 (US EPA, 1998) and for Europe of 9.5MtC_{eq}. Regional breakdown and trend from Olivier (2000). For other HFC emissions see the Appendix to this Chapter.

[d] Perfluorocarbons (PFCs) have the general chemical formula C_xF_{2x+2}.The manufacturing industry is thought to be responsible for all PFC emissions, mainly CF_4 and C_2F_6. On the basis of recent atmospheric concentration data, Harnisch (1998) estimates emissions of 10,500 tonnes and 2000 per year respectively (20 MtC_{eq}). Most of these emissions are the by-product of aluminium smelting; a smaller but growing contribution is from plasma etching in semi-conductor manufacturing and use as solvent 1.4 - 4 MtC_{eq} (Victor and McDonald, 1999; Harnisch *et al*, 1998). Some applications for higher carbon PFCs have also been identified and may become significant. C_3F_8 (1.4MtC_{eq}) is emitted as a result of various activities, like plasma etching, fire extinguishers and as an additive to the refrigerant R-413a. Emissions of c-C_4F_8 (4MtC_{eq}) may result from the pyrolysis of fluoropolymers, whereas C_6F_{14} originates from use of this substance as a solvent (5 MtC_{eq}) (Harnisch *et al*., 1998; Harnisch, 2000). Regional breakdown is based on Victor and McDonald (1999) and is only for CF_4 and C_2F_6.

[e] Maiss and Brenninkmeijer (1998) estimate the following breakdown of 1995 emissions (in tonnes SF_6): switchgear manufacturers: 902; utilities and accelerators: 3476; magnesium industry: 437; electronics industry: 327; "using adiabatic properties": 390; other uses: 498; total 6076. The regional breakdown is extrapolated from Victor and MacDonald (1999).

[f] Price *et al*., 1999.

ized countries on a per capita basis uses about 10 times as much energy as in developing countries.

The CO_2 emissions by the industrial sector worldwide in 1990 amounted to 1,250MtC. A breakdown of 1990/1995 emissions is given in *Table 3.17*. However, these emissions are only the direct emissions, related to industrial fuel consumption. The indirect emissions in 1990, caused by industrial electricity consumption, are estimated to be approximately 720MtC (Price *et al*., 1998 and Price *et al*,. 1999). In the period 1990 to 1995 carbon emissions related to energy consumption have grown by 0.4% per year.

Note that the energy-related CO_2 in a number of sectors are partly process emissions, e.g., in the refineries and in the production of ammonia, steel, and aluminium (Kashiwagi *et al*., 1996). However, the statistics often do not allow us to make a proper separation of these emissions.

Olivier *et al.,* (1996) also report 91MtC of non-energy use (lubricants, waxes, etc.) and 167MtC for feedstock use (naphtha, *etc*.). Further work on investigating the fact of these carbon streams is necessary; knowledge about emission reduction options is still in an early stage (Patel and Gielen, 1999; Patel, 1999).

An overview of industrial greenhouse gas emissions is given in *Table 3.17*. The manufacturing industry turns out to be responsible for about one-third of emissions of greenhouse gases that are subject to the Kyoto Protocol. Non-CO_2 greenhouse gases make up only about 6% of the industrial emissions.

Underlying Causes for Emission Trends

Unander *et al*. (1999) have analysed the underlying factors for the development of energy consumption in OECD countries in the period 1990 to 1994. Generally, the development of energy use can be broken down into three factors: volume, structure and energy efficiency. In the period examined, development of production volume differed from country to country, ranging from a 2.0% growth per annum in Norway to a 1.4% per annum decline in Germany. The second factor is structure: this is determined by the shares that the various sectors have in the total industrial production volume. A quite remarkable result is that in nearly all countries, structural change within the manufacturing industry has an increasing effect on energy use, i.e. there is a shift towards more energy-intensive industrial sectors. This is a contrast with earlier periods. Finally, Unander *et al*. (1999) found – with some exceptions – a continuing decline in energy intensity within sectors, be it at a lower pace than in the period 1973 to 1986. For more results see *Table 3.18*.

In the paper by Unander *et al*. (1999), energy intensity is measured in terms of energy use per unit of value added. An indicator more relevant to the status of energy efficiency in a country is the specific energy consumption, corrected for structural differences. Also, such an indicator shows a continuous downward trend, as can be seen in *Figure 3.12*. Similar results were obtained for the iron and steel industry (Worrell *et al*., 1997a).

A substantial part of industrial greenhouse gas emissions is related to the production of a number of primary materials. Relevant to this is the concept of dematerialization (the reduction of society's material use per unit of GDP). For most individual materials and many countries dematerialization can be observed. Cleveland and Ruth (1999) reviewed a range of studies that show this. They suggest that it cannot be concluded to be due to an overall decoupling of economy and material inputs, among other reasons because of the inability to measure aggregate material use. Furthermore, they note that some analysts observe relinking of economic growth and material use in more recent years. They warn against "gut" feeling that technical change, substitution, and a shift to the "information age" inexorably lead to decreased materials intensity and reduced environmental impact.

3.5.3 New Technological and Other Options for CO_2 and Energy

3.5.3.1 *Energy Efficiency Improvement*

Energy efficiency improvement can be considered as the major option for emission reduction by the manufacturing industry. A wide range of technologies is available to improve energy efficiency in this industry. An overview is given in *Table 3.19*. Note that the total technical potential consists of a larger set of

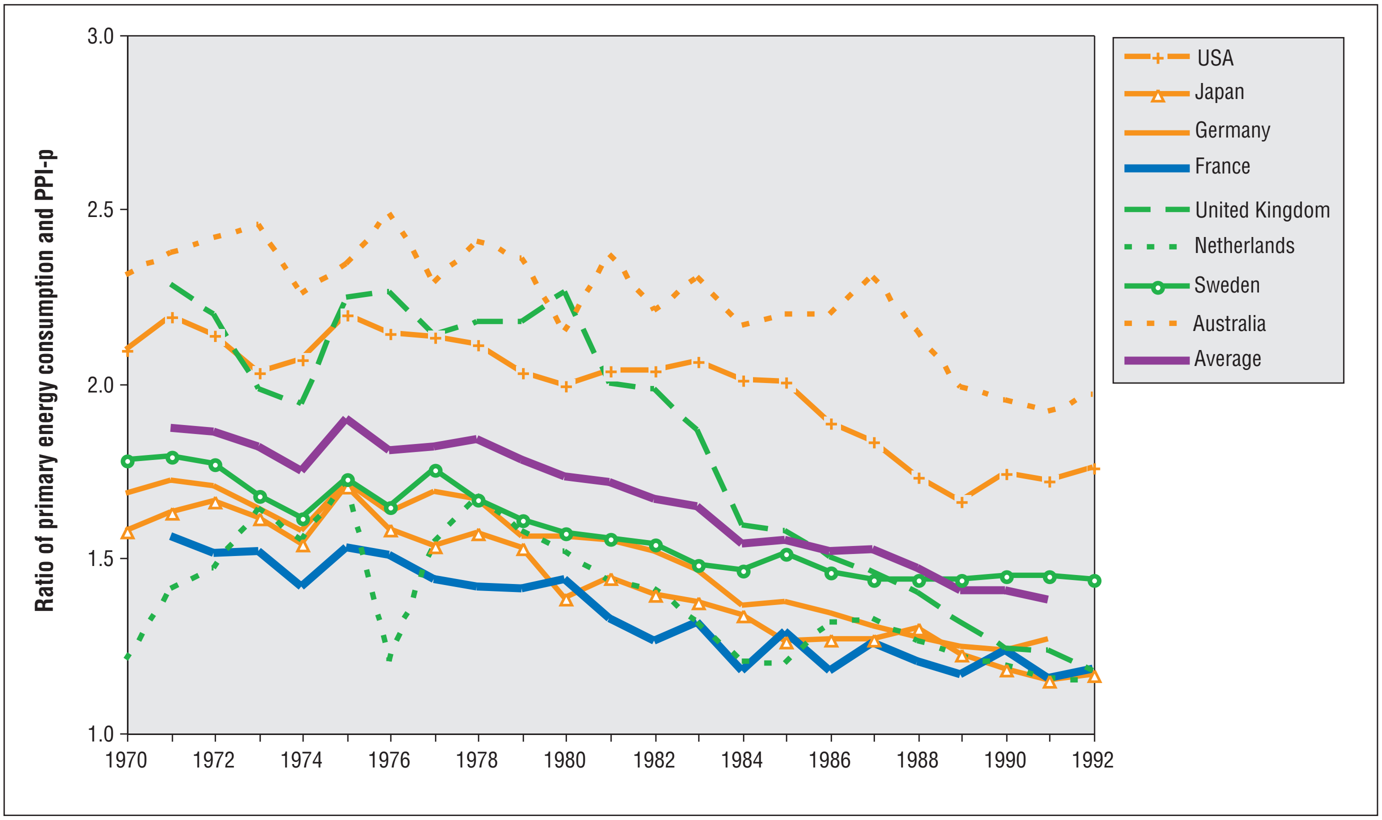

Figure 3.12: *Development of the primary energy demand per unit of production in the pulp and paper industry (PPI-p) in OECD countries.*

Table 3.18: *Average annual rates of change in manufacturing energy use, and the degree to which changes in volume, structure and energy intensity contribute to such change*
Source: Unander *et al*. (1999).

Country	**Development in energy use**			**Effect of volume development on energy use**			**Effect of structural change in industry on energy use**			**Effect of energy intensity changes within sectors on energy use**		
	1973-1986	1986-1990	1990-1994	1973-1986	1986-1990	1990-1994	1973-1986	1986-1990	1990-1994	1973-1986	1986-1990	1990-1994
Australia	0.3%	3.3%	0.8%	1.1%	3.2%	1.9%	0.0%	0.6%	-0.4%	-1.2%	-2.1%	0.1%
Canada	N/A	0.7%	0.8%	2.0%	1.7%	1.4%	N/A	-0.1%	0.4%	N/A	-0.8%	-1.0%
Denmark	-1.1%	-3.3%	1.5%	2.1%	-0.6%	0.9%	-0.3%	-0.1%	0.0%	-2.9%	-2.6%	0.7%
Finland	1.7%	3.3%	1.8%	2.9%	3.2%	1.6%	-0.1%	0.3%	1.6%	-2.0%	-0.2%	-1.5%
France	-2.3%	1.3%	0.7%	1.2%	3.2%	-0.5%	-0.2%	0.1%	0.0%	-3.3%	-2.0%	1.2%
Germany	-1.8%	0.6%	-0.5%	1.1%	2.7%	-1.4%	-0.4%	-0.5%	1.0%	-2.6%	-1.6%	-0.1%
Italy	-1.8%	3.8%	-0.7%	3.4%	4.0%	0.2%	0.0%	0.2%	0.4%	-5.2%	-0.4%	-1.4%
Japan	-1.8%	3.5%	-0.1%	3.2%	6.3%	-0.4%	-2.0%	-0.2%	0.1%	-3.0%	-2.6%	0.2%
Netherlands	-4.0%	4.4%	0.0%	1.8%	2.8%	0.6%	1.1%	-0.4%	0.8%	-6.9%	2.0%	-1.5%
Norway	0.1%	-0.9%	1.5%	0.5%	-1.3%	2.0%	0.6%	2.2%	0.8%	-1.1%	-1.8%	-1.3%
Sweden	-1.4%	0.0%	0.0%	1.3%	1.5%	1.3%	-0.4%	0.3%	2.8%	-2.2%	-1.9%	-4.1%
UK	-3.6%	0.0%	-2.4%	-0.7%	3.9%	-0.2%	-0.4%	-0.3%	-0.5%	-2.6%	-3.6%	-1.6%
USA	-1.9%	2.9%	1.9%	2.0%	3.0%	1.8%	-1.1%	-0.5%	0.1%	-2.8%	0.5%	1.6%

Table 3.19: *Overview of important examples of industrial energy efficiency improvement technologies and indications of associated emission reduction potentials and costs. For an explanation see the legend below. Note that the scale is not linear. Cost may differ from region to region. This overview is not meant to be comprehensive, but a representation of the most important options.*
Sources: Kashiwagi *et al*. (1996), De Beer *et al*. (1994), ETSU (1994), WEC (1995a or b), IEA Greenhouse Gas R&D Programme (2000a), Martin *et al*. (2000).

Sector	**Technology**	**Potential in 2010**	**Emission reduction costs**	**Remarks**
All industry	Implementation of process control and energy management systems	■■■■	-	Estimate: 5% saving on primary energy demand worldwide
	Electronic adjustable speed drives	■■	++	In industrial countries ~30% of industrial electricity demand is for electric drive systems
	High-efficiency electric motors	■■	+ *	
	Optimized design of electric drive systems, including low-resistance piping and ducting	■■	+++	Not known for developing countries.
	Process integration, e.g., by applying pinch technology	■■■■	+	Savings vary per plant from 0%-40% of fuel demand; costs depend on required retrofit activity.
	Cogeneration of heat and power	■■■■	-	
Food, beverages and tobacco	Application of efficient evaporation processes (dairy, sugar)	■	+	
	Membrane separation	■	++	
Textiles	Improved drying systems (e.g., heat recovery)	■	++	
Pulp and paper	Application of continuous digesters (pulping)	■	+	Applicable to chemical pulping only; energy generally supplied as biofuels
	Heat recovery in thermal mechanical pulping	■	+++	Energy generally supplied as biofuels
	Incineration of residues (bark, black liquor) for power generation	■	+	
	Pressing to higher consistency, e.g., by extended nip press (paper making)	■	-	Not applicable to all paper grades
	Improved drying, e.g., impulse drying or condensing belt drying	■■	-	Pre-industrial stage; results in a smaller paper machine (all paper grades)
	Reduced air requirements, e.g., by humidity control in paper machine drying hoods	■	+	
	Gas turbine cogeneration (paper making)	■■	-	
Refineries	Reflux overhead vapour recompression (distillation)	■	+	
	Staged crude preheat (distillation)	■	+	
	Application of mechanical vacuum pumps (distillation and cracking)	■■	+	
	Gas turbine crude preheating (distillation)	■■	-	Applicable to 30% of the heat demand of refineries
	Replacement of fluid coking by gasification (cracking)	■	+	
	Power recovery (e.g., at hydrocracker)	■	-	
	Improved catalysts (catalytic reforming)	■■	+	

(continued)

Table 3.19: *continued*

Sector	Technology	Potential in 2010	Emission reduction costs		Remarks
Fertilizers	Autothermal reforming	■	-	*	
	Efficient CO_2 separation (e.g., by using membranes)	■	+	*	Saving depends strongly on opportunities for process integration of old and new techniques.
	Low pressure ammonia synthesis	■	+	*	Site-specific: an optimum has to be found between synthesis pressure, gas volumes to be handled, and reaction speed
Petrochemicals	Mechanical vapour recompression (e.g., for propane/propene splitting)	■	+		
	Gas turbine cogeneration	■	-		Not yet demonstrated for furnace heating
	De-bottlenecking	■■	-		Estimate: 5% saving on fuel demand
	Improved reactors design, e.g., by applying ceramics or membranes	■	+		Not yet commercial
	Low pressure synthesis for methanol	■	+	*	Site-specific: an optimum has to be found between synthesis pressure, gas volumes to be handled, and reaction speed
Other chemicals	Replacement of mercury and diaphragm processes by membrane electrolysis (chlorine)	■	+	*	In some countries, e.g., Japan, membrane electrolysis is already the prevailing technology
	Gas turbine cogeneration	■■	-		
Iron and steel	Pulverized coal injection up to 40% in the blast furnace (primary steel)	■■	-		Maximum injection rate is still topic of research
	Heat recovery from sinter plants and coke ovens (primary steel)	■■	+		
	Recovery of process gas from coke ovens, blast furnaces and basic oxygen furnaces (primary steel)	■■■	-		
	Power recovery from blast furnace off-gases (primary steel)	■	+		
	Replacement of open-hearth furnaces by basic oxygen furnaces (primary steel)	■■■	-	*	Mainly former Soviet Union and China
	Application of continuous casting and thin slab casting	■■■	-	*	Replacement of ingot casting
	Efficient production of low-temperature heat (heat recovery from high-temperature processes and cogeneration)	■	++		Heat recovery from high temperature processes is technically difficult
	Scrap preheating in electric arc furnaces (secondary steel)	■	+		
	Oxygen and fuel injection in electric arc furnaces (secondary steel)	■	-		
	Efficient ladle preheating	■			
	Second-generation smelt reduction processes (primary steel)	■■■	-		First commercial units expected after 2005
	Near-net-shape casting techniques	■■	-		Not yet commercial
Aluminium	Retrofit existing Hall-Héroult process (e.g., alumina point-feeding, computer control)	■	-/+		
	Conversion to state-of-the-art PFBF technology	■	+		
	Wettable cathode	■	+++		Not yet commercial
	Fluidized bed kilns in Bayer process	■	++		
	Cogeneration integrated in Bayer process				

(continued)

Table 3.19: *continued*

Sector	Technology	Potential in 2010	Emission reduction costs	Remarks
Cement and other non-metallic minerals	Replacement of wet process kilns	■■	-/+ *	
	Application of multi-stage preheaters and pre-calciners	■	+	No savings expected in retrofit situations
	Utilization of clinker production waste heat or cogeneration for drying raw materials	■■	-	
	Application of high-efficiency classifiers and grinding techniques	■	+	
	Application of regenerative furnaces and improving efficiency of existing furnaces (glass)	■	+	Costs of replacing recuperative furnaces by regenerative furnaces are high (++)
	Tunnel and roller kilns for bricks and ceramic products	■	- *	
Metal processing and other light industry	Efficient design of buildings, air conditioning and air treatment systems, and heat supply systems	■	- *	
	Replacement of electric melters by gas-fired melters (foundries)	■	- *	
	Recuperative burners (foundries)	■	- *	
Cross-sectoral	Heat cascading with other industrial sectors	■■	+	
	Waste heat utilization for non-industrial sectors	■■	+	

Legend

Potential: ■ = 0-10MtC; ■■ = 10-30MtC; ■■■ = 30-100MtC; ■■■■ > 100MtC.

Annualized costs at discount rate of 10%: - = benefits are larger than the costs; + = US$0-US$100/tC ; ++ = US$100-US$300/tC; +++ > US$300/tC

An asterisk (*) indicates that cost data are only valid in case of regular replacement or expansion.

options and differs from country to country (see Section 3.5.5). Especially options for light industry are not worked out in detail. An important reason is that these sectors are very diverse, and so are the emission reduction options. Nevertheless, there are in relative terms probably more substantial savings possible than in heavy industry (see, e.g., De Beer *et al*., 1996). Examples of technologies for the light industries are efficient lighting, more efficient motors and drive systems, process controls, and energy saving in space heating.

An extended study towards the potential of energy efficiency improvement was undertaken by the World Energy Council (WEC, 1995a). Based on a sector-by-sector analysis (supported by a number of country case studies) a set of scenarios is developed. In a baseline scenario industrial energy consumption grows from 136EJ in 1990 to 205EJ in 2020. In a state-of-the-art scenario the assumption is that replacement of equipment takes place with the current (1995 in this case) most efficient technologies available; in that case industrial primary energy requirement is limited to 173EJ in 2020. Finally, the *ecologically driven/advanced technology* scenario assumes an international commitment to energy efficiency, as well as rapid technological progress and widespread application of policies and programmes to speed up the adoption of energy efficient technologies in all major regions of the world. In that case energy consumption may stabilize at 1990 levels. The difference between baseline and ecologically driven/advanced technology is approx. 70EJ, which is roughly equivalent to 1100 MtC. Of this reduction approx. 30% could be realized in OECD countries; approx. 20% in economies-in-transition, and approximately 50% in developing countries. The high share for developing countries can be explained by the high production growth assumed for these countries and the currently somewhat higher specific energy use in these countries.

Apart from these existing technologies, a range of new technologies is under development. Important examples are found in the iron and steel industry. Smelt reduction processes can replace pelletizing and sinter plants, coke ovens, and blast furnaces, and lead to substantial savings. Near net shape casting techniques for steel avoids much of the energy required for rolling (De Beer *et al*., 1998). Other examples are black liquor gasification in the pulp industry, improved water removal processes for paper making, e.g., impulse drying and air impingement drying, and the use of membrane reactors in the chemical industry. A further overview is given in Blok *et al*.

(1995). Although some of these options already can play a role in the year 2010 (see *Table 3.19*), their full implementation may take some decades. De Beer (1998) carried out an in-depth analysis for three sectors (paper, steel and ammonia). He concludes that new industrial processes hold the promise to reduce the current gap between industrial best practice and theoretical minimum required energy use by 50%.

3.5.3.2 Fuel Switching

In general not much attention is paid to fuel switching in the manufacturing industry. Fuel choice to a large extent is sector dependent (coal for dominant processes in the iron and steel industry, oil products in large sectors in the chemical industry). Nevertheless, there seems to be some potential. This may be illustrated by the figures presented in *Table 3.20* where – per sector – the average carbon intensity of fuels used in industry is compared to the country with the lowest carbon intensity. This indicates that fuel switching within fossil fuels can reduce CO_2 emissions by 10%–20%. However, it is not clear whether the switch is feasible in practical situations, or what the costs are. However, there are specific options that combine fuel switching with energy efficiency improvement. Examples are: the replacement of oil- and coal-fired boilers by natural-gas fired combined heat and power (CHP) plant; the replacement of oil-based partial oxidation processes for ammonia production by natural-gas based steam reforming; and the replacement of coal-based blast furnaces for iron production by natural-gas based direct reduction. Daniëls and Moll (1998) calculate that costs of this option are high under European energy price conditions. In the case of lower natural gas prices this option may be more attractive.

3.5.3.3 Renewable Energy

See Section 3.8.4.3 for an extensive assessment of renewable energy technology.

3.5.3.4 Carbon Dioxide Removal

Carbon dioxide recovery from flue gases is feasible from industrial processes that are operated on a sufficiently large scale. Costs are comparable with the costs of recovering CO_2 from power plant flue gases. See the discussion of these options in Section 3.8.4.4.

However, there are a number of sectors where cheaper recovery is possible. These typically are processes where hydrogen is produced from fossil fuels, leaving CO_2 as a by-product. This is the case in ammonia production (note that some of the CO_2 is already utilized), and increasingly in refineries. Costs can be limited to those of purification, drying and compression. They can be on the order of about US$30/tC avoided (Farla *et al.*, 1995). Another example of carbon dioxide recovery connected to a specific process is the recovery of CO_2 from the calcination of sodium bicarbonate in soda ash production. The company Botash in Botswana recovers and reuses 70% of the CO_2 generated this way (Zhou and Landner, 1999). There are several industrial gas streams with a high CO_2 content from which carbon dioxide recovery theoretically is more efficient than from flue gas (Radgen, 1999). However, there are no technical solutions yet to realize this (Farla *et al.*, 1995).

3.5.3.5 Material Efficiency Improvement

In heavy industry most of the energy is used to produce a limited number of primary materials, like steel, cement, plastic, paper, etc. Apart from process changes that directly reduce the CO_2 emissions of the processes, also the limitation of the use of these primary materials can help in reducing CO_2 emissions of these processes. A range of options is available: material efficient product design (Brezet and van Hemel, 1997); material substitution; product recycling; material recycling; quality cascading; and good housekeeping (Worrell *et al.*, 1995b). A review of such options is given in a report for the UN (1997).

Table 3.20: *Specific carbon-emission factors for fossil fuel use in manufacturing industry*
The figures are calculated on the basis of the IEA Energy Balances

Sector	Specific carbon emission (kg/GJ)	Lowest specific carbon emission found (kg/GJ)
Iron and steel industry	23.6	19.8[a]
Chemical industry	19.1	15.3
Non-ferrous metals industry	19.2	15.3
Non-metallic minerals industry	20.4	16.7
Transportation equipment industry	17.3	15.3
Machine industry	17.7	15.5
Food products industry	18.4	15.6
Pulp and paper industry	18.5	15.3
Total industry	20.1	18.1

[a] Excludes Denmark (no primary steel production)

An interesting integral approach to material efficiency improvement is the suggestion of the "inverse factory" that does not transfer the ownership of goods to the consumers, but just gives the right of use, taking back the product after use for the purpose of reuse or recycling (Kashiwagi *et al*., 1999).

Some quantitative studies are available on the possible effects of material efficiency improvement. For the USA, Ruth and Dell' Anno (1997) calculate that the effect of increased glass recycling on CO_2 emissions is limited. According to these authors, light-weighting of container glass products may be more promising. In addition, Hekkert *et al*. (2000) show that product recycling of glass bottles (instead of recycling the material to make new products) is also a promising way to reduce CO_2 emissions.

For packaging plastics it is estimated that more efficient design (e.g., use of thinner sheets) and waste plastic recycling could lead to savings of about 30% on the related CO_2 emissions. Hekkert *et al*. (2000) found a technical potential for CO_2 emission reduction for the *total* packaging sector (including paper, wood, and metals) of about 50%.

Worrell *et al*. (1995c) estimate that more efficient use of fertilizer by, e.g., improved agricultural practices and slow release fertilizer, in the Netherlands may lead to a reduction of fertilizer use by 40%.

Closed-loop cement recycling is not yet technically possible (UN, 1997). A more important option for reducing both energy-related and process emissions in the cement industry is the use of blended cements, where clinker as input is replaced by, e.g., blast furnace slag or fly ash from coal combustion. Taking into account the regional availability of such inputs and maximum replacement, it is estimated that about 5%–20% of total CO_2 emissions of the cement industry can be avoided. Costs of these alternative materials are generally lower than those of clinker (IEA Greenhouse Gas R&D Programme, 1999). Note that these figures are based on a static analysis for the year 1990 (Worrell *et al*., 1995a).

Some integral approaches give an overview of the total possible impact of changes in the material system. Gielen (1999) has modelled the total Western European materials and energy system, using a linear optimization model (Markal). In a baseline scenario emissions of greenhouse gases in the year 2030 are projected to be 5000 MtC_{eq}. At a cost of US$200/tC 10% of these emissions can be avoided through "material options"; at a cost of US$800/tC this increases to 20%. Apart from "end-of-pipe" options, especially material substitution is important, e.g., replacement of petrochemical feedstocks by biomass feedstocks (see also Chapter 4); steel by aluminium in the transport sector; and concrete by wood in the buildings sector. At higher costs, waste management options (energy recovery, plastics recycling) are also selected by the model. Gielen (1999) notes that in his analysis the effect of material efficiency of product design is underestimated.

A study for the UN (1997) estimates that the effect of material efficiency improvement in an "ecologically-driven/advanced technology" scenario in the year 2020 could make up a difference of 40 EJ in world primary energy demand (approximately 7% of the baseline energy use), which is equivalent to over 600 Mt of carbon emissions.

3.5.4 Emission Reduction Options for Non-CO_2 Greenhouse Gases

Non-CO_2 gases from manufacturing (HFCs, PFCs, SF_6, and N_2O) are increasingand. Furthermore, PFCs and SF_6 have extremely long atmospheric lifetimes (thousands of years) and GWP values (thousands of times those of CO_2) resulting in virtually irreversible atmospheric impacts. Fortunately, there are technically-feasible, low cost emission reduction options available for a number of applications. Since the SAR, implementation of major technological advances have led to significant emission reductions of N_2O and the fluorinated greenhouse gases produced as unintended by-products. For the case of fluorinated gases being used as working fluids or process gases, process changes, improved containment and recovery, and use of alternative compounds and technologies have been adopted. On-going research and development efforts are expected to further expand emission reduction options. Energy efficiency improvements are also being achieved in some refrigeration and foam insulation applications, which use fluorinated gases. Emission reduction options by sector are highlighted below. The Chapter 3 Appendix reviews use and emissions of HFCs and PFCs being used as substitutes for ozone-depleting substances.

3.5.4.1 Nitrous Oxide Emissions from Industrial Processes

Adipic acid production. Various techniques, like thermal and catalytic destruction, are available to reduce emissions of N_2O by 90% – 98% (Reimer *et al*., 2000). Reimer *et al*. (2000) report costs of catalytic destruction to be between US$20 and US$60/tN_2O, which is less than US$1/$tC_{eq}$. Costs of thermal destruction in boilers are even lower. The inter-industry group of five major adipic acid manufacturers worldwide in 1991 to 1993 have agreed on information exchange and on a substantial emission cut before the year 2000. These major producers probably will have reduced their joint emissions by 91%. It is estimated that emissions from the 24 plants producing adipic acid worldwide will be reduced by 62% in the year 2000 compared to 1990 (Reimer *et al*., 2000).

Nitric acid production. Concentrations of N_2O in nitric acid production off-gases are lower than in the case of adipic acid production. Catalytic destruction seems to be the most promising option for emission reduction. Catalysts for this purpose are under development in a few places in the world. Oonk and Schöffel (1999) estimate that emissions can be reduced to a large extent at costs between US$2 and US$10/tC_{eq}.

3.5.4.2 PFC Emissions from Aluminium Production

The smelting process entails electrolytic reduction of alumina (Al_2O_3) to produce aluminium (Al). The smelter pot contains alumina dissolved in an electrolyte, which mainly consists of molten cryolite (Na_3AlF_6). Normal smelting is interrupted by an "anode effect" that is triggered when alumina concentrations drop; excess voltages between the anode and alumina bath result in the formation of PFCs (CF_4 and C_2F_6) from carbon in the anode and fluorine in the cryolite (Huglen and Kvande, 1994; Cook, 1995; Kimmerle and Potvin, 1997). Several processes for primary aluminium production are in use, with specific emissions ranging from typically 0.15 to 1.34 kg CF_4 per tonne Al[16] depending on type of technology (determined by anode type and alumina feeding technology) (IAI, 2000). Measurements made at smelters with the best available technology (point feed prebake) indicate an emissions rate as low as 0.006 kg CF_4 per tonne Al (Marks *et al.*, 2000). Worldwide average emissions for 1995 are estimated to range from 0.26 to 0.77 kg CF_4 per tonne Al (Harnisch *et al.*, 1998; IEA, 2000). Manufacturers have carried out two surveys on the occurrence of anode effects and associated PFC-emissions (IPAI, 1996; IAI, 2000). Based on 60% coverage of world production (no data on Russia and China) they estimated a mean emission value of 0.3 kg CF_4 per tonne Al in 1997. Emission reductions were achieved from 1990 to 1995 by conversion to newer technologies, retrofitting existing plants, and improved plant operation. Industry-government partnerships also played a significant role in reducing PFC emissions. As of November 1998, 10 countries (which accounted for 50% of global aluminium production in 1998) have undertaken industry-government initiatives to reduce PFC emissions from primary aluminium production (US EPA, 1999d). It has been estimated that emissions could be further reduced via equipment retrofits, such as the addition or improvement of computer control systems (a minor retrofit) and the conversion to point-feed systems (a major retrofit). One study estimated 1995 emissions could be reduced an additional 10%–50% (depending on technology type and region) with maximum costs ranging from US\$110/tCO_{2eq} for a minor retrofit to nearly US\$1100/tCO_{2eq} for a major retrofit (IEA, 2000). A second study estimates that 1995 emissions could be reduced by 40% at costs lower than US\$30/tC_{eq}, by 65% at costs lower than US\$100/tC_{eq} and by 85% at costs lower than US\$300/tC_{eq} (Harnisch *et al.*, 1998; 15% discount rate, 10 year amortization).

The development of an inert, non-carbon anode is being pursued through governmental and industrial research and development efforts. A non-carbon anode would remove the source of carbon for PFC generation, thereby eliminating PFC emissions (AA, 1998). A commercially viable design is expected by 2020.

3.5.4.3 PFCs and Other Substances used in Semiconductor Production

The semiconductor industry uses HFC-23, CF_4, C_2F_6, C_3F_8, c-C_4F_8, SF_6 and NF_3 in two production processes: plasma etching thin films (etch) and plasma cleaning chemical vapour deposition (CVD) tool chambers. These chemicals are critical to current manufacturing methods because they possess unique characteristics when used in a plasma that currently cannot be duplicated by alternatives. The industry's technical reliance on high GWP chemicals is increasing as a consequence of growing demand for semiconductor devices (15% average annual growth), and ever-increasing complexity of semiconductor devices.

Baseline processes consume from 15%-60% of influent PFCs depending on the chemical used and the process application (etch or CVD). PFC emissions, however, vary depending on a number of factors: gas used, type/brand of equipment used, company-specific process parameters, number of PFC-using steps in a production process, generation of PFC by-product chemicals, and whether abatement equipment has been implemented. Semiconductor product types, manufacturing processes, and, consequently, emissions vary significantly across worldwide semiconductor fabrication facilities.

PFC use by the semiconductor industry began in the early 1990s. Global emissions from semiconductor manufacturing have been estimated at 4 MtC_{eq} in 1995 (Harnisch *et al.*, 1998). Options for reducing PFC emissions from semiconductor manufacture include process optimization, alternative chemicals, recovery and/or recycling, and effluent abatement. A number of emission reduction options are now commercially available. For plasma-enhanced CVD chamber cleans, switching to PFCs that are more fully dissociated in the plasma or installing reactive fluorine generators upstream of the chamber is favoured. For etch tools, PFC abatement is currently available (Worth, 2000). However, the size of wafers being processed and the design and age of the fabrication facility have a major impact on the applicability of PFC emission reduction technology. A recent study for the EU (Harnisch and Hendriks, 2000) estimated that 60% of projected emissions from this sector could be abated through the use of NF_3 in chamber cleaning at US\$110/tC_{eq}. According to the same study another 10% are available through alternative etch chemistry at no costs and about 20% through oxidation of exhausts from etch chambers at US\$330/tC_{eq}. The remaining emissions from existing systems are assumed to be currently virtually unabatable.

Through the World Semiconductor Council, semiconductor manufacturers in the EU, Japan, Korea, Taiwan (China), and the USA have set a voluntary emission reduction target to lower PFC emissions by at least 10% by 2010 from 1995 (1997 for Korea and 1997/1999 average for Taiwan (China) baselines (World Semiconductor Council, 1999). Members of the World Semiconductor Council represent over 90% of global semiconductor manufacture.

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[16] C_2F_6 emissions typically are 10% of CF_4 emissions.

3.5.4.4 HFC-23 Emissions from HCFC-22 Production

HFC-23 is generated as a by-product during the manufacture of HCFC-22 and emitted through the plant condenser vent. There are about 20 HCFC-22 plants globally. Additional new plants are expected in developing countries as CFC production plants are converted to comply with the Montreal Protocol and demand for refrigeration grows. Although HCFC-22 is an ozone-depleting chemical and production for commercial use will be phased out between 2005 and 2040, production as a feedstock chemical for synthetic polymers will continue.

Technologies available to reduce emissions of HFC-23 have been reviewed by the Research Triangle Institute (RTI, 1996; Rand *et al*., 1999) and March Consulting Group (March Consulting, 1998). Two emission reduction options were identified.

- Optimization of the HCFC-22 production process to minimize HFC-23 emissions. This technology is readily transferable to developing countries. Process optimization is relatively inexpensive and is demonstrated to reduce emissions of fully optimized plants to below 2% of HCFC-22 production. Nearly all plants in developed countries have optimized systems.
- Thermal destruction technologies are available today and can achieve emissions reductions of as high as 99%, although actual reductions will be determined by the fraction of production time that the destruction device is actually operating. Cost estimates are 7 ECU/tC for the EU (March Consulting, 1998, 8% discount rate).

3.5.4.5 Emissions of SF_6 from the Production, Use and Decommissioning of Gas Insulated Switchgear

SF_6 is used for electrical insulation, arc quenching, and current interruption in electrical equipment used in the transmission and distribution of high-voltage electricity. SF_6 has physical properties that make it ideal for use in high-voltage electric power equipment, including high dielectric strength, excellent arc quenching properties, low chemical reactivity, and good heat transfer characteristics. The high dielectric strength of SF_6 allows SF_6-insulated equipment to be more compact than equivalent air-insulated equipment. An SF_6-insulated substation can require as little as 10% of the volume of an air-insulated substation. Most of the SF_6 used in electrical equipment is used in gas-insulated switch gear and circuit breakers. SF_6 in electric equipment is the largest use category of SF_6 with global estimates of over 75% of SF_6 sales going to electric power applications (SPS, 1997). Options to reduce emissions include upgrading equipment with low emission technology, and improved handling during installation maintenance and/decommissioning (end-of-life) of SF_6-insulated equipment, which includes the avoidance of deliberate release and systematic recycling. Guidelines on equipment design to allow ease of gas recycling, appropriate gas handling and recycling procedures, features of gas handling and recycling equipment, and the impact of voluntary emission reduction programmes are contributing to the reduction of emissions from this sector (Mauthe *et al*, 1997; Causey, 2000).

Significant emissions may also occur during the manufacturing and testing of gas-insulated switch gear when the systems are repeatedly filled with SF_6 and re-evacuated (Harnisch and Hendriks, 2000). Historically these emissions have been in the range of 30%-50% of the total charge of SF_6. The existence and appropriate use of state-of-the art recovery equipment can help to reduce these emissions down to at least 10% of the total charge of SF_6.

3.5.4.6 Emissions of SF_6 from Magnesium Production and Casting

In the magnesium industry, a dilute mixture of SF_6 with dry air and/or CO_2 is used as a protective cover gas to prevent violent oxidation of the molten metal. It is assumed that all SF_6 used is emitted to the atmosphere. 7% of global SF_6 sales is estimated to be for magnesium applications (SPS, 1997). Manufacturing segments include primary magnesium production, die casting, gravity casting and secondary production (i.e., scrap metal recycling). Because of differing production processes and plant scale, emission reduction potential varies across manufacturing segments. Emissions of SF_6 in magnesium casting can potentially be reduced to zero by switching to SO, a highly toxic and corrosive chemical used over20 years ago as a protective cover gas. Harnisch and Hendriks (2000) estimate that net costs of switching from SF_6 to SO_2-based cover gas systems are about US\$1/tC_{eq}, but as a result of the high toxicity and corrosivity of SO_2 much more careful handling and gas management is required. In many cases the specific usage of SF_6 can be reduced by operational changes, including moderate technical modifications (Maiss and Brenninkmeijer, 1998). Companies may also reduce SF_6 emissions and save money by carefully managing the concentration and application of the cover gas (IMA, 1998). A study is currently beingundertaken to identify and evaluate chemical alternatives to SF_6 and SO_2 for magnesium melt protection (Clow and Hillls, 2000).

3.5.4.7. Some Smaller Non-CO_2 Emission Reduction Options

There are a number of small emission sources of SF_6, some of which are considered technically unnecessary. For example, SF_6 has been used as a substitute for air, hydrogen or nitrogen in sport shoes and luxury car tyres to extend the lifetime of the pressurized system. SF_6 in sport shoes has been used by a large global manufacturer for over a decade under a patented process. Soundproof windows have been manufactured with SF_6 in several countries in Europe.

Small quantities of SF_6 are used as a dielectric in the guidance system of radar systems like the airborne warning and control system (AWACS) aircraft and as a tracer gas for pollutant dispersion studies. Small quantities of PFCs and SF_6 are used in medical applications such as retina repair, collapsed lung expansion, and blood substitution (UNEP, 1999).

Table 3.21: *Overview of greenhouse gas emission reduction options in industry (excludes energy efficiency improvement, see Table 3.19). Note that the scales are not linear.*

Sector	**Technology**	**Potential in 2010**	**Emission reduction costs**	**Remarks**
All industry	Fuel switching	■■■	?	Rough estimate
Fertilizer, refineries	Carbon dioxide removal	■■	+	Excludes carbon dioxide removal from flue gases
Basic materials industries	Material efficiency improvement	■■■■	–/+/++	First estimate of potentials; option is not yet worked out in detail
Cement industry	Application of blended cements	■■■	–	
Chemical industry	Nitrous oxide emission reduction	■■	+	Excludes emission reduction measures taken before the year 2000
Aluminium industry	PFC emission reduction	■	+/–	
Chemical industry	HFC-23 emission reduction	■■	+	

Legend

Potential: ■ = 0-10MtC; ■■ = 10-30MtC; ■■■ = 30-100MtC; ■■■■ > 100MtC

Annualized costs at discount rate of 10%:

– = benefits are larger than the costs; + = US$0-100/tC; ++ = US$100-300/tC; +++ > US$300/tC

3.5.4.8 Summary of Manufacturing Industry GHG Emission Reduction Options

An overview of greenhouse gas emission reduction options in manufacturing industry due to fuel switching, carbon dioxide removal, material efficiency improvements, and reduction of non-CO_2 greenhouse gases emissions practices is presented in *Table 3.21*, which complements information from *Table 3.19*.

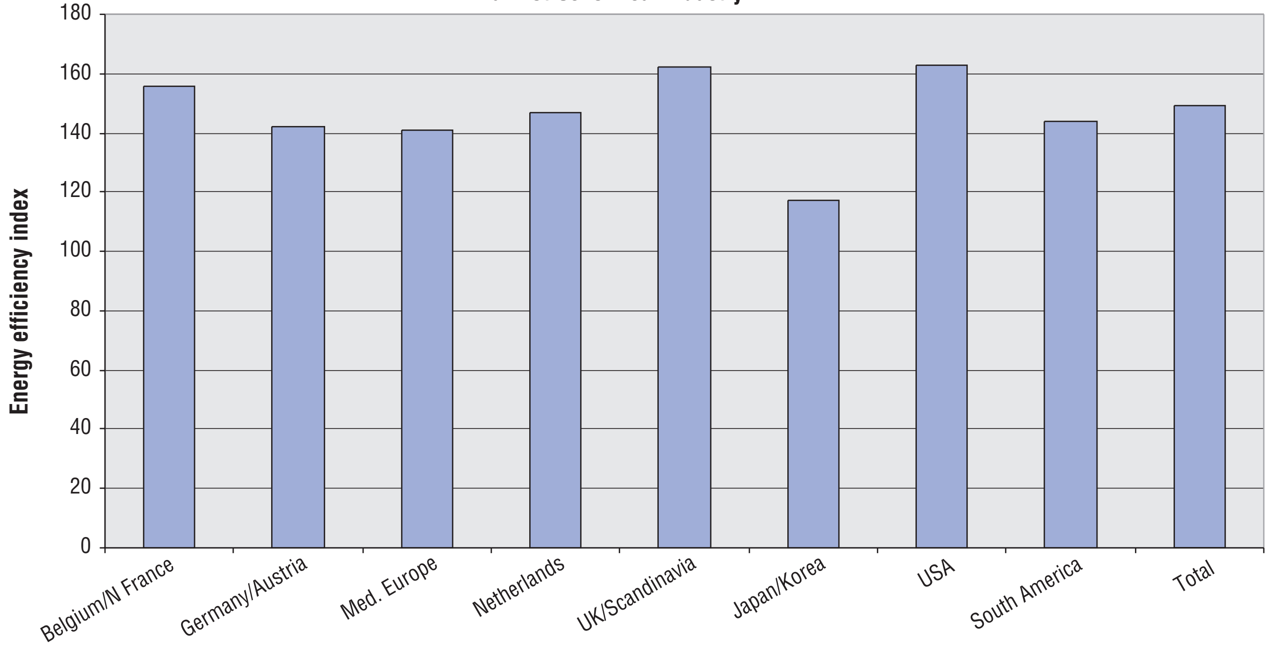
3.5.5 Regional Differences

Differences in emission reduction potential are mainly caused by differences in specific energy consumption of industrial processes. In recent years attention was paid to developing methods to compare energy efficiency levels on a physical basis (Phylipsen *et al*., 1998a), in addition to methods that compare energy efficiency levels on a monetary basis (see, e.g., Schipper and Meyers, 1992). Energy efficiency indicators on a physical basis start from the level of energy consumption per unit of product (e.g., expressed in GJ/t). However, countries may differ in the production structure per sector (i.e. differences in product mix and associated differences in feedstocks used). Correction for such differences can take place by relating the specific energy consumption level for each product to a best practice level, resulting in a so-called energy efficiency index. The more efficient the aggregate of processes in a sector in a country, the lower the energy efficiency index. The energy efficiency indices are scaled in such a way that if all processes were operated at the best-practice level, the index would be 100.

Results up to now are presented in *Figure 3.13*. Apart from correction for structure, international comparison of energy efficiency requires correction for statistical errors. A common source of error in the process industries is the double counting of fuels (e.g., in the iron and steel industry double counting of coke input to the blast furnace and blast furnace gas). After correction for such errors the energy efficiency indicators – like those presented in *Table 3.19* – show a typical uncertainty of 5% (Farla, 2000).

Despite the remaining uncertainties, some conclusions can be drawn from these data. In general Japan and South Korea and countries in Western Europe show the lowest energy efficiency index (i.e., they are most efficient). Developing countries, economies in transition and some OECD countries (like the USA and Australia) show higher levels of this index. However, there are certainly exceptions; for instance, some developing countries show fairly low levels of the energy efficiency index for some sectors. This may be explained by the fact that these countries are developing at a high rate, and hence apply relatively young and modern technology. In general the countries with the highest energy efficiency index will have the highest technical potential for energy efficiency improvement. The dif-

a. Petrochemical industry



b. Ammonia production

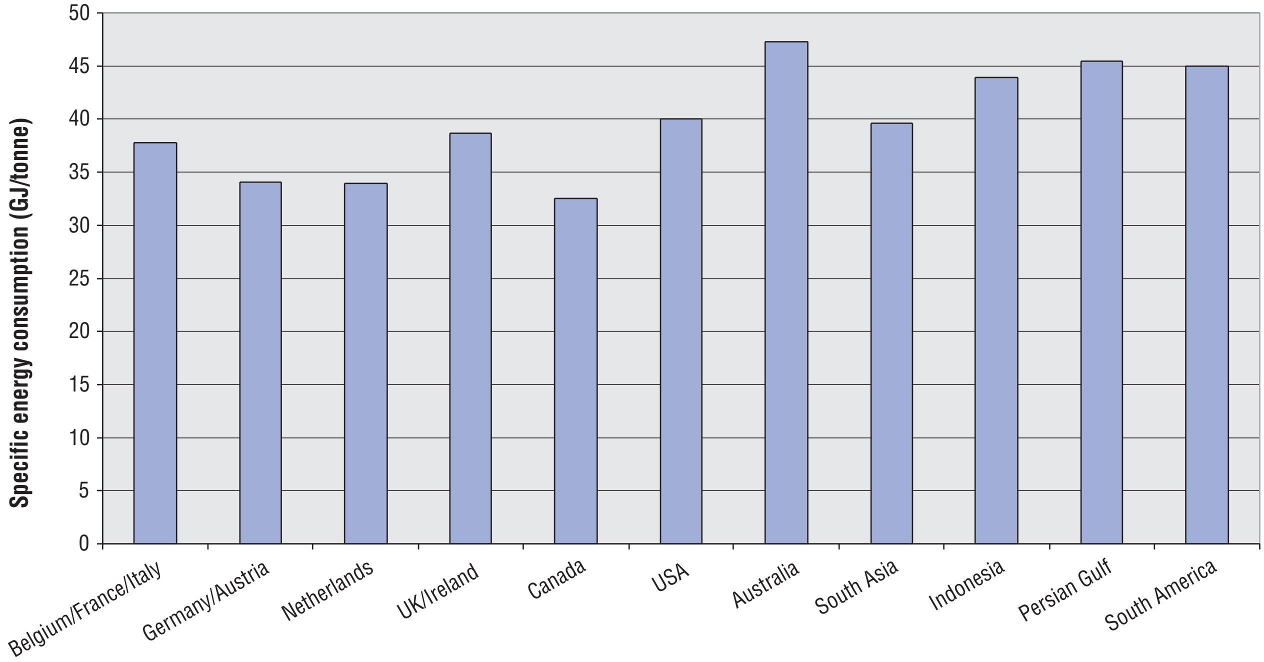
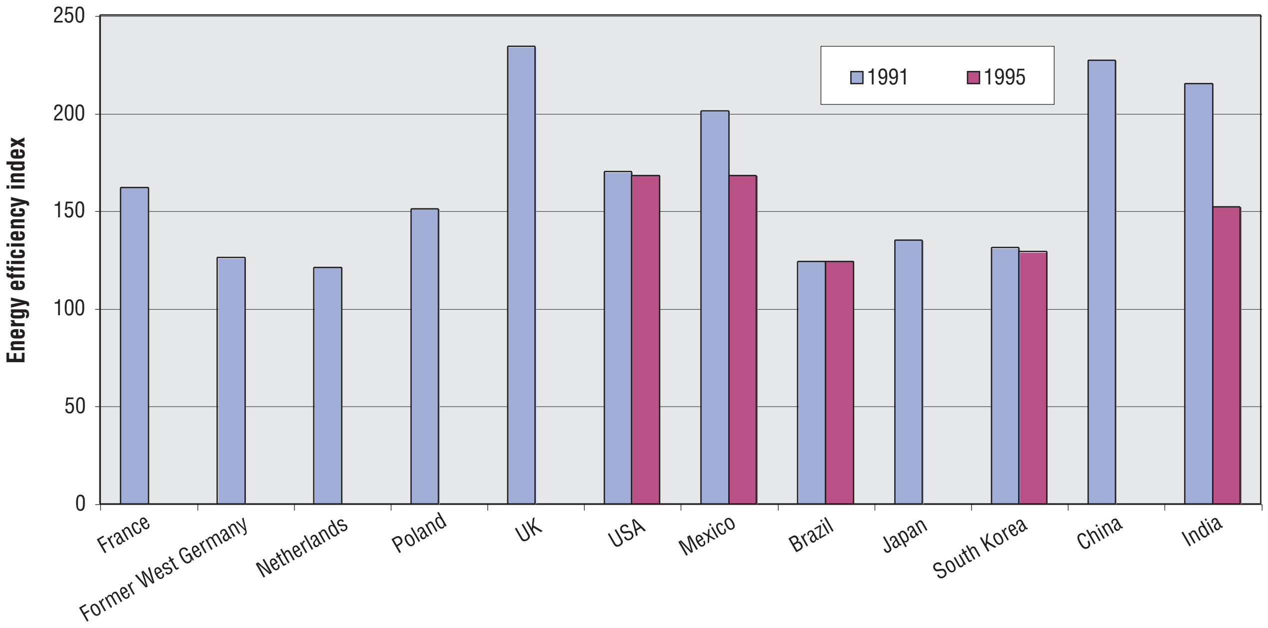


Figure 3.13a-b: *Relative levels of energy efficiency for selected industrial sectors in various countries. The aggregate energy efficiency index (EEI) is calculated as:*

$$EEI = (\Sigma_i P_i \cdot SEC_i)/(\Sigma_i P_i \cdot SEC_{i,BP}),$$

where P_i *is the production volume of product i;* SEC_i *is the specific energy consumption for product i, and* $SEC_{i,BP}$ *is a best-practice reference level for the specific energy consumption for product i. By applying this approach a correction is made in order to account for structural differences between countries in each of the tracked industrial sectors. A typical statistical uncertainty for these figures is 5%. Because of statistical errors higher uncertainties may occur in individual cases.*

c. Iron and steel production



d. Cement production

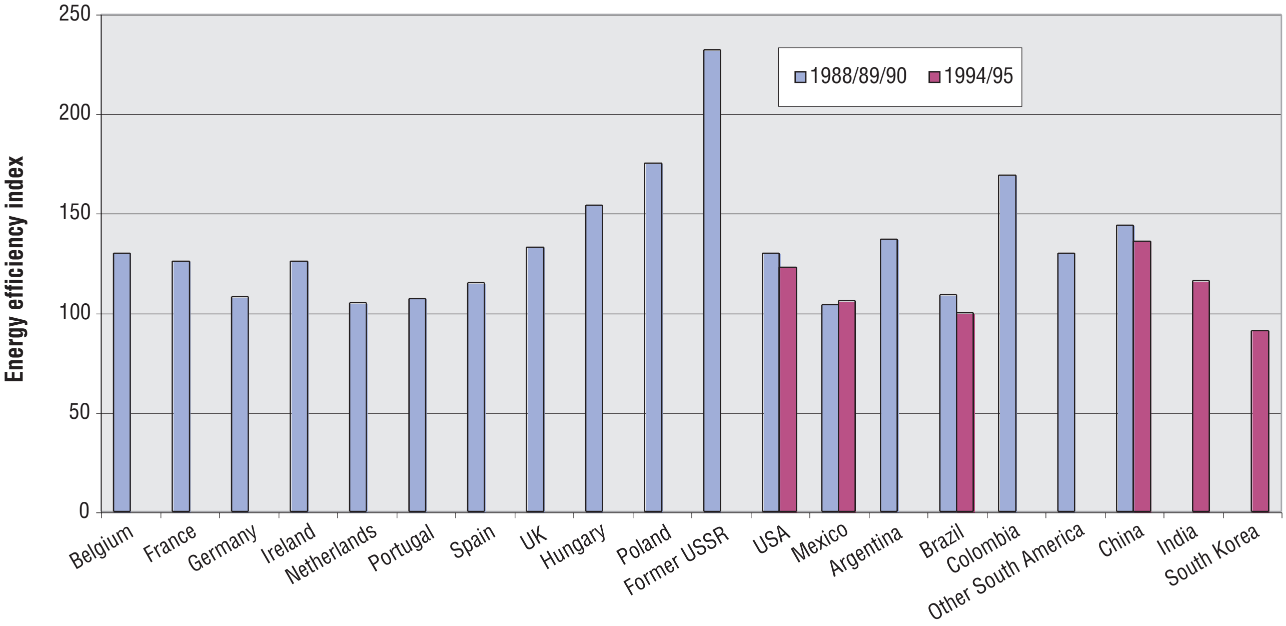


Figure 3.13c - d: *Relative levels of energy efficiency for selected industrial sectors in various countries. The aggregate energy efficiency index (EEI) is calculated as:*

$$EEI = (\Sigma_i P_i \cdot SEC_i)/(\Sigma_i P_i \cdot SEC_{i,BP}),$$

where P_i is the production volume of product i; SEC_i is the specific energy consumption for product i, and $SEC_{i,BP}$ is a best-practice reference level for the specific energy consumption for product i. By applying this approach a correction is made in order to account for structural differences between countries in each of the tracked industrial sectors. A typical statistical uncertainty for these figures is 5%. Because of statistical errors higher uncertainties may occur in individual cases.

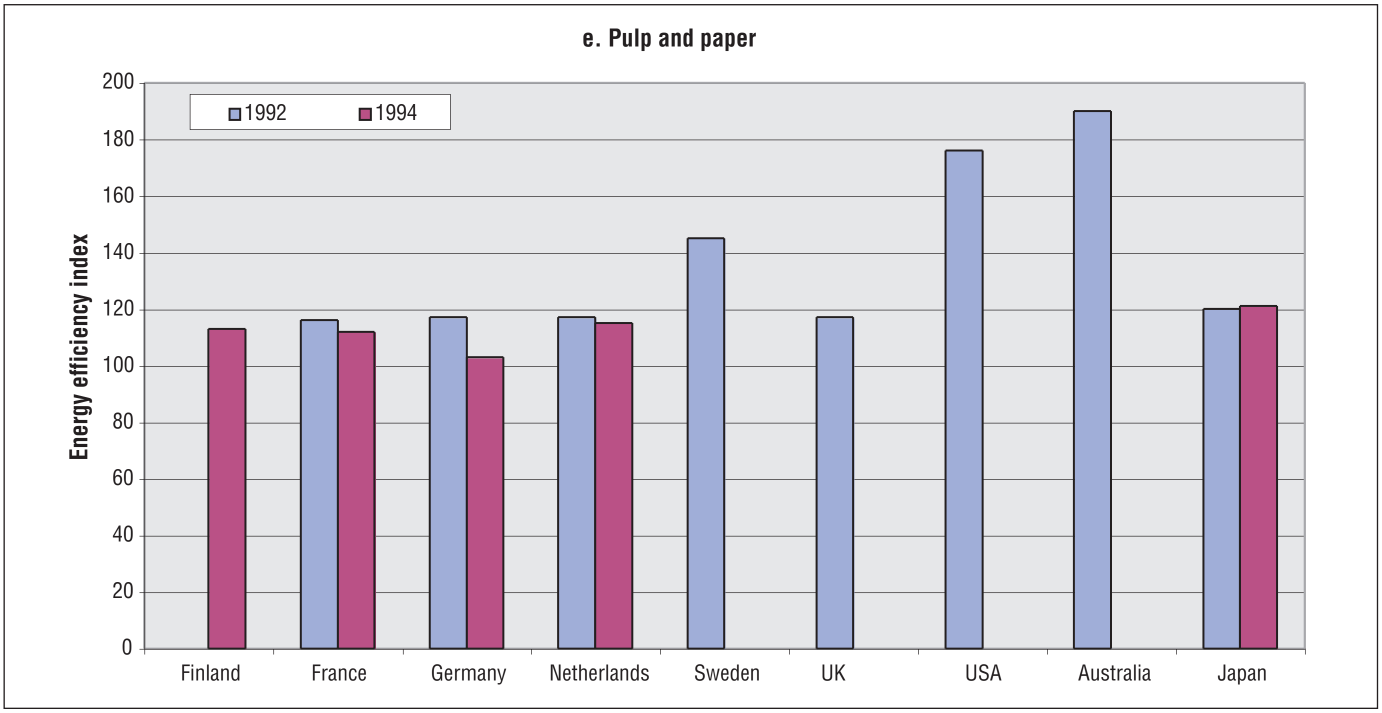


Figure 3.13e: *Relative levels of energy efficiency for selected industrial sectors in various countries. The aggregate energy efficiency index (EEI) is calculated as:*

$$EEI = (\Sigma_i P_i \cdot SEC_i)/(\Sigma_i P_i \cdot SEC_{i,BP}),$$

where P_i *is the production volume of product i;* SEC_i *is the specific energy consumption for product i, and* $SEC_{i,BP}$ *is a best-practice reference level for the specific energy consumption for product i. By applying this approach a correction is made in order to account for structural differences between countries in each of the tracked industrial sectors. A typical statistical uncertainty for these figures is 5%. Because of statistical errors higher uncertainties may occur in individual cases.*

ferences in economic potential may be smaller, as a consequence of the lower energy prices that often occur in the less efficient countries. In this section a number of regional studies – mainly into energy efficiency in industry – are reviewed.

3.5.5.1 China

Industry is responsible for 75% of commercial energy end-use in China (IEA, 1997d). The period from 1980 to 1996 has seen a strong economic growth and growth of industrial production, but also a substantial decline of the energy/GDP ratio of about 4% per year (China Statistical Yearbook). The share of energy efficiency and structural change in this decline is uncertain, but it is clear that substantial energy efficiency improvement was obtained (Zhou and Hu, 1999; Sinton, 1996). Nevertheless, Chinese industry is still substantially less energy efficient than most OECD countries (Wu and Wei, 1997), see also *Figure 3.13*. Within industry, the steel industry is most important, consuming 23% of industrial energy use in 1995 (IEA, 1997d). Zhou and Hu (1999) analysed the differences between the Chinese and the efficient Japanese iron and steel industry and identified a range of measures to improve the specific energy consumption of the Chinese steel industry. Important measures are the recovery of residual gases (2.7GJ/t steel); boiler modification and CHP (2.1 GJ/t); improved feedstock quality (2.1GJ/t); wider application of continuous casting (1.0GJ/t); and others (2.0GJ/t). The total leads to a reduction of 25% compared to the present average of 35.6GJ/t (Zhou and Hu, 1999). An analysis of future prospects by Worrell (1995) shows that, in the case steel production grows from 93Mt in 1995 to 140Mt in 2020, energy consumption in the Chinese steel industry is likely to grow. But the growth can be very moderate if modern technologies, like smelt reduction and near-net-shape casting, are adopted. Also for two other important sectors, the building materials industry and the chemical industries, substantial technical saving potentials are reported (Zhou and Hu, 1999). Liu *et al*. (1995) report for the cement industry – consuming 10% of industrial energy use in 1995 – a potential for reduction of the specific energy consumption of 32% in the period 1990 to 2000; associated investments are estimated at 105 billion yuan (~US$13 billion). Important economically viable options are comprehensive retrofit of vertical kilns (e.g., improving refractory lining) and wet kilns, and kiln diameter enlargement and retrofit. Similar savings can be reached when adding a pre-calciner to the kilns, which is, however, the most expensive option. All cost-effective measures add up to a 20% reduction of primary energy consumption compared to the base line energy use in 2010 (Sinton and Yang, 1998).

3.5.5.2 Japan

In Japan, industry accounts for nearly half of the final energy demand. Industrial energy demand is stabilizing, mainly because of the shift from heavy industry to sectors like electrical machinery, precision instruments, and motor vehicles.

Substantial energy efficiency improvements have been obtained, and Japan is now one of the most efficient countries in the world (see also *Figure 3.13*). Nevertheless, there are still energy efficiency improvement potentials. Current technical potential is 10%–12% in the iron and steel industry. Under the influence of a carbon tax, the potential is 8% in the cement industry and 10% in the chemical industry. Costs of saving energy are in the majority of the cases lower than energy purchase costs at a 5% discount rate (Kashiwagi *et al*., 1999). Kainuma *et al*. (1999) have carried out an analysis of various policies using the AIM model and find maximum absolute reductions of industrial CO_2 emissions of 15% (in the base case the absolute emission reduction is 3%). The increasing concern about the climate change issue has required setting a new higher target to curb energy use to the FY 1996 level in FY 2010, which requires an energy savings of approximately 10% of final demand in the industrial sector by the revision of the Energy Conservation Law put into force in April 1999 (MITI, 1999).

3.5.5.3 Latin America

In Latin American countries, industry consumes about 30% of final energy use. Energy intensity has increased, partly because of a deterioration of the energy efficiency in the heavy industries. Substantial energy efficiency improvement potentials are reported, see *Table 3.22*.

Table 3.22: ***Potential energy savings in energy intensive industries in Latin America. The table shows the percentage reduction of average specific energy consumption that can be achieved with additional investments (Pichs, 1998).***

	Short term/ small investments	**Long term/ medium size investments**
Steel	5 - 7	5 – 13
Aluminium	2 - 4	10 – 15
Oil	7 - 12	15 – 25
Fertilizer	2 - 5	20 – 25
Glass	10 - 12	15 – 20
Construction	10 - 15	15 – 20
Cement	10 - 20	10 – 30
Pulp and paper	10 - 15	10 – 16
Food	8 - 18	12 – 85
Textile	12 - 15	15 – 17

As an example it is useful to give some information on industrial electricity use in Brazil. Industry accounts for 48% of electricity consumption in Brazil, about half of this is for electric motors. Geller *et al*. (1998) report low-cost saving possibilities of 8%–15%. The use of energy-efficient motors is more costly (typically 40% more investment than conventional), but still simple payback times range from 1 to 7 years. Such motors could save about 3% of industrial electricity use. In addition, variable speed controls may save 4% of industrial electricity use (Moreira and Moreira, 1998).

3.5.5.4 USA and Canada

The manufacturing industry is responsible for one-third of total USA energy use and for nearly half of total Canadian energy use. A set of studies is available regarding possible developments of carbon dioxide emissions in this sector. A comparison of three of these studies was presented by Ruth *et al*. (1999); see *Table 3.23*. All three studies do not present a technical or economic potential, but take into account incomplete penetration of available technologies. The outcomes in the *policy case* for the USA range from a 2% carbon dioxide emission growth to a strong decline. The two studies for the USA rely on the same model, but differ in the extent to which technologies are implemented. Furthermore, there are differences in assumed structural development and the treatment of combined generation of heat and power.

For the USA a series of studies have determined the static potentials for three energy-intensive sectors. A study of the iron and steel industry concludes that steel plants are relatively old. A total of 48 cost-effective measures were identified that can reduce carbon dioxide emissions per tonne of steel from this sector by 19% (Worrell *et al*., 1999). For the cement industry a cost-effective potential of 5% excluding blending (30 technologies) and 11% including blending was calculated (Martin *et al*., 1999). For the pulp and paper industry the cost-effective potential is 14% (16% including paper recycling) and the technical potential 25% (37% including recycling) (Martin *et al*., 2000).

For the important Canadian pulp and paper industry for 2010 (compared to 1990) a technical potential for reduction of specific energy consumption of 38% was found; the cost-effective potential is 9% (Jaccard, 1996). All these cost-effective potentials are calculated from the business perspective (e.g., for the USA a pay-back criterion of 3 years is used).

3.5.5.5 Africa

Typically the industry in Africa is characterized by slow replacement of equipment like motors, boilers, and industrial furnaces. Small and medium enterprises are the most affected as a result of limited financial resources and skills. Greenhouse gas emission mitigation opportunities identified in past national studies in Southern Africa (UNEP/Southern Centre, 1993; CEEZ, 1999; Zhou, 1999) are centred on retrofitting boilers and motors, cogeneration using waste process heat, and introduction of high efficiency motors on replacement. The costs for implementing these measures are in the range of negative to low per tonne of carbon.

Table 3.23: *Change in carbon emissions from the industrial sector, 1990 to 2010, base and policy cases.*
Source: Ruth *et al*. (1999)

		USA – I (Interlaboratory Working Group, 1997)	**USA – II (Bernow *et al*., 1997)**	**ERG (Bailie *et al*., 1998)**
Base case, 2010 emissions relative to 1990	*fuel*	+20%	+20%	+25%
	Electricity	+28%	+24%	+50%
	Total	+22%	+23%	+29%
Policy case, 2010 emissions relative to 1990	*Fuel*	+7%	-13%	+7%
	Electricity	-6%	-54%	+28%
	Total	+2%	-28%	+11%

Table 3.24: *Energy efficiency improvement potential in terms of reduction of aggregate specific energy consumption compared to frozen efficiency. In the figures for Germany combined generation of heat and power is not included, in the Netherlands it is (*see Blok *et al.,* 1995).

	Germany (BMBF, 1995; Jochem and Bradke, 1996) (discount rate 4%)	**The Netherlands** (De Beer *et al*., 1996) (discount rate 10%)	**United Kingdom** (discount rates vary by sector)
Technical potential	1995/2005: 20% 1995/2020: 25%	1990/2000: heavy industry: 25% light industry: 40%	1990/2010 high-temperature industries: 45% low-temperature industries: 32% horizontal technologies (excluding CHP): 15% (ETSU, 1994)
Economic potential	1995/2005: 7%.to 13% 1995/2020: 16% to 20%	1990/2000: heavy industry: 20% light industry: 30%	1990/2000 all industry 24% of CO_2 (ETSU, 1996)

3.5.5.6 Western Europe

Industry in Western Europe is relatively efficient, as was shown in *Figure 3.13*. For some countries results of detailed studies into the technical and economic potential for energy efficiency are shown in *Table 3.24*. These studies show that the economic potential for energy efficiency improvement typically ranges from 1.4%–2.7% per year, whereas the technical potential may be up to 2.2%–3.5% per year[17].

Assessment of total potential for energy efficiency improvement

The previous overview gives results for a range of studies carried out for a variety of countries. It should be noted that the studies differ in starting points, methods of analysis, and completeness of the analysis. Some studies give technical or economic potentials, others take into account implementation rates in an accelerated policy context.

Nevertheless, it may be concluded that in all world regions substantial potentials for energy efficiency improvement exist. This is also the case for regions like Western Europe and Japan that – according to *Figure 3.13* – were already fairly efficient. For the other regions energy efficiency improvement potentials generally are higher, although both detailed sector studies and comprehensive overviews are lacking for most countries.

In order to make an estimate of the worldwide potential of enhanced energy efficiency improvement a number of assumptions are made. It is assumed growth of industrial production in physical terms to be 0.9% per annum in the OECD region; 1.0% per annum in economies in transition; 3.6% per annum in the Asian developing countries; 3.9% per annum in the rest of

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[17] The 1995 to 2020 potentials for Germany are lower on an annual basis, but this may be due to the long time-frame underestimating the potential.

the world. Autonomous energy efficiency improvement is assumed to lead to a reduction of specific energy use by 0.5%–1.0% per year (assumption for the average: 0.75%). The total is equivalent to the outcomes in terms of CO_2 emissions in the SRES-B2 scenario. For calculating the potential of industrial energy efficiency improvement, it is assumed that from the year 2000 the enhanced energy efficiency improvement is 1.5%–2.0% per year in the OECD countries (average); and 2%–2.5% per year in the other world regions. Starting from the energy use and emission figures quoted in section 3.5.2, a potential of 300–500MtC is calculated for the year 2010 and 700–900MtC for the year 2020. These figures are consistent with earlier estimates, e.g. WEC, 1995a).

3.5.6 Conclusions

It once again becomes clear that enhanced energy efficiency improvement remains the main option for emission reduction in the manufacturing industry. There are substantial differences in the level of energy efficiency between countries and also potentials differ. For most OECD countries and for a number of developing countries extended inventories of emission reduction options in industry exist. However, the focus is still very much on the heavy industrial sector. The total potential of energy efficiency improvement for the year 2010 can be estimated to be 300–500MtC for the year 2010. It seems possible to develop new technologies to sustain energy efficiency improvement in the longer term; if such innovations materialize the potential can be 700 - 900MtC for the year 2020. The larger part of these emission reductions can be attained at net negative costs.

A category of options to which only limited attention was paid in relation to greenhouse gas emission reduction is material efficiency improvement. It is clear that substantial technical potentials exist. These may be sufficient to attain emission reductions on the order of 600MtC in the year 2020 (UN, 1997). However, a significant effort is needed in selection, development, and implementation of such options. For the shorter term the potential will be substantially smaller (e.g., 200MtC), because of the complexity of introducing these options.

For virtually all sources of non-CO_2 greenhouse gases in the manufacturing industry, options are available that can reduce emissions substantially, in some sectors to near zero. However, the total contribution to the emission reduction is limited: approximately 100MtC_{eq} emission reduction is possible at a cost less than US\$30/tC_{eq}.

3.6 Agriculture and Energy Cropping

3.6.1 Introduction

Agriculture contributes to over 20% of global anthropogenic greenhouse gas emissions as a result of:

- CO_2 (21%–25% of total CO_2 emissions) from fossil fuels used on farms, but mainly from deforestation and shifting patterns of cultivation;
- CH_4 (55%–60% of total CH_4 emissions) from rice paddies, land use change, biomass burning, enteric fermentation, animal wastes;
- N_2O (65%–80% of total N_2O emissions) mainly from nitrogenous fertilizers on cultivated soils and animal wastes (OECD, 1998).

Direct emissions of greenhouse gases occur during agricultural production processes from soils and animals and as a result of meeting demands for heat, electricity, and tractor and transport fuels. In addition, indirect N_2O emissions are induced by agricultural activities (Mosier *et al*, 1998b) and CO_2 also results from the manufacturing of other essential inputs such as machinery, inorganic fertilizers, and agrio-chemicals. Emissions occur at various stages of the production chain and full life cycle analyses are necessary to identify their extent.

In developing countries such as India, emissions mainly arise from ruminant methane, field burning of agricultural residues, and paddy cultivation. Mitigation is difficult to achieve but research into more frequent draining of paddy fields, reduction in the use of nitrogenous fertilizers, and improved diets of cattle is ongoing. Cattle numbers are expected to increase 50% by 2020, which would largely offset any methane avoidance.

As for energy inputs, in many developing countries traditional agriculture still depends on human labour and animal power together with firewood for cooking. Modern agriculture in industrialized countries relies on direct fossil fuel inputs together with embedded energy in fertilizers, and for transport to markets. In the USA each food item purchased has been transported an average of over 2500km (Resources for the Future, 1998) and even further in Europe and Australasia. Recent data for OECD countries suggest the embodied energy in food and drink is 42 GJ per person per year, being 10 times the energy content of the food (Treloar and Fay, 1998).

Increasing energy inputs to meet the growing needs for food and fibre are shown in *Figure 3.14*. Demand has declined in EITs, increased only slightly in Latin America and Africa in spite of population increases, and increased significantly elsewhere. In developing countries the provision and uptake of “leapfrog” technologies to enable human energy to be replaced by non-fossil fuel energy could be stimulated (Best, 1998).

Primary production methods used by farmers, foresters, and fisheries are not energy intensive compared with the industrial and transport sectors, so carbon dioxide emissions are comparatively small, being 217MtC in 1995 (*Table 3.1*) from an annual energy demand of around 3% of total consumer energy (*Table 3.25*).

The worldwide trend towards energy intensification (GJ/ha) of food and fibre production grown on arable land continues.

Table 3.25: *Energy use in the agricultural sector in 1995 and annual growth rates in the preceding periods* (Price *et al*., 1998).

	Fuel			**Electricity**			**Primary energy use**		
	Annual growth rate '71-'90	Annual growth rate '90-'95	Cons. 1995 (EJ)	Annual growth rate '71-'90	Annual growth rate '90-'95	Cons. 1995 (EJ)	Annual growth rate '71-'90	Annual growth rate '90-'95	Cons. 1995 (EJ)
OECD Countries	2.3%	1.4%	2.36	1.8%	2.3%	0.20	2.2%	1.6%	2.97
EIT	4.4%	-14.1%	1.04	4.7%	-2.7%	0.22	4.5%	-10.6%	1.71
DCs Asia-Pacific	2.8%	2.4%	1.25	7.9%	8.2%	0.59	4.8%	5.6%	3.03
Rest of the World	3.5%	13.1%	1.05	8.2%	11.6%	0.17	4.7%	12.6%	1.56
World	3.2%	-1.4%	5.70	5.3%	4.6%	1.18	3.8%	0.8%	9.28

China, for example, began its "socialism marketing system" recently with the aim of changing agriculture from traditional to more modern production methods (Zhamou and Yanfei, 1998). As a result, total food production on the same land area is projected to rise by around 15% and the standard of living for farmers will be higher but also associated with higher risk. Without greater access to modern energy sources, food and fibre production is unlikely to increase (FAO, 1995). The energizing of the food production chain in terms of quantity and quality is necessary for the attainment of global food security to meet demand for more than one year. To meet the targets of the World Food Summit to reduce the undernourished population to half the current level by 2015, a 4 to 7 fold increase in current commercial energy inputs into agriculture, particularly in developing countries, is anticipated (Best, 1998). In order for agricultural production to be undertaken in a more sustainable manner, one can use husbandry methods and management techniques to minimize the inputs of energy, synthetic fertilizers, and agrio-chemicals on which present industrialized farming methods depend. Any method of reducing these inputs in both developed and developing countries using new technologies must be considered.

Integrated assessment methodologies, which include both direct and indirect energy inputs, have been developed for

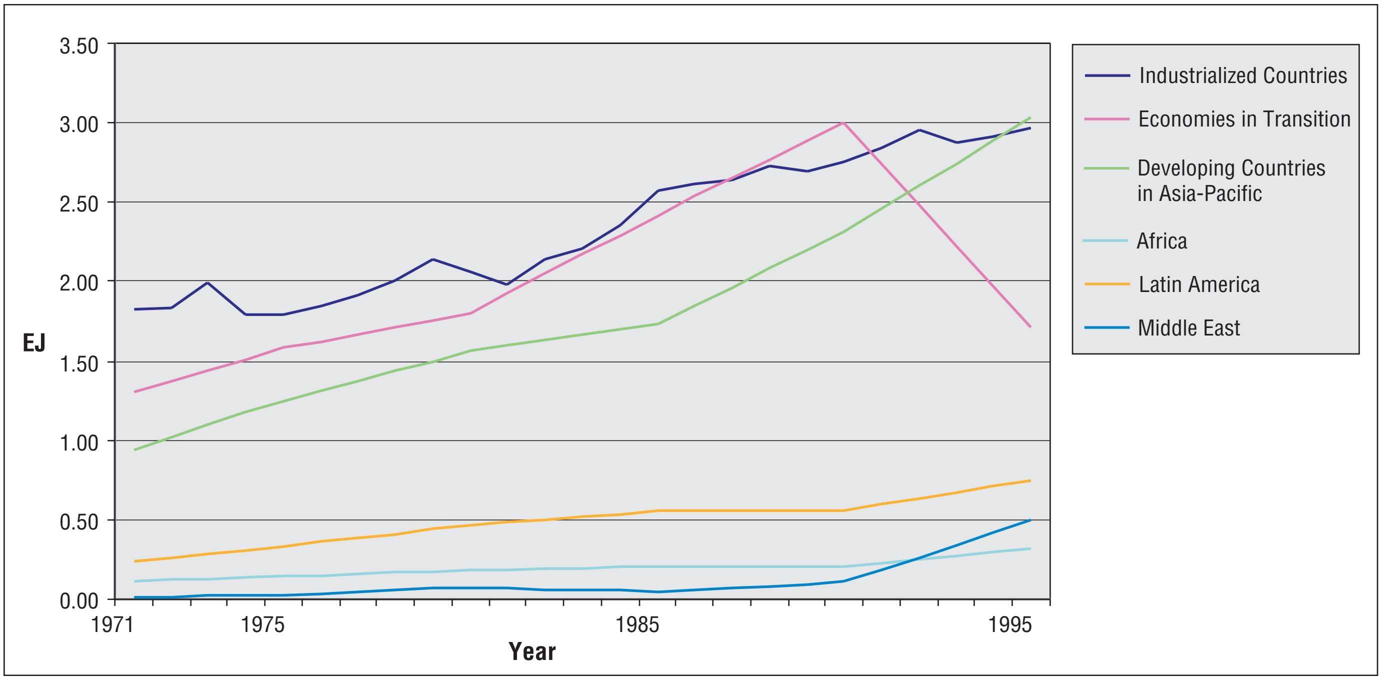

Figure 3.14: *Energy use in the agricultural sector from 1971 to 1995.*

***Table 3.26:** Major sources of methane and nitrous oxide by region in 1995 (MtC_{eq}/yr).*
(Adapted from OECD, 1998)

Source	Canada	USA	Europe	Japan	EIT	Oceania	World
CH_4 animals	2.9	23.6	39.5	1.2	34.6	21.0	438.1
CH_4 animal wastes	0.8	11.9	18.7	2.5	12.3	1.6	84.0
N_2O fertilizer	2.4	21.0	15.0	0.7	18.9	4.1	112.4
N_2O animal wastes	0.8	4.8	8.2	0.6	7.2	1.6	85.6

crops by Kramer *et al*. (1999) and for milk production by Wells (1999). Both studies analysed the complete production chain up to the "farm gate" and both identified fertilizer inputs as being the major contributor of carbon emissions from the system. For example, manufacturing nitrogenous fertilizers in Germany has specific cumulative energy inputs of around 59MJ/kg of fertilizer (having been reduced by energy efficiency methods from 78MJ/kg in 1970), whereas in the USA they remain at a higher level and have slightly increased (Scholz, 1998).

Spedding (1992) expounded the view that if abundant renewable energy supplies were to become available, then energy would be the only important natural resource since all other natural resources could be generated and all waste streams neutralized. In theory even soil could be considered to be a dispensable resource since crops could be grown hydroponically in nutrient solutions, though in practice this would not be feasible. Agricultural industries can contribute to a more sustainable energy future by providing biomass products. Surplus crop and animal waste products (where not used for soil amendments or fertilizers) can be used as bioenergy sources. Growing crops for energy is well understood, though usually only economically viable where some form of government incentive exists or the environmental benefits are fully recognized (Sims, 1997). Possible conflicts of land use for sustainable food production, soil nutrient depletion, water availability, and biodiversity need to be addressed.

Farming, fishing, and forestry continue to grow in energy intensity to meet the ever-increasing global demands for food and fibre. The present challenge is to offset this trend by introducing more efficient production methods and greater adoption of new technologies and practices. Whilst reducing energy intensity, agriculture must also become more sustainable in terms of reduced nutrient inputs, lower environmental impacts, and with zero depletion of the world's natural resources such as fish and topsoil. This can only be successfully achieved if practical support is received from primary producers, and this will only occur if other benefits are perceived (Section 3.6.4.5).

As to methane and nitrous oxide, accurate measurement of these anthropogenic greenhouses gas emissions poses challenges as they arise from diffuse sources and wide ranges are quoted. Methane arises from conversion of tropical rainforests to pasture (120-480MtC/yr); rice paddies (120-600MtC/yr); ruminants (390-600MtC/yr); and animal wastes (60-160MtC/yr). Nitrous oxide mainly arises from use of mineral nitrogenous fertilizers (140-200MtC/yr); use of organic fertilizers (140-200 MtC/yr); and deforestation by burning and subsequent cultivation (200-260MtC/yr) (Ahlgrimm, 1998). Another estimate for total agricultural N_2O emissions exceeded 840MtC_{eq}/yr (6.3 TgN/yr) but also included manure storage, animal droppings on pasture (Oenema *et al.,* 1997), and cultivation of organic soils (Kroeze and Mosier, 1999). OECD regional sources give lower estimates (*Table 3.26*). Thus there remains a high degree of uncertainty concerning the actual levels of N_2O emissions, since many countries have not yet adopted the IPCC revised 1996 guidelines for national greenhouse gas inventories for emissions from agricultural systems.

Strategies for reducing methane emissions from paddy rice and ruminant animals are being evaluated (Yagi *et al*., 1997), as are techniques to reduce N_2O emissions by better treatment of wastes, improved pasture and animal management, and improved use of nitrogenous fertilizers. Reducing N_2O emissions has to be achieved in areas of intensive agriculture by reducing the N surplus of the system. Improvements in modelling nitrogen and carbon fluxes for agricultural ecosystems have recently been developed (see, for example, Li, 1998, 1999) and applied on the county level for the USA (Li 1995, Li *et al*. 1996) and for China (Li *et al*., 1999). By considering the specific interaction between agricultural management with climate and soil conditions, the model simulations have demonstrated large potentials for mitigating N_2O and other greenhouse gas emissions by changing management practices. These include adjusting fertilizer use in poor or rich soils; altering timing of fertilizer or manure applications based on rainfalls; and altering timing and depth of tillage. Based on the modelled results for the USA and China, the most effective way to reduce agricultural N_2O emissions and to ensure adequate crop yields is to optimize fertilizer use in arable soils, particularly those which contain soil organic carbon greater than 3%. However, farmers will need to first accept this management practice if it is to be implemented. A full discussion on the complexities of soil carbon is provided in the Special Report on *Land Use, Land Use Change, and Forestry* (IPCC, 2000).

There is debate whether such process-based, spatially and temporally integrated models are ready to be used for country inventories and would be better than the IPCC methodology (Frolking, 1998). Considerable uncertainty remains as a result of the sensitivity of underlying assumptions (as discussed at the European Federation of Clean Air and Environmental Protection Associations' Second International Symposium on Non-CO_2 Greenhouse Gases, Noordwijkerhout, Netherlands, 8-10 September, 1999). Validation by independent atmospheric budget measurements is needed.

Land clearance activities are covered in Chapter 4; the transportation of products from the "farm gate" to the market or processing plant in Section 3.4; and processing of the agricultural, horticultural, forest, or fish products in Section 3.5.

3.6.2 Summary of the Second Assessment Report

Little has changed in the industrialized agricultural sector during the past few years apart from the continuing trends towards genetically modified crops and animals, and reduced chemical input production methods (Section 3.6.4.2). Farming systems remain a major contributor of anthropogenic emissions, not just from energy inputs but mainly from methane from ruminants (cattle, goats and sheep), livestock wastes, rice paddy fields, and nitrous oxide from the application of nitrogenous fertilizers, and circulation of N within crop and livestock production. Land use change activities, such as the clearance of forests by burning and cultivation to provide more land for agricultural production with subsequent soil degradation, are also major contributors (Chapter 4). Carbon sequestration by soils continues to be quantified and estimates refined further, including the effects from reducing organic matter losses by changing to minimum tillage techniques. Improved farm management can result in lower emissions of CH_4 and N_2O and increased soil carbon uptake.

New energy saving technologies, such as ice bank refrigeration for milk cooling (CAE, 1996), continue to be developed, but need to be widely implemented if they are going to have any significant effects on global greenhouse gas emissions. Methods to reduce emissions by the agricultural sector are outlined in section 3.6.4. Energy crop production continues to provide a possible alternative land use where suitable land is available and markets exist for the products.

3.6.3 Historic and Future Trends

Although on-farm energy intensity (GJ/ha) continues to increase, energy inputs per unit of production (GJ/t) have tended to decline in modern intensive industrialized agricultural systems, mainly caused by increasing crop yields (IPCC, 1996). The current trend in OECD countries is towards less intensive farming systems because of public concerns for animal welfare, reduced chemical inputs, and increasing demand for organically grown food. If this demand continues it could lead to reduced GJ/ha and also to lower GJ/t if yields can be maintained, (though this is generally not the case for low input farming). Conversely, in developing countries energy use (both GJ/ha and GJ/t) is increasing in attempts to increase yields (t/ha) by substituting machinery for manual labour, developing irrigation schemes, and improving crop storage systems to reduce losses. For example, Indian agricultural production has increased threefold since 1970 to 200Mt of food in 1998, whilst during this period animal energy/ha declined 35%, and diesel and electricity inputs increased by over 15 times (Prasad, 1999).

The development and introduction of biotechnology and gene technology could offer new chances to accelerate and support the traditional plant and animal breeding procedures. However, the conflict between food security and environmental risks is yet to be resolved. In developing countries uptake of transgenic technologies would require support of the farmers in adopting non-traditional techniques. If, following a comprehensive risk assessment, public confidence in producing genetically modified organisms is obtained, it could ultimately result in:

- yield increases per hectare of food and fibre crops;
- improved performance efficiency of livestock animals;
- reduced inputs of agrio-chemicals and fertilizers because of new resistant cultivars; and
- development of low input cultivars with improved nutrient and water use efficiency.

Energy inputs per unit of product could be reduced by around 10%-20% as a result, and methane and nitrous oxide emissions also lowered. For energy crops, improvements through traditional plant breeding techniques have barely begun. Opportunities for developing high yielding crops more suitable for energy purposes (such as high erucic acid oilseed rape) using genetic engineering techniques by transferring genes through recombinant DNA technology also have potential (Luhs and Friedt, 1998).

More difficult to predict are changes in diet and food consumption based on availability, quality, health, and environmental decisions. New protein sources will also impact on land use as will the growing of new crops to provide biomaterials specifically for manufactured products.

Social problems in rural areas continue to occur as does urban drift, particularly in developing countries, resulting from unemployment caused by substitution of manual labour by fossil fuel powered tractors and machinery. Rural economies are also struggling financially (even in developed countries where farm subsidies are available) because of current surpluses of many food and fibre commodities leading to low prices. Therefore, limited funds are available for investment in more modern, less energy intensive equipment. Further evaluation of combining traditional manual techniques with modern crops and scientific knowledge to improve sustainability is required.

Possible removal of agricultural subsidies in Europe and the USA is a further threat to the future profitability of these rural regions (which may then need to be stimulated through a government development plan), but could have beneficial effects in terms of reducing greenhouse gas emissions (Storey, 1997). However, it will also be an opportunity for unsubsidized energy crops to compete more successfully with the more traditional uses of the land.

3.6.4 New Technological Options and Social and Behavioural Issues

3.6.4.1 Uptake of Management Techniques

These include use of conservation tillage techniques, improved soil, pasture, and livestock management, paddy field management, careful use of nitrogenous fertilizers, better tractor operation, and irrigation scheduling as outlined in *Table 3.27*.

Crop production in heated greenhouses is particularly energy intensive, and in many cases intended to satisfy luxury demands for vegetables grown out of season or cut flowers (Japan Resources Association, 1994). A range of options exist to reduce the energy inputs (CAE, 1996).

3.6.4.2 Uptake of New Technologies

There is potential for improving yields of food, fibre, and energy crops yet reducing inputs by using genetic selection or modification. Animals can also be bred to convert feed more efficiently. Transgenetic technologies will be difficult to implement unless publicly supported. Following careful scientific research, including life cycle assessment analyses, and stringent government controls over the release of genetically modified organisms into the environment, then it may be possible that future agricultural production systems will involve lower inputs of nutrients and energy. The extent of the uptake of such developments will be largely based on assessments of risks, benefits, and public perceptions and is hard to predict.

Options to increase soil carbon levels are given in *Table 3.27*. Emissions of soil carbon of around 0.2–3tC/ha resulting from cultivation can be reduced by using zero or minimum tillage techniques. However, a reverse of land use activities would soon lose any accumulated soil carbon. In Canada a group of 7 energy companies are paying farmers (through an insurance company acting as an aggregator of credits), CAN$1.50–13/ha/yr to change to zero tillage so they can claim the resulting carbon credits for the effective accumulation period (Ag Climate, 1999). The return to farmers depends on the recruiting and support programme costs, scientific proof of higher carbon gains, and the extent to which other on-farm carbon emission reduction activities are implemented.

3.6.4.3 Energy Cropping

Other than traditional forest crops (see Chapter 4), a number of annual and perennial species have been identified as having high efficiency properties when converting solar energy into stored biomass which can then be converted into heat, electricity or transport fuels with zero or very low carbon emissions (Veenendal *et al*., 1997). (Conversion of biomass is described in Section 3.8.4.3.2 and biofuels for transport in Section 3.4.4).

High yielding short rotation forest crops or C4 plants (e.g., sugar cane and sorghum) can give stored energy equivalents of over 400 GJ/ha/yr at the commercial scale, leading to very positive input/output energy balances of the overall system (El Bassam, 1996). Ethanol production from maize and other cereals in the USA, from sugar cane in Brazil, and biodiesel from oilseed rape in Europe, are being commercially produced but are subject to commodity price fluctuations and government support. The relatively low energy yields per hectare for many oil crops (around 60 to 80GJ/ha/yr for oil) compared with crops grown for cellulose or starch/sugar (200–300GJ/ha/yr), has led to the US National Research Council advising against any further research investment (NRC, 1999b).

Liquid biofuels (see Section 3.4.4.6) when substituted for fossil fuels will directly reduce CO_2 emissions. Therefore, a combination of bioenergy production with carbon sink options can result in maximum benefit from mitigation strategies. This can be achieved by planting energy crops such as short rotation coppice into arable or pasture land, which increases the carbon density of that land, while also yielding a source of biomass. Converting the accumulated carbon in the biofuels for energy purposes, and hence recycling it, alleviates the critical issue of maintaining the biotic carbon stocks over time as for a forest sink. Increased levels of soil carbon may also result from growing perennial energy crops (IEA Bioenergy, 1999), but a detailed life cycle assessment is warranted for specific crops and regions.

Land needed to grow energy crops competes directly with food and fibre production unless grown on marginal or degraded land, or unless surplus land is available. For the USA and Europe. Hall and Scrase (1998) calculated there to be sufficient land physically available to grow crops to supply all human needs of food, fibre, and energy at current population levels, though the study did not include social, economic, and logistical constraints. Sufficient labour, water, and nutrients must also be available if a sustainable and economic bioenergy industry is to be developed. On marginal lands, such as the increasingly saline soils of Australia, growing short rotation eucalyptus in strips between blocks of cereal crops can help lower the water table and hence, under certain circumstances, reduce the soil saline levels to bring back the natural fertility. However, water demands can be high for short rotation forest crops so the resulting overall effects are yet to be determined. An additional benefit is that the decentralization of energy production using energy crops to supply local conversion plants creates

Table 3.27: *Uptake of management techniques and new technologies to reduce greenhouse gas emissions in the agricultural sector*

Management techniques	**Techniques and technologies to be considered**	**References**
Conservation tillage	Conventional tillage consumes 60% of the tractor fuel used in industrialized crop production and decreases soil carbon. Minimum and zero cultivation techniques save tractor fuel, conserve soil moisture, and reduce soil erosion. Uptake is continuing worldwide. Greater chemical weed control may be required. Benefits need to be achieved without reducing crop yields which is more likely under dry conditions as a result of moisture conservation. Animal powered versions of conservation tillage used in developing countries can also reduce the manual drudgery. Cost of uptake in Botswana is around US$31 – 38/tC saved. Globally 150-175MtC/yr sequestration is possible.	Allmaras and Dowdy (1995) Derpsch, 1998 UNEP/Southern Centre (1993) Zhou (1999)
Soil carbon uptake	Typical agricultural soils contain 100-200tC/ha to 1m depth. Overuse of soils leads to degradation, salinization, erosion, and desertification, and will lead to lower organic matter contents with consequent carbon emissions. A change of land use of intensively cultivated soils could result in increased organic matter and carbon sequestration till the soil finds a new balance. Total sequestration potential of world cropland is around 750- 1000MtC/yr for 20-50 years from: erosion control (80-120MtC/yr), restoration (20-30MtC/yr), conservation tillage and crop residue management (150-170MtC/yr), reclamation of saline soils (20-40MtC/yr), improved cropping (180-240MtC/yr) and C offsets through energy crop production (300-400MtC/yr).	Lal and Bruce (1999) Takahashi and Sanada (1998) Batjes (1998) IPCC (2000)
Paddy rice	Estimates have been corrected downwards to around 360MtC/yr. Emissions can be reduced by intermittent flooding and greater use of inorganic fertilizers, but these benefits will be offset by increasing areas grown to meet increasing food demand.	Ahlgrimm (1998) Neue (1997) Mosier *et al*. (1998a)
Nitrogenous fertilizers	Anthropogenic agricultural nitrous oxide emissions (over 800MtC/yr) released after application of N fertilizers as a result of nitrification and denitrification and from animal wastes, exceed carbon emissions from fossil fuels used in agriculture. Measuring emissions is difficult (±85%) because of soil variability. Reductions resulting from use of N fertilizer strategies, slow release fertilizers, organic manures and nitrification inhibitors, could tentatively cut emissions by 30% on a global scale. Costs would be between US$0 – 14/tC in Europe for 3-4MtC/yr. Genetically engineered leguminous plants may have further potential.	Augustin *et al*. (1998) Hendriks *et al*. (1998) Kramer *et al*. (1999) Kroeze and Mosier (1999)
Tractor operation and selection	Correct operation of tractors and size matching to machinery can save fuel, improve tyre life, reduce soil compaction, and save time. Behavioural change by driver education is required but with cheap diesel fuel there is little incentive.	Sims *et al*. (1998)
Irrigation scheduling	Applying water only as needed saves both water and energy for pumping. Cheap and accurate field soil moisture sensors are necessary but not yet available.	Schmitz and Sourell (1998)

(continued)

Table 3.27: *continued*

New technologies	Techniques and technologies to be considered	References
Ruminant enteric methane	Average methane emissions of grazing animals in temperate regions are 76.8 kg/head/yr for dairy cattle; beef cattle, 67.5kg; deer, 30.6kg; goats, 16.5kg; and sheep, 15.1kg. Reduction is by either improving the productivity of the animal or reducing emissions by chemical, antibiotic control (vaccines) or biological methods (bacteriocins) without affecting animal performance. Poor animal diet in developing countries produces higher methane per unit of production. A range of options are being researched, but limited economic analysis of mitigation opportunities has been conducted other than in Europe (15MtC/yr at US$0-14/tC). Selective breeding and magnesium licks may be cheap options. The reduction in ruminant livestock numbers caused by reduced demand for meat, milk (for health reasons) and wool products may continue. Since the sources of emissions are dispersed, they will be difficult to measure, and therefore challenging to include within an enforceable trading regime.	Storey (1999) Ullyatt *et al*. (1999)
Postharvest crop losses	A reduction in postharvest crop losses could make a significant impact on energy use, particularly in developing countries such as India, where average losses for cereals average 10% up to 25% loss of the harvested perishables including fruit, meat, milk, and fish. Solar drying on the ground leads to vermin and pest losses. Storage in sealed buildings with natural ventilation and solar heated air will reduce losses for minimal energy inputs. For fresh crops, refrigeration and heat pumps are used to maintain the cool chain but energy inputs can be significant. Solar panels on refrigerated truck roofs are technically feasible but not economic.	Prasad (1999)
Global positioning systems	Commercially available GPS and GIS systems are available to map then monitor the position of working tractors to enable strategic applications of fertilizers and chemicals to be applied depending on crop yields and soil types. Plantation forest mapping is also used to plan roads and harvests. Energy inputs can be saved as a result.	Oliver (1999)
Controlled environment	Crops grown in greenhouses can use less energy per production unit if the available growing area is increased and better control of heating and ventilation occurs. The effects on energy inputs of producing fish by aquacultural methods rather than sea trawling needs investigation.	CAE (1996)

employment in rural areas (Grassi, 1998; El Bassam *et al*., 1998; Moreira and Goldemberg, 1999).

Certain woody crops and also perennial grasses grown to produce biomass have theoretically high dry matter yields, but commercial yields are often lower than expected from those produced in small plot research trials. In Sweden, for example, where 16,000 ha of coppice *Salix* species have been planted, around 2000ha were harvested for the first time during the winters of 1996 to 1998 to yield only 4.2 oven dry t/ha/yr on average (Larsson *et al*., 1998). With better management, genetic selection, and grower experience once viable markets for the product are established, it had been anticipated that commercial yields closer to 10 oven dry t/ha/yr would result.

Correct species selection to meet specific soil and climatic site conditions is necessary in order to maximize yields in terms of MJ/ha/yr (Sims *et al*., 1999). For example, the saccharose yield of Brazilian sugar cane has increased 10% to 143kg/t of fresh cane (70% moisture content wet basis) since 1990. Methods of identifying appropriate species based on non-destructive yield measurements and species fuelwood characteristics have been developed (Senelwa and Sims, 1998). Energy balance ratios for each unit of energy input required to produce solid fuels from short rotation forest crops are up to 1: 30, and can be even higher when crop residues are also utilized (Scholz, 1998). Woody crops normally require less energy inputs per hectare than food crops.

Forest sinks are covered in Chapter 4 and also in the Special Report on *Land Use, Land-Use Change and Forestry* (IPCC, 2000), but there is a link between these low cost sinks and eventually using some of the biomass grown for energy purposes. Once the limited area of available land is covered in forest sinks, no more planting will be possible and recycling of the carbon to displace fossil fuels may then become feasible. Economic mechanisms to link a forest sink project with a biofuel project have been suggested (Read, 1999).

3.6.4.4 Crop and Animal Wastes

Crop residues such as straw, bagasse, and rice husks, if not returned to the land for nutrient replenishment and soil conditioning, could be used more in the future for heat and power generation, at times in co-combustion with coal, and in appropriate conversion equipment now that the technology is well proven. Wood residues used in small-scale biomass gasifiers will become reliable and more cost effective in time, but at present have some operational risk attached, particularly under developing country conditions (Senelwa and Sims, 1999).

Animal manures and industrial organic wastes are currently used to generate biogas. For example, in Denmark there are 19 decentralized community scale biogas plants for electricity generation (Nielsen *et al*., 1998). Biogas can also be used for cogeneration, direct heating or as a transport fuel.

3.6.4.5 Behavioural Changes

Many farmers in both developed and developing countries will remain unlikely to change their traditional production methods in the short term unless there are clear financial incentives to do so. Behavioural changes as a result of advisors educating members of farming communities to adopt new measures have rarely succeeded to date. Cultural factors have a strong influence on the general unwillingness to accept inappropriate development and hence new ideas. Changing attitudes are unlikely to occur unless farmers can also perceive personal co-benefits such as increased profitability, time saving, cost reductions, improved animal health, increased soil fertility, and less arduous tasks. Regulations in some form are the alternative (OECD, 1998a) but would probably be difficult to monitor, particularly in developing countries. Education of local extension officers is needed to encourage the uptake of new methods and more rapid implementation into the field. These barriers are discussed in section 5.4.5.

Dietary changes from meat to fish or vegetables could help reduce emissions by 55MtC$_{eq.}$ in Europe alone (Gielen *et al*, 1999) and possibly release land for energy cropping.

3.6.5 Regional Differences

Comparative regional studies of agricultural emissions per unit of GDP or per hectare or per capita would show significant differences but as a result of local farming systems, climate, and management techniques employed, a useful comparison between regions is not possible. Standard methods for measuring and reporting of agricultural emissions are being developed and will enable more accurate and useful comparisons to be made between alternative production systems in the future (Kroeze and Mosier, 1999).

Developing countries are slowly moving towards using modern food and fibre production techniques. Economies in transition are also implementing modern production methods encouraged by foreign investors but many challenges remain. From a sustainability point of view, traditional methods may well be preferable.

3.6.6 Technological and Economic Potential

A summary of the technical and market potential for reducing greenhouse gas emissions from the agricultural industry is given in *Table 3.36*. If agricultural production per hectare in developing countries could be increased to meet the growing food and fibre demand as a result of a greater uptake of new farming techniques, modern technologies and improved management systems, then there would be less incentive for deforestation to provide more agricultural land.

3.7 Waste

3.7.1 Summary of the Second Assessment Report

The major emphasis in the SAR was on the reduction of greenhouse gases associated with industrial recycling in the metals, glass and paper industries. These topics are addressed in the industrial Section 3.5 of this chapter. There was a less systematic account of the methane emissions from landfills, or of the consumer dimension of recycling, both of which will be emphasized here.

3.7.2 Historic and Future Trends

Waste and waste management affect the release of greenhouse gases in five major ways: (1) landfill emissions of methane; (2) reductions in fossil fuel use by substituting energy recovery from waste combustion; (3) reduction in energy consumption and process gas releases in extractive and manufacturing industries, as a result of recycling; (4) carbon sequestration in forests, caused by decreased demand for virgin paper; and (5) energy used in the transport of waste for disposal or recycling. Except for the long-range transport of glass for reuse or recycling, transport emissions of secondary materials are often one or two orders of magnitude smaller than the other four factors (Ackerman, 2000).

3.7.2.1 Landfills

Worldwide, the dominant methods of waste disposal are landfills and open dumps. Although these disposal methods often have lower first costs, they may contribute to serious local air and water pollution, and release high GWP landfill gas (LFG). LFG is generated when organic material decomposes anaerobically. It comprises approximately 50%-60% methane, 40%-45% CO_2 and the traces of non-methane volatile organics and halogenated organics. In 1995, US, landfill methane emissions of 64 MtC_{eq} slightly exceed its agricultural sector methane from livestock and manure.

Methane emission from landfills varies considerably depending on the waste characteristics (composition, density, particle size), moisture content, nutrients, microbes, temperature, and pH (El-Fadel, 1998). Data from field studies conducted worldwide indicate that landfill methane production may range over six orders of magnitude (between 0.003-3000g/m^2/day) (Bogner *et al*,. 1995). Not all landfill methane is emitted into the air; some is stored in the landfill and part is oxidized to CO_2. The IPCC theoretical approach for methane estimation has been complemented with more recent, site-specific models that take into account local conditions such as soil type, climate, and methane oxidation rates to calculate overall methane emissions (Bogner *et al*,. 1998).

Laboratory experiments suggest that a fraction of the carbon in landfilled organic waste may be sequestered indefinitely in landfills depending upon local conditions. However, there are no plausible scenarios in which landfilling minimizes GHG emissions from waste management. For yard waste, GHG emissions are roughly comparable from landfilling and composting; for food waste, composting yields significantly lower emissions than landfilling. For paper waste, landfilling causes higher GHG emissions than either recycling or incineration with energy recovery (US EPA, 2000).

3.7.2.2 Recycling and Reuse

Recycling involves the collection of materials during production or at the end of a product's useful lifetime for reuse in the manufacturing process. The degree of treatment varies from simple remelting of glass, aluminium, or steel, to the breaking apart and reconstitution of paper or other fibres (e.g., textiles or carpets), to depolymerization of plastics and synthetic fibres to monomers, which are then used instead of petrochemicals to synthesize new polymers.

In many cases, manufacturing products from recycled materials is less energy intensive and associated with fewer GHG emissions than making products from virgin materials. This is especially true for aluminium and steel, which are energy intensive and release significant process GHGs during production (CO_2 and PFCs). A US EPA analysis finds lower GHG emissions over the product life cycle from recycling than from virgin production and disposal of paper, metals, glass, and plastics under typical American conditions (US EPA, 2000).

Overall energy consumption is lower for recycled paper than for virgin paper, yet there is some debate over life cycle GHG emissions between paper recycling (Blum *et al*., 1997; Finnveden and Thomas, 1998; US EPA, 1998) and paper consumption with energy recovery (Bystroem and Loennstedt, 1997; Ruth and Harrington, 1998; IIED, 1996). These conflicting analyses make different underlying assumptions concerning the fuel displaced by energy released from paper incineration, the energy source for the electricity used in paper production, how the recycled paper is utilized, and how much carbon sequestration can be credited to uncut forests because of recycling. In all studies, landfilling of paper clearly releases more GHGs than either recycling or incineration.

The life cycle environmental impact and GHG emissions from recycling are usually higher than reusing products. This may not hold true if the used materials have to be transported over long distances. To address this issue, some countries such as Germany, Norway, Denmark, and other European countries have standardized bottles for local reuse.

3.7.2.3 Composting and Digestion

Composting refers to the aerobic digestion of organic waste. The decomposed residue, if free from contaminants, can be used as a soil conditioner. As noted above under landfilling, GHG emissions from composting are comparable to landfilling for yard waste, and lower than landfilling for food waste. These estimates do not include the benefits of the reduced need for synthetic fertilizer, which is associated with large CO_2 emissions during manufacture and transport, and N_2O releases during use. USDA research indicates that compost usage can reduce fertilizer requirements by at least 20% (Ligon, 1999), thereby significantly reducing net GHG emissions (see Section 3.6).

Composting of yard waste has become widespread in many developed countries, and some communities compost food waste as well. Small, low-technology facilities handling only yard waste are inexpensive and generally problem-free. Some European and North American cities have encountered difficulties implementing large-scale, mixed domestic, commercial and industrial bio-waste collection and composting schemes. The problems range from odour complaints to heavy metal contamination of the decomposed residue. Also, large-scale composting requires mechanical aeration which can be energy intensive (40-70 kW/t of waste) (Faaij *et al.,* 1998). However, facilities that combine anaerobic and aerobic digestion are able to provide this energy from self-supplied methane. If 25% or more of the waste is digested anaerobically the system can be self-sufficient (Edelmann and Schleiss, 1999).

For developing countries, the low cost and simplicity of composting, and the high organic content of the waste stream make small-scale composting a promising solution. Increased composting of municipal waste can reduce waste management costs and emissions, while creating employment and other public health benefits.

Anaerobic digestion to produce methane for fuel has been successful on a variety of scales in developed and developing countries. The rural biogas programmes based upon manure and agricultural waste in India and China are very extensive. In industrial countries, digestion at large facilities utilizes raw materials including organic waste from agriculture, sewage sludge, kitchens, slaughterhouses, and food processing industries.

3.7.2.4 Incineration

Incineration is common in the industrialized regions of Europe, Japan and the northeastern USA where space limitations, high land costs, and political opposition to locating landfills in communities limit land disposal. In developing countries, low land and labour costs, the lack of high heat value materials such as paper and plastic in the waste stream, and the high capital cost of incinerators have discouraged waste combustion as an option.

Waste-to-energy (WTE) plants create heat and electricity from burning mixed solid waste. Because of high corrosion in the boilers, the steam temperature in WTE plants is less than 400 degrees Celsius. As a result, total system efficiency of WTE plants is only between 12%–24% (Faaij *et al*., 1998; US EPA, 1998; Swithenbank and Nasserzadeh, 1997). Net GHG emissions from WTE facilities are usually low and comparable to those from biomass energy systems, because electricity and heat are generated largely from photosynthetically produced paper, yard waste, and organic garbage rather than from fossil fuels. Only the combustion of fossil fuel based waste such as plastics and synthetic fabrics contribute to net GHG releases, but recycling of these materials generally produces even lower emissions.

3.7.2.5 Waste Water

Methane emissions from domestic and industrial wastewater disposal contribute about 10% of global anthropogenic methane sources (30-40Mt annually). Industrial wastewater, mainly from pulp and paper and food processing industries, contributes more than 90% of these emissions, whereas domestic and commercial wastewater disposal contributes about 2 Mt annually. Unlike methane emissions from solid waste, most of the methane from wastewater is believed to be generated in non-Annex I countries, where wastewater is often untreated and stored under anaerobic conditions (SAR).

3.7.3 New Technological and Other Options

3.7.3.1 Landfill Management

LFG capture and energy recovery is a frequently applied landfill management practice. There have been many initiatives during the past few years to capture and utilize LFG in gas turbines; a number of such facilities are currently generating electricity. US regulations now require capture of an average of 40% of all landfill methane nationwide. Yet even after compliance with those regulations, it remains profitable (at a carbon price of zero or negative cost) to capture 52% of the landfill methane. At a price of US\$20/tC_{eq} (in 1996 dollars), an additional 19% of the methane could be captured, an amount that approaches the estimated maximum practical attainable level (US EPA, 1999a). Official estimates suggest that approximately half, or 35MtC_{eq}, of landfill methane could be recovered by 2000.

Other studies have found that the methane yield from landfills is about 60-170 l/kg of dry refuse (El-Fadel *et al*., 1998). Some landfills produce electricity from LFG by installing cost effective gas turbines or technologically promising, but still expensive fuel cells (Siuru, 1997). Later reports dispute this claim (US EPA, 2000).

One study suggests that landfilling of branches, leaves and newspaper sequesters carbon even without LFG recovery, whereas food scraps and office paper produce a net increase in GHGs, even from landfills with methane recovery (US EPA, 1998).

3.7.3.2 Recycling

Many programmatic initiatives and incentives can boost the rate of recycling. The potential gains are quite large: if every-one in the USA increased from the national average recycling rate to the per capita recycling rate achieved in Seattle, Washington, the result would be a reduction of 4% of total US GHG emissions (Ackerman, 2000). While often associated with affluent countries, recycling is also an integral part of the informal economy of developing countries; innovative approaches to recycling have been adopted in poor neighbourhoods of Curitiba, Brazil, and in other cities.

The literature on techniques for increasing the rate of recycling is too extensive for adequate citation here (see, for example, Ackerman (1997) and numerous sources cited there). One much-discussed initiative is the use of variable rates, or pay-per-bag/per-can charges for household solid waste collection. This provides a clear financial incentive to the householder to produce less waste, particularly when accompanied by free curbside recycling (Franke *et al*., 1999). Strict packaging and lifetime product responsibility laws for manufacturers in Germany have brought about innovations in the manufacture and marketing of a wide range of products. Other market incentives such as repayable deposits on glass containers, lead acid batteries, and other consumer products have led to major gains in recycled materials in many countries. Voluntary recycling programmes have met with a mixed range of success, with commercial and institutional recycling of office paper and cardboard, and curbside recovery of mixed household materials generally having higher recycling rates. Countries such as Austria and Switzerland successfully require separation of household waste into many disaggregated categories for high value recovery.

3.7.3.3 Composting

Increased composting of household food waste would reduce GHG emissions, but may be difficult to achieve in developed countries, where an additional separation of household waste would be required. In low-income developing countries, the high proportion of food waste in household and municipal waste makes composting attractive as a primary waste treatment technology.

Other new opportunities involve composting or anaerobic digestion of agricultural and food industry wastes. Livestock manure management accounts for 10% of US methane emissions; capture of about 70% of the methane from livestock manure appears technologically feasible. Some 20% of the feasible methane capture is profitable under existing conditions, with a carbon price of zero; 28% can be recovered at US\$20/tC$_{eq}$ and 61% at US\$50/tC$_{eq}$(US EPA, 1999a).

Biogas facilities intentionally convert organic waste to methane; use of the resulting methane can substitute for fossil fuels, reducing GHG emissions. High ammonia content (e.g., in swine manure) can inhibit conversion of organic waste to methane. This problem can be avoided by mixing agricultural waste with other, less nitrogenous wastes (Hansen *et al*., 1998). Wastes with high fat content can, on the other hand, enhance and increase methane output. In Denmark, a number of biogas facilities have been running successfully, accepting livestock manure as well as wastes from food processing industries (Schnell, 1999). In Germany and Switzerland, pilot projects compress the methane from biogas plants and supply it to natural gas vehicles. Canadian engineers have completed a pilot project using a mixture of waste-activated sludge, food waste, industrial sludge from potato processing, and municipal waste paper. Methane production reached 50 l/kg of total solids, and heavy metal contamination was found to be far below regulatory levels (Oleszkiewicz and Poggi-Varaldo, 1998). Woody waste with high lignin content cannot be converted to methane, and yard waste is better handled by composting.

3.7.3.4 Incineration

New combustion technologies with higher efficiencies of energy production and lower emissions are currently being developed:

- Fluidized bed combustion (FBC) is a very efficient and flexible system that can be used for intermittent operation, and can run with solid, liquid, or gaseous fuels. Despite high operating costs, this low pollution combustion technology is increasingly used in Japan, and has also been used in Scandinavia and the USA (NEDO, 1999; http://www.residua.com/wrftbfbc.html).

- Gasification (partial incineration with restricted air supply) and pyrolysis (incineration under anaerobic conditions) are two technologies that can convert biomass and plastic wastes into gas, oil, and combustible solids. Gasification of biomass produces a gas with a heating value of 10%-15% that of natural gas. When integrated with electricity production, it can prove economically and environmentally attractive; it appears best suited for clean biomass, such as wood wastes. Pilot projects are now using pyrolysis for plastic wastes, and for mixed municipal solid waste (MSW); they potentially have very high energy efficiency (Faaij *et al*., 1998). Combined pyrolysis and gasification (Thermoselect) and combined pyrolysis and combustion (Schwelbrenn-Verfahren) have also been developed and implemented.

- Co-incineration of fossil fuel jointly with waste leads to improved energy efficiency. Stringent emission standards in some countries may limit the extent to which co-incineration is possible (Faaij *et al*., 1998). In other countries, emission standards for industrial combustion processes are less tight than those for incinerators, leading some to fear that co-incineration might produce higher emissions of air pollutants (Kossina and Zehetner, 1998).

3.7.3.5 Wastewater Treatment

Conventional sewage collection is very water intensive. Vacuum toilets, using less than 1 litre per flush, have long been used on ships and have now been installed in the new ICE trains in Germany. Human waste collected in this way can then be anaerobically digested. This process reduces GHG emissions and water usage is minimal. Acceptance of this technology has been slow because of cost (Schnell, 1998).

Modular anaerobic or aerobic systems are available (Hairston *et al*., 1997). Anaerobic digestion has the advantage of generating methane that can be used as a fuel, yet many sewage treatment plants simply flare it. The potential for energy generation is clearly very large. New York City's 14 sewage plants, for example, generate 0.045 billion cubic metres of methane every year, most of which is flared. Cities such as Los Angeles sell methane to the local gas utility, and one New York plant and the Boston Harbor facility were equipped with fuel cells in 1997. This new technology successfully provides needed electricity and heat, but is still expensive.

Because of concerns about contamination of sewage sludge by heavy metals, policies in many countries now encourage incineration rather than soil application. However, the energy needed to dry the sludge for incineration leads to a net increase in GHGs. Alternatives to sludge incineration are anaerobic digestion, gasification, wet oxidation, and co-incineration with coal. These technologies are under development and yield improved energy efficiencies and low GHG emissions (Faaij *et al*., 1998).

3.7.4 Regional Differences

Individual countries have adopted different strategies and innovations in waste management that reduce GHG emissions. It is not possible to provide a comprehensive description in this chapter, but a sampling of different national and regional strategies is summarized below.

3.7.4.1 Germany

Germany promotes recycling through the world's most stringent return requirements for packaging and many other goods, including automobiles; materials management is the responsibility of the manufacturer through the end of product life, including ultimate disposal or reuse of the materials from which it is made. This has led to high recycling rates, but also to high monetary costs, prompting ongoing controversy in Germany and elsewhere.

Every year Germany generates about 30 million tonnes of solid municipal waste. German landfills emit yearly 1.2-1.9Mt of methane, accounting for 25%-35% of Germany's methane emissions and about 3%-7% of national GWP. To meet the provisions of a 1993 law requiring that by 2005 all wastes disposed in landfills have to have a total organic carbon content of less than 5% will require incineration. Under this law methane emissions are projected to drop by two-thirds by 2005, and by 80% by 2015 (Angerer and Kalb, 1996).

3.7.4.2 USA

The USA produces about 200 million tonnes of municipal waste each year. In 1997, 55% was landfilled, 28% was recycled or composted, and 17% was incinerated (US EPA, 1999b). The 11.6Mt of methane emitted by landfills accounts for 37% of anthropogenic methane emissions, or about 4% of national GHG emissions. US regulations now require the largest landfills to collect and combust LFG, which is projected to reduce emissions to 9.1Mt in 2010 (US EPA, 1999a). There are more than 150 LFG-to-energy projects in operation, and 200 more in development, promoted by government technical support and tax incentives (Kerr, 1998; Landfill, 1998).

If all the material currently recycled in the USA were instead landfilled, national GHG emissions would increase by 2%, even with the new LFG regulations (Ackerman, 2000). More than 9,000 municipal recycling programmes collect household materials, and numerous commercial enterprises also recycle material. Many innovative uses of recycled materials are reducing emissions in manufacturing; for example, remanufacture of commercial carpet from recovered fibres lowers energy inputs by more than 90%, and some products are now said to have zero net GHG impacts (Hawken *et al*., 1999).

3.7.4.3 Japan

With a large waste stream and very limited land area, Japan relies heavily on both recycling and incineration as alternatives to landfilling. Widespread participation in recycling recovers not only easily recycled materials such as metals and glass, but also large quantities of unconventional recycled materials, such as aseptic packaging (juice boxes).

Japan has approximately 1,900 waste incineration facilities of which 171 produce electric power with a capacity of 710MW. A major new commitment to create high efficiency waste to energy facilities has been announced by the Japanese government. In 1998 a corrosion resistant, high temperature, fluidized bed WTE facility achieved 30% conversion efficiency to electricity with low dioxin and stack gas emissions. The facility can accept mixed municipal and industrial waste including plastics and recovers ash for road foundations and recyclable metals (NEDO, 1999).

3.7.4.4 India

Recycling is a very prevalent part of Indian society. Unskilled labourers, working in the informal economy, collect newspapers, books, plastic, bottles, and cans and sell them to commercial recyclers. In recent years a shift from collecting for reuse to collecting for recycling has taken place. Because of changing lifestyles and increased consumption of goods, the use of recyclables has increased dramatically over the past few years (from 9.6% in 1971 to 17.2% in 1995). Paper accounts for 6% and ash and fine earth for 40%. Total compostable matter is over 42% of the waste stream.

Plastic in the waste stream increased from 0.7% in 1971 to 4%-9% in 1996, and is expected to grow rapidly. Though current consumption is 1.8 kg/capita/yr compared to a world average of 18 kg and a US average of 80 kg, India recycled between 40-80% of its plastics, compared to 10%-15% in developed nations. There are about 2000 plastic recycling facilities in India, which often cause serious environmental harm as a result of outdated technology. Current per capita paper consumption is 3.6 kg, compared to a world average of 45.6 kg. Paper consumption is projected to increase to 8 kg by 2021. India imports approximately 25% of its paper fibre as waste paper from the US and Europe.

Almost 90% of solid waste is deposited in low-lying dumps and is neither compacted nor covered; 9% is composted. In 1997, landfill emissions were India's third largest GHG contributors, equivalent to burning 11.6Mt of coal (Gupta *et al*., 1998).

3.7.4.5 China

China generated 108 million tonnes of municipal waste in 1996, an amount that is increasing every year by 8%-10%. In 1995, the GEF approved an action plan and specific projects for methane recovery from municipal waste (Li, 1999).

According to a survey of ten cities, the per capita waste generation averages 1.6kg/day, but in some rapidly developing cities in southern China, per capita waste production is almost as high as in developed countries (e.g., Shenzhen, 2.62 kg/day). Between 60%-90% of Chinese municipal solid waste is high moisture organic material with a low heat value. The composition of waste is changing, with cinder and soil content decreasing while plastic, metal, glass and organic waste are increasing. Kitchen waste has replaced coal cinder as the largest component, raising the water content. By the end of 1995, incineration treatment capacity was 0.9% of total MSW.

Estimates are that in 2010 China will produce 290 million tonnes of MSW. If 70% is disposed of in landfills with methane collection, the landfill gas recovered could be equivalent to 40 to 280 billion m^3 of natural gas (Li, 1999).

3.7.4.6 Africa

The average annual solid waste generation in Africa is estimated to be about 0.3 to 0.5t/ capita and for a population for Africa of about 740 million in 1997, the total continent's annual generated waste could be as much as 200 million tonnes. It is estimated that anything from 30%–50% if the waste is not subjected to proper disposal, presenting severe health and environmental hazards (INFORSE, 1997). With few financial resources, and population increasing at 3% per annum, with the most rapid growth in urban regions from migration, this poses a serious challenge for waste management in the future.

An analysis of energy content of MSW generated in South Africa alone indicates that if one-third were utilized for combustion energy it would be equivalent to 2.6% of the total electricity distributed in 1990 (529Million GJ) by the country's largest utility, ESKOM. Technologies are not yet available on the continent to make this a reality.

Mitigating CH_4 through extraction of landfill gas for energy use has been estimated to cost below US\$10/tC_{eq} in Africa (Zhou, 1999). Both incineration of MSW and extraction of landfill gas have significant potential to reduce emissions of methane in Africa, and will provide the co-benefit of addressing the severe waste management problem on the continent.

3.7.5 Technological and Economic Potential

Economic analysis of waste management strategies yields widely varying results, with far less reliable standard cost estimates than in fields such as energy production. In the USA, the most successful communities report that ambitious waste reduction, recycling, and composting programmes cost no more than waste disposal, and often cost significantly less (US EPA, 1999c). Overall, average recycling costs appear to be slightly above landfill disposal costs (Ackerman, 1997). Not all waste management strategies have been fully analyzed for their economic potential or distributional cost and benefit implications. The waste hierarchy (reduce, reuse, recycle, incinerate, landfill) on which many countries' waste policies are based has not been comprehensively evaluated on a country and materials specific basis (Bystroem and Loennstedt, 1997).

Integrated waste management that considers environmental protection, economic efficiency, social acceptability, flexibility, transparency, market-oriented recovery and recycling, appropriate economies of scale, and continuous improvement is being developed throughout Europe (Franke *et al*., 1999).

Considering only GHG emissions, the most favourable management options are those that reduce fossil fuels use in manufacturing as does recycling, or replace them as does incineration with energy recovery. There is, however, disagreement over the most ecological waste disposal method. Some argue for incineration of all solid waste in modern, energy recovering incinerators (Pipatti and Savolainen, 1996; Aumonier, 1996); others advocate increased composting and anaerobic digestion of organic wastes (Ackerman, 1997; Dehoust *et al*., 1998; Finnveden and Thomas, 1998; Ligon, 1999). The estimated GHG emissions for different scenarios depend heavily on the parameter assumptions made in each model. If GHGs from waste disposal are the only concern, incineration with energy recovery is the most favourable solution. If economic and other environmental factors (e.g., emissions of heavy metals) are taken into account the answer is less clear. Also, if the whole life cycle and not just the disposal of the material is considered, recycled materials usually are associated with lower GHG emissions than virgin materials. Numerous technologies appropriate to differing national needs are available at a range of technological complexities for reducing GHGs from waste. Many options are highly cost effective, and can lead to significant reductions on the order of several per cent of national greenhouse gas emissions. Source reduction is indisputably the most environmentally sound and cost effective tool to reduce GHG emissions from solid waste.

3.8 Energy Supply, Including Non-Renewable and Renewable Resources and Physical CO_2 Removal

3.8.1 Introduction

This section reviews the major advances in the area of GHG mitigation options for the electricity and primary energy supply industries that have emerged since IPCC (1996). The global electricity supply sector accounted for almost 2,100MtC/yr or 37.5% of total carbon emissions. Under business-as-usual conditions, annual carbon emissions associated with electricity generation, including combined heat and power production, is projected to surpass the 4,000MtC mark by 2020 (IEA, 1998b). Because a limited number of centralized and large emitters are easier to control than millions of vehicle emitters or small boilers, the electricity sector is likely to become a prime target under any future involving GHG emission controls and mitigation.

3.8.2 Summary of the Second Assessment Report

Chapter 19 of the IPCC Second Assessment Report (1996) gave a comprehensive guide to mitigation options in energy supply (Ishitani and Johansson, 1996). The chapter described technological options for reducing greenhouse gas emissions in five broad areas:

- *More efficient conversion of fossil fuels.* Technological development has the potential to increase the present world average power station efficiency from 30% to more than 60% in the longer term. Also, the use of combined heat and power production replacing separate production of power and heat, whether for process heat or space heating, offers a significant rise in fuel conversion efficiency.
- *Switching to low-carbon fossil fuels and suppressing emissions.* A switch to gas from coal allows the use of high efficiency, low capital cost combined cycle gas turbine (CCGT) technology to be used. Opportunities are also available to reduce emissions of methane from the fossil fuel sector.
- *Decarbonization of flue gases and fuels, and CO_2 storage.* Decarbonization of fossil fuel feedstocks can be used to make hydrogen-rich secondary fuel for use in fuel cells in the longer term. CO_2 can be stored, for example, in depleted gas fields.
- *Increasing the use of nuclear power.* Nuclear energy could replace baseload fossil fuel electricity generation in many parts of the world if acceptable responses can be found to concerns over reactor safety, radioactive waste transport, waste disposal, and proliferation.
- *Increasing the use of renewable sources of energy.* Technological advances offer new opportunities and declining costs for energy from renewable sources which, in the longer term, could meet a major part of the world's demand for energy.

The chapter also noted that some technological options, such as CCGTs, can penetrate the current market place, whereas others need government support by improving market efficiency, by finding new ways to internalize external costs, by accelerating R&D, and by providing temporary incentives for early market development of new technologies as they approach commercial readiness. The importance of transferring efficient technologies to developing countries, including technologies in the residential and industrial sectors and not just in power generation, was noted.

The Energy Primer of the IPCC Second Assessment Report (Nakicenovic *et al.*, 1996) gave estimates of energy reserves and resources, including the potential for various nuclear and renewable technologies which have since been updated (WEC, 1998b; Goldemberg, 2000; BGR, 1998). A current version of the estimates for fossil fuels and uranium is given in *Table 3.28a*. The potential for renewable forms of energy is discussed later.

A variety of terms are used in the literature to describe fossil fuel deposits, and different authors and institutions have various meanings for the same terms which also vary for different fossil fuel sources. The World Energy Council defines resources as "the occurrences of material in recognisable form" (WEC, 1998b). For oil and gas, this is essentially the amount of oil and gas in the ground. Reserves represent a portion of these resources and is the term used by the extraction industry. British Petroleum notes that proven reserves of oil are "generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions" (BP, 1999). Resources, therefore, are hydrocarbon deposits that do not meet the criteria of proven reserves, at least not yet. Future advances in the geosciences and upstream technologies – as in the past – will improve knowledge of and access to resources and, if demand exists, convert these into reserves. Market conditions can either accelerate or even reverse this process.

The difference between conventional and unconventional occurrences (oil shale, tar sands, coalbed methane, clathrates, uranium in black shale or dissolved in sea water) is either the nature of existence (being solid rather than liquid for oil) or the geological location (coal bed methane or clathrates, i.e., frozen

Table 3.28a: *Aggregation of fossil energy occurrences and uranium, in EJ*

	Consumption		**Reserves**	**Resources**[a]	**Resources**	**Additional**
	1860-1998	**1998**			**base**[b]	**occurrences**
Oil						
Conventional	4,854	132.7	5,899	7,663	13,562	
Unconventional	285	9.2	6,604	15,410	22,014	61,000
Natural gas[c]						
Conventional	2,346	80.2	5,358	11,681	17,179	
Unconventional	33	4.2	8,039	10,802	18,841	16,000
Clathrates						780,000
Coal	5,990	92.2	41,994	100,358	142,351	121,000
Total fossil occurrences	13,508	319.3	69,214	142,980	212,193	992,000
Uranium – once through fuel cycle[d]	1,100	17.5	1,977	5,723	7,700	2,000,000[e]
Uranium – reprocessing & breeding[f]			120,000	342,000	462,000	>120,000,000

[a] Reserves to be discovered or resources to be developed as reserves

[b] Resources base is the sum of reserves and resources

[c] Includes natural gas liquids

[d] Adapted from OECD/NEA and IAEA, 2000. Thermal energy values are reactor technology dependent and based on an average thermal energy equivalent of 500 TJ per t U. In addition, there are secondary uranium sources such as fissile material from national or utility stockpiles, reprocessing former military materials, and from re-enriched depleted uranium

[e] Includes uranium from sea water

[f] Natural uranium reserves and resources are about 60 times larger if fast breeder reactors are used (Nakicenovic *et al*., 1996)

Table 3.28b: *Aggregation of fossil energy occurrences, in GtC*

	Consumption		**Reserves**	**Resources**[a]	**Resources**	**Additional**
	1860-1998	**1998**			**base**[b]	**occurrences**
Oil						
Conventional	97.1	2.7	118	153	271	
Unconventional	5.7	0.2	132	308	440	1,220
Natural gas[c]						
Conventional	35.9	1.2	82	179	261	
Unconventional	0.5	0.1	123	165	288	245
Clathrates	-	-	-	-	-	11,934
Coal	156.4	2.4	1,094	2,605	3,699	3,122
Total fossil occurrences	295.6	6.5	1,549	3,410	4,959	16,521

- Negligible volumes

[a ,b] and [c] see *Table 3.28a*

ice-like deposits that probably cover a significant portion of the ocean floor). Unconventional deposits require different and more complex production methods and, in the case of oil, need additional upgrading to usable fuels. In essence, unconventional resources are more capital intensive (for development, production, and upgrading) than conventional ones. The prospects for unconventional resources depend on the rate and costs at which these can be converted into quasi-conventional reserves.

3.8.3 Historic Trends and Driving Forces

Table 3.28a categorizes fossil deposits into reserves, resources and additional occurrences for both conventional and unconventional oil and gas deposits. The categories reflect the definitions of reserves and resources given above, with the exception that resources are further disaggregated into resources and occurrences so as to better reflect the speculative nature associated with their technical and economic feasibility (Rogner, 1997, 2000a).

Table 3.28b presents the global fossil resource data of *Table 3.28a* in terms of their respective carbon content. Since the onset of the industrial revolution, almost 300GtC stored in fossil fuels have been oxidized and released to the atmosphere. The utilization of all proven conventional oil and gas reserves would add another 200GtC, and those of coal more than 1,000

GtC. The fossil fuel resource base represents a carbon volume of some 5,000GtC indicating the potential to add several times the amount already oxidized and released to the atmosphere during the 21st century. To put these carbon volumes into perspective, cumulative carbon emissions associated with the stabilization of carbon dioxide at 450ppm are estimated to be at 670GtC. *Figure SPM.2* combines the reserve and resource estimates with cummulative emissions for various reference and stabilization scenarios, taken from other chapters and the IPCC WGI report.

Potential coal reserves are large – of that there is little doubt. However, there is an active debate on the ultimate size of recoverable oil reserves. The pessimists see potential reserves as limited, pointing to the lack of major new discoveries for 25 years or so (Laherrere, 1994; Hatfield, 1997; Campbell, 1997; Ivanhoe and Leckie, 1993). They see oil production peaking around 2010. The optimists point to previous pessimistic estimates being wrong. They argue that "there are huge amounts of hydrocarbons in the Earth's crust" and that "estimates of declining reserves and production are incurably wrong because they treat as a quantity what is really a dynamic process driven by growing knowledge" (Adelman and Lynch, 1997; Rogner, 1998a). They further point to technological developments such as directional drilling and 3D seismic surveys which are allowing more reserves to be discovered and more difficult reserves to be developed (Smith and Robinson, 1997). The optimists see no major supply problem for several more decades beyond 2010.

Estimates of gas reserves have increased in recent years (IGU, 2000; Rogner, 2000a; Gregory and Rogner, 1998) as there is much still to be discovered, often in developing countries that have seen little exploration to date. The problem in the past has been that there needed to be an infrastructure to utilize gas before it could have a market, and without an infrastructure, exploration appeared unattractive. The development of CCGT power stations (discussed below) means that a local market for gas can more readily be found which could encourage wider exploration. In the longer term, it is estimated that very substantial reserves of gas can be extracted from the bottom of deep oceans in the form of methane clathrates, if technology can be developed to extract them economically

With uranium, there has only been very limited exploration in the world to date but once more is required, new exploration is likely to yield substantial additional reserves (Gregory and Rogner, 1998; OECD-NEA and IAEA, 2000) (see *Table 3.28a)*.

The other major supply of energy comes from renewable sources, which meet around 20% of the global energy demand, mainly as traditional biomass and hydropower. Modern systems have the potential to provide energy services in sustainable ways with almost zero GHG emissions (Goldemberg, 2000).

The following sections focus on energy supply and conversion technologies in which there have been developments since the Second Assessment Report and which may be key to achieving substantial reductions in greenhouse gas emissions in the coming decades.

On a global basis, in 1995 coal had the largest share of world electricity production at 38% followed by renewables (principally hydropower) at 20%, nuclear at 17%, gas at 15%, and oil at 10%. On current projections, electricity production is expected to double by 2020 compared to 1995 and energy used for generation to increase by about 80% as shown in *Table 3.29* (IEA, 1998b).

- Coal is projected to retain the largest share with a 90% increase in use from strong growth in countries such as India and China reflecting its importance there, steady growth in the USA but a decline in Western Europe.
- Gas is projected to grow strongly in many world regions reflecting the increasing availability of the fuel, with an overall increase of 160%.
- Nuclear power is projected to decline slightly on a global basis after 2010. Capacity additions in developing countries and in economies in transition roughly balance the capacity being withdrawn in OECD countries. Few new power stations will be built in many countries without a change in government policies. IAEA projections for 2020 cover a range from a 10% decline to an optimistic 50% increase in nuclear generating capacity (IAEA, 2000a).
- Hydropower is projected to grow by 60%, mainly in China and other Asian countries.
- New renewables have expanded substantially, in absolute terms, throughout the 1990s (wind 21% per year, solar PV more than 30% per year); these are projected to grow by over tenfold by 2020, but they would still supply less than 2% of the market.

3.8.4 New Technological Options

3.8.4.1 Fossil Fuelled Electricity Generation

3.8.4.1.1 Pulverized Coal

In a traditional thermal power station, pulverized coal (or fuel oil or gas) is burned in a boiler to generate steam at high temperature and pressure, which is then expanded through a steam turbine to generate electricity. The efficiencies of modern power stations can exceed 40% (lower heating value (LHV)), although the average efficiency, worldwide, of the installed stock is about 30% (Ishitani and Johansson, 1996). The typical cost of a modern coal- fired power station, with SO_2 and NO_x controls, is US$1,300/kW (Ishitani and Johansson, 1996). These costs vary considerably and can be more than 50% higher depending on location. Less efficient designs with fewer environmental controls are cheaper.

Table 3.29: *Past and projected global electricity production, fuel input to electricity production and carbon emissions from the electricity generating sector*
(Source: IEA, 1998b)

Global electricity generation (TWh)

	1971	1995	2000	2010	2020
Oil	1,100	1,315	1,422	1,663	1,941
Natural gas	691	1,932	2,664	5,063	8,243
Coal	2,100	4,949	5,758	7,795	10,296
Nuclear	111	2,332	2,408	2,568	2,317
Hydro	1,209	2,498	2,781	3,445	4,096
Renewables	36	177	215	319	433
Total	5,247	13,203	15,248	20,853	27,326

Fuel input (EJ)

	1971	1995	2000	2010	2020
Oil	11	13	14	15	18
Natural Gas	10	24	29	43	62
Coal	26	57	65	85	106
Nuclear	1	25	26	28	25
Hydro	4	9	10	12	15
Renewables	0	1	2	3	5
Total	53	129	146	187	230

CO_2 emissions (MtC)

	1971	1995	2000	2010	2020
Oil	224	258	273	307	350
Natural gas	158	362	443	662	946
Coal	668	1,471	1,679	2,185	2,723
Nuclear	0	0	0	0	0
Hydro	0	0	0	0	0
Renewables	0	0	0	0	0
Total	1,050	2,091	2,395	3,155	4,019

Average emissions per kWh

	1971	1995	2000	2010	2020
gC/kWh	200	158	157	151	147

The development of new materials allows higher steam temperatures and pressures to be used in "supercritical" designs. Efficiencies of 45% are quoted in the Second Assessment Report, although capital costs are significantly higher at around US$1,740/kW (Ishitani and Johansson, 1996). More recently, efficiencies of 48.5% have been reported (OECD, 1998b) and with further development, efficiencies could reach 55% by 2020 (UK DTI, 1999) at costs only slightly higher than current technology (Smith, 2000).

3.8.4.1.2 Combined Cycle Gas Turbine (CCGT)

Developments in gas turbine technology allow for higher temperatures which lead to higher thermodynamic efficiencies. The overall fuel effectiveness can be improved by capturing the waste heat from the turbine exhaust in a boiler to raise steam to generate electricity through a steam turbine. Thus in such a CCGT plant, electricity is generated by both the gas and steam turbines driving generators. The efficiency of the best available natural gas fired CCGTs currently being installed is now around 60% (LHV) (Goldemberg, 2000) and has been improving at 1% per year in the past decade. Typical capital costs for a power station of 60% efficiency are around US$450-500/kW, including selective catalytic reduction (for NO_x), dry cooling, switchyard, and a set of spares. Costs can be higher in some regions, especially if new infrastructure is required. These costs have been falling as efficiencies improve (IIASA-WEC, 1998). Together with high availability and short construction times, this makes CCGTs highly favoured by power station developers where gas is available at reasonable prices. Developments in the liquefied natural gas markets could further expand the use of CCGTs. Further improvements might allow electricity generating efficiencies of over 70% to be achievable for CCGTs within a reasonable period (Gregory and Rogner, 1998).

3.8.4.1.3 Integrated Gasification Combined Cycle (IGCC)

IGCC systems utilize the efficiency and low capital cost advantages of a CCGT by first gasifying coal or other fuel. Gasifiers are usually oxygen blown and are at the early commercial stage (Goldemberg, 2000). Coal and difficult liquid fuels such as bitumens and tar can be used as feedstocks. Biomass fuels are easier to gasify (Section 3.8.4.3.2), which may reduce the cost and possibly the efficiency penalty as an oxygen plant is not required (Lurgi GmbH, 1989). Gas clean-up prior to combustion in the gas turbine, which is sensitive to contaminants, is one of the current areas of development. The potential efficiency of IGCCs is around 51%, based on the latest CCGTs of 60% efficiency (Willerboer, 1997). Vattenfall, using a GE Frame 6 gas turbine, indicated a net efficiency of 48% in trials (Karlsson *et al*., 1998), and an efficiency of 50%-55% was claimed to be achievable by using the latest gas turbine design. With continuing development in hot gas cleaning and better heat recovery as well as the continuing development of CCGTs, commercially available coal- or wood-fired IGCC power stations with efficiencies over 60% may be feasible by 2020.

In addition to the potential high efficiencies, IGCC offers one of the more promising routes to CO_2 capture and disposal by converting the gas from the gasifier into a stream of H_2 and CO_2 via a shift reaction. The CO_2 can then be removed for disposal before entering the gas turbine (see Section 3.8.4.4). The resultant stream of H_2 could be used in fuel cells and not just in a gas turbine.

3.8.4.1.4 Cogeneration

Combined heat and power (CHP) generation can yield fuel energy utilization rates of up to 90% and can therefore be an effective GHG mitigation option. CHP is possible with all heat machines and fuels (including nuclear, biomass and solar thermal) from a few kW-rated to 1000MW steam-condensing power plants. At the utility level the employment of CHP is closely linked with industrial heat loads as well as the availability or development of district heating and/or cooling networks. These are energy transmission systems suited for the distribution of heat and/or cooling within areas with sufficiently high heat/cooling load densities (Kalkum *et al*., 1993; Rogner, 1993). The expanded use of natural gas may provide a basis for increased dispersed cogeneration. Industrial CHP utilizes temperature differentials between the heat source and the process temperature requirements for electricity generation. More recently, in some countries electricity market deregulation has made it easier for large industrial users to generate their own electricity as well as heat by being more easily able to sell any surplus electricity (see Section 3.8.5.1). Conversely, following deregulation in Germany and elsewhere, large grid CHP has suffered market loss as a consequence of existing surplus generating capacity and independent generation. There is good potential for cogeneration of biomass including bagasse in developing countries such as India, where the market potential is 3500MW. However, a heat demand is necessary for CHP plants to be implemented successfully.

3.8.4.1.5 Fuel Cells

Several types of fuel cell compete for early entry into a variety of prospective markets (Gregory and Rogner, 1998). Proton exchange membrane, phosphoric acid, fuel cells (PAFCs) and solid oxide fuel cells are the current technology options. Each type has its own distinctive characteristics such as operating temperatures, efficiency ranges, fuel use, markets and costs[18]. The potential advantages of fuel cells over gas turbines include smaller unit sizes at similar efficiencies, the potential of a low or quasi zero GHG emission technology at the point of use, lower maintenance costs, less noise and, eventually, better economic performance.

The internal fuel is hydrogen, but some fuel cell types can use fuels such as CO, methanol, natural gas or even coal if externally converted to hydrogen at the plant via gasification and steam reforming or partial oxidation. Alternatively, some fuel cell designs perform the hydrogen conversion step internally as an integral part of the technology.

Hydrogen production from hydrocarbon fuels generates some airborne emissions (NO_x, CO, CO_2 and NMVOCs) but these are – with the exception of CO_2 - orders of magnitude lower than those associated with combustion cycles. The electrochemistry of most fuel cells demands the use of sulphur-free natural gas, hence no SO_2 emissions occur. CO_2 emissions are a function of the electrical efficiency and as such are comparable with the efficient CCGT. Non fossil-derived hydrogen, e.g., by way of solar powered electrolysis or from methanol derived from biomass, can be used with virtually zero GHG emissions.

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[18] Although primarily targetted for electricity generation in less densely populated rural areas (distributed generation), fuel cell manufacturers have always had high aspirations for the transport market.

Proton exchange membrane (PEM) conversion efficiencies are currently at 45%-48%[19] using hydrogen as the onboard fuel, and are expected to approach 55%-60% in the near term future. The joint venture between the leading PEM fuel cell producer and major automobile manufacturers aimed at mass producing PEMs for vehicle propulsion targets to bring down costs to less than US$500/kW$_e$ by 2000 and to less than US$250/kW$_e$ by 2010 (Rogner, 1998b). In the very long term, costs comparable to current internal combustion engines of approximately US$50/kW$_e$ have been suggested (Lovins, 1996).

Phosphoric acid fuel cells (PAFCs) operate at around 200ºC and pressures up to 8 bar. At present, PAFCs, in particular the 200 kW ONSI PC25, are commercially the most advanced fuel cells in the market place and have accumulated more than one million hours of operating experience world-wide. Stationary PAFC applications include the world's largest fuel cell power plant of 11 MW in Goi, Japan, which was in test operation from 1991 to 1997, commissioned by Tokyo Electric Power Company (TEPCO). Natural gas to electricity conversion was 36 to 38% efficient. Overall fuel effectiveness with waste heat utilization can be as high as 80%. Capital costs for an integrated system, including a fuel processor based on natural gas, are expected to decline to about US$1,500/kW$_e$ by 2000. Long-term costs will depend on manufacturing volumes, but industry experts project costs below US$700/kW$_e$ by 2010 (Tauber and Jablonski, 1998) at electrical efficiencies of 50% and overall fuel effectiveness of 90% for cogeneration.

Molten carbonate fuel cells (MCFC) operating at 650ºC open the possibility of using carbonaceous fuels and internal reforming. With steam turbines in a bottoming cycle, the overall electrical efficiency could be as high as 65%. There are still major technical problems associated with MCFCs such as electrode corrosion, the sintering of the structural fuel cell material, and sensitivity to fuel impurities.

The operating temperature of 1000ºC of solid oxide fuel cells (SOFCs) allows internal reforming and produces high quality by-product heat for cogeneration or for use in a bottoming cycle. The development of suitable materials and the fabrication of ceramic structures are presently the key technical challenges facing SOFCs. They are currently being demonstrated in a 100-kilowatt plant and are expected to be competitive with traditional fossil-fired generation early in the 21st century. Installation costs will eventually reach about US$700/kW$_e$ (EPRI, 1997) though other sources report US$1,620/kW$_e$ for the period 2005-2010 (OECD, 1998b).

Hybrid SOFC/CCGT systems have projected efficiencies of 72 to 74%, and, depending on R&D progress, would represent the ultimate fossil fuel based electricity generation (Federal Energy Technology Center, 1997). Typical plant sizes would be 1 to 100 MW and, fuelled with natural gas, would produce the lowest emissions of all fossil fuel electricity generating options of about 75–80gC/kWh.

3.8.4.2 Nuclear Power

3.8.4.2.1 Present Situation

Nuclear power is a mature technology with 434 nuclear reactors operating in 32 countries in 1999, with a total capacity of around 349GW$_e$ generating 2,398 TWh or some 16% of global electricity generation in 1999 (IAEA, 2000b). In general, the majority of current nuclear power plants worldwide are competitive on a marginal cost basis in a deregulated market environment[20].

The life cycle GHG emissions per kWh from nuclear power plants are two orders of magnitude lower than those of fossil-fuelled electricity generation and comparable to most renewables (EC, 1995; Krewitt *et al*., 1999; Brännström-Norberg *et al*., 1996; Spadaro *et al*., 2000). Hence it is an effective GHG mitigation option, especially by way of investments in the lifetime extension of existing plants.

Whether or not nuclear power would be accepted in the market place depends on new capacities becoming economically competitive and on its ability to restore public confidence in its safe use.

3.8.4.2.2 Nuclear Economics

Where gas supply infrastructures are already in place, new nuclear power plants at US$1700–US$3100/kW$_e$ (Paffenberger and Bertel, 1998) cannot compete against natural gas-fuelled CCGT technology at current and expected gas prices (OECD, 1998b). Nuclear power can be competitive versus coal and natural gas, especially if coal has to be transported over long distances or natural gas infrastructures are not in place. Discount rates are often critical in tilting the competitive balance between nuclear power and coal. A study (OECD, 1998b) surveyed the costs of nuclear, coal, and natural gas-fuelled electricity generation in 18 countries for plants that would go into operation in 2005. The results, estimated for both 5% and 10% discount rates, showed that nuclear power is the least cost option in seven countries at a 5% discount rate (generating cost range US$0.025–0.057/kWh), but only in two countries at a 10% discount rate (generating cost range US$ 0.039–0.080/kWh). In fully deregulated markets such as the UK's, rates of return in excess of 14% have been required at which level new nuclear plant construction would not be competitive at current fossil fuel market prices[21].

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[19] For fuel cells all efficiencies cited are based on higher heating values (HHV).

[20] Because of low operating costs and the fact that many nuclear power plants are already fully depreciated.

[21] Rising coal and gas market prices such as observed for oil in 2000 would change the competitive position of nuclear substantially.

3.8.4.2.3 Waste Disposal

Technological approaches for safe and long-term disposal of high-level radioactive waste have been extensively studied (Posiva Oy, 1999; EC, 1999). One possible solution involves deep geological repositories, however, no country has yet disposed of any spent fuel or high-level waste in such a repository because of public and political opposition (NEA, 1999). Several countries are actively researching this issue. Long-term disposal of radioactive wastes should not be an intractable problem from a technical perspective, because of the small quantities of storage space required (Goldemberg, 2000; Rhodes and Beller, 2000). Radioactive waste storage density limits defined for storing light water reactor (LWR) fuel at Yucca Mountain are about 41 m^2/MW_e of nuclear generating capacity for a power plant over its expected 30 years of operating life[22] (Kadak, 1999). High level waste volumes can be further reduced if spent fuel is reprocessed so that most of the plutonium and unused uranium is extracted for reuse. The remaining high-level waste is compacted and "vitrified" (melted with other ingredients to make a glassy matrix), and placed into canisters that are appropriate for long-term disposal. However, reprocessing of spent fuel and the separation of plutonium are often viewed as potentially opening the door for nuclear weapons proliferation. For this and economic reasons, several countries therefore prefer once-through fuel cycles and direct disposal of spent reactor fuel.

Because of the low waste volumes, it may be plausible to accumulate high level radioactive wastes in a few sites globally rather than every country seeking national solutions (Goldemberg, 2000) These international repositories would be operated and controlled by an international organization which would also assume the responsibility of safeguarding these sites (McCombie, 1999a; 1999b; McCombie *et al*., 1999; Miller *et al*., 1999). For the time being, most governments remain committed to identifying suitable high-level waste disposal or interim storage solutions within their own national territories.

In the longer run, fundamentally new reactor configurations may need to be developed that are based on innovative designs that integrate inherent operating safety features and waste disposal using previously generated radioactive waste as fuel and, by way of transmutation, convert nuclear waste or plutonium to less hazardous and short-lived isotopic substances (Rubbia, 1998).

Present technology can be used to reduce the growth of the plutonium stocks by use of mixed plutonium/uranium oxide fuels (MOX) in thermal reactors. Belgium, France, Germany, and Switzerland use MOX fuels in existing reactors. Japan also has been progressing its MOX utilizing programme.

3.8.4.2.4 New Reactor Technologies

The future of nuclear power will depend on whether it can meet several objectives simultaneously – economics, operating safety, proliferation safeguards, and effective solutions to waste disposal. While present new nuclear power plants already incorporate unprecedented levels of safety based on in-depth designs, their economics need further improvement to be competitive in most markets. Safe waste disposal for approximately 1 million years is technically feasible (Whipple, 1996) and would add US$0.0002/kWh to generating costs (Kadak, 1999; Goldemberg, 2000). Disposal cost estimates for Sweden are higher, i.e., US$0.0013. Proliferation is a political issue primarily, but can also be addressed by technology. Evolutionary technology improvements of existing designs are important elements for the near-term viability of nuclear power but may not be sufficient to meet all the objectives optimally. For example, smaller grid sizes in developing countries demand smaller unit size reactors. Therefore, new technology that addresses these objectives by integral design holds the key to the future of nuclear power.

Building on more than 40 years of experience with LWR technology, major nuclear reactor vendors have now developed modified LWRs that offer both improved safety and lower cost (CISAC, 1995; Kupitz and Cleveland, 1999). These evolutionary development efforts resulted in standardized designs for which there can be a high degree of confidence that performance and cost targets will be met. All employ active but simplified safety systems, and some have some passive safety features.

One reactor in this category is the Westinghouse AP600, a 600 MW_e pressurized water reactor (PWR). The design is simpler than existing PWRs and modular, with about half the capacity of most existing PWRs—which allows some components to be factory built and assembled faster onsite at lower cost than for plants that are entirely field constructed. The AP600 is expected to be safer than existing PWRs, constructed in three years, and costs about 15% less than existing PWRs of the same capacity (NPDP, 1998)[23].

Other examples include the ABB/Combustion Engineering System 80+ and the GE Advanced Boiling Water Reactor (ABWR)[24]. The System 80+ is a large (1,350 MW_e) unit for which the estimated core damage frequency is two orders of magnitude lower than for its predecessor. The ABWR has as a design objective stepped-up operating safety and a target capital cost that is 20% less than for BWRs previously built in Japan (NPDP, 1998). Two ABWRs are now operating in Japan. Two more are under construction in Japan and also in Taiwan/China.

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[22] The actual high-level waste accumulated over 30 years amounts to approximately 1 m^3/MWe.

[23] In late 1999 the AP600 received Design Certification from the US Nuclear Regulatory Commission.

[24] Both designs received Design Certification from the US Nuclear Regulatory Commission in 1997.

In Europe, a Framatome/Siemens joint venture has developed the European pressurized water reactor (EPR), a 1,450 to 1,750 MW_e system designed to specifications endorsed by utilities in Europe—with hoped-for economies of scale at this large unit size. The EPR is being offered on the international market.

One of the innovative designs is the pebble bed modular reactor (PBMR) developed by the South African utility ESKOM. The fundamental concept of the design is to achieve a plant that has no physical process, however unlikely, that could cause a radiation-induced hazard outside the site boundary. This is principally achieved in the PBMR[25].

The current ESKOM assessment is that the capital cost of a production of 1000MW_e block of 10 modules will be US\$1,000/kW_e (US\$1,200/kW_e for the prototype). The low capital costs are the result of a much lower energy density of the reactor core than present reactor technologies; the elimination of heat exchangers; use of a direct helium turbine; the shift of the containment from the plant periphery to the pebble fuel; a high in-shop manufacturing component of the plant, and a short construction period of 2 years. This would produce attractive generating costs with unprecedented safety aspects. As a base load station with a depreciation period of 20 years and at a 10% discount rate, the expected cost of power would be approximately US\$0.018/kWh including the full fuel cycle and decommissioning. These costs are low indeed and in part the result of engineering optimism. Other studies based on the less advanced modular high temperature reactor (HTR) designs conclude that generating costs may range from US\$0.020 to US\$0.034/kWh (Lako, 1996). Kadak (1999) estimates the unit capital cost for a PBMR plant with some different design characteristics at twice the ESKOM value, i.e., US\$2,090/kW_e which results in generating costs of US\$0.033/kWh but still less than average present technology.

3.8.4.2.5 GHG Mitigation Potential

Increased performance and lifetime extension of the currently existing nuclear reactors often present a zero-costs greenhouse gas mitigation option. However, given current market conditions, new nuclear power capacity is a least-cost alternative in only some countries usually characterized by limited indigenous fossil resources or by large distances between resource location and consumption centres. Under such circumstances nuclear power is a zero cost mitigation option. If the optimistic PBMR generating costs can be accomplished, this would certainly imply negative mitigation costs. For new nuclear plants of state-of-the art designs, a value of US\$0 to 40/tC avoided would put nuclear at par with coal-fired electricity, while it would take a value of a US\$100 to 250/tC for nuclear power to break even with natural gas combined cycle electricity (IEA, 1998a; Rogner, 2000b). Based on the current global electricity mix, nuclear power avoids some 600MtC of carbon per year (Rogner, 1999).

The most recent projection of the International Atomic Energy Agency (IAEA) is that in the absence of any policies with regard to climate change, capacity in 2020 could be in the range 300GW_e to 520GW_e (from 349GW_e in 1999). This means that the share of nuclear power in total power generation could decline to 6% - 8% by 2020 (IAEA, 2000a). Compared to the reference case of the IEA World Energy Outlook (IEA, 1998b), the higher projection of IAEA would avoid the emission of 87MtC in 2010 and 281MtC in 2020 over and above the reference case assuming that nuclear power displaces coal-fired electricity[26]. Maintaining the past nuclear share in global electricity generation would avoid annually 280MtC in 2010 and 550MtC in 2020 (again above the IEA reference case of approximately 600GtC).

3.8.4.3 Renewable Energy Conversion Technologies

Natural energy flows vary from location to location, and make the techno-economic performance of renewable energy conversion highly site-specific. Intermittent sources such as wind, solar, tidal, and wave energy require back-up if not grid connected, while large penetration into grids may eventually require storage and/or back-up to guarantee reliable supply. Therefore, it is difficult to generalize costs and potentials.

3.8.4.3.1 Hydropower

Hydroelectricity remains the most developed renewable resource worldwide with global theoretical potential ranges from 36,000 to 44,000TWh/yr (World Atlas, 1998). Approximately 65% of the technical hydro potential has been developed in Western Europe, and 76% in the USA. This indicates a limit caused by societal and environmental barriers. For many developing countries the total technical potential, based on simplified engineering and economic criteria with few environmental considerations, has not been fully measured. The economic potential resulting from detailed geological and technical evaluations, but including social and environmental issues, is difficult to establish because these parameters are strongly driven by societal preferences inherently uncertain and difficult to predict. A rate of utilization between 40% and 60% of a region's technical potential is therefore a reasonable assumption and leads to a global economic hydro-electricity potential of 7,000 to 9,000TWh/yr (see *Table 3.30*).

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[25] The integrated heat loss from the reactor vessel exceeds the decay heat production in the post accident condition, and the peak temperature reached in the core during the transient is below the demonstrated fuel degradation point and far below the temperature at which the physical structure is affected. The prospect of a "core melt" scenario is therefore zero.

[26] The nuclear mitigation potential is based on the following assumption: between 2000 and 2020 nuclear capacities increase to the 520GW_e of the high IAEA projection and substitute incremental coal capacities with global average efficiencies of 39.4% and 44.1% in 2010 and 2020, respectively (compared to 33.1% and 35.1% in the IEA World Energy Outlook (IEA, 1986)). The nuclear share in global electricity generation would then amount to 13%.

Table 3.30: *Annual large hydroelectric development potential (TWh/yr)*

	Theoretical potential		**Technological potential**		**Economic potential**	
	TWh[a]	TWh[b]	TWh[a]	TWh[b]	TWh[a]	TWh[b]
Africa	3,307	3,633	1,896	1,589	815	866
North America	5,817	5,752	1,509	1,007	912	957
Latin America	7,533	8,800	2,868	3,891	1,198	2,475
Asia (excluding former USSR)	15,823	14,138	4,287	4,096	1,868	2,444
Australasia	591	592	201	206	106	168
Europe	3,128	3,042	1,190	942	774	702
Former USSR	3,583	3,940	1,992	2,105	1,288	1,093
World	**39,784**	**39,899**	**13,945**	**13,839**	**6,964**	**8,708**

[a] World Atlas, 1999

[b] International Water Power & Dam Construction, 1997

Numerous small (<10MW), mini (<1MW) and micro (<100kW) scale hydro schemes with low environmental impacts continue to be developed globally. The extent of this resource, particularly in developing countries such as Nepal, Oceania, and China, is unknown but likely to be of significance to rural communities currently without electricity.

Large-scale hydropower plant developments can have high environmental and social costs such as loss of fertile land, methane generation from flooded vegetation, and displacement of local communities (Moomaw *et al*., 1999b). At the 18,200 MW Three Gorges dam under construction in China, 1.2 million people have been moved to other locations. Another limitation to further development is the high up-front capital investment which the recently privatized power industries are unlikely to accept because of the low rates of return.

The remote locations of many potential hydro sites result in high transmission costs. Development of medium (<50MW) to small (<10MW) scale projects closer to demand centres will continue. In countries where government or aid assistance is provided to overcome the higher investment costs/MW at this scale, power generation costs around US$0.065/kWh will result (UK DTI, 1999). Mini- and micro-hydro low head turbines are under development but generating costs at this scale are likely to remain high, partly as a result of the cost of the intake structure needed to withstand river flood conditions. Even at this small scale, environmental and ecological effects often result from taking water from a stream or small river and discharging it back again, even after only a short distance.

3.8.4.3.2 Biomass Conversion

Globally, biomass has an annual primary production of 220 billion oven-dry tonnes (odt) or 4,500 EJ (Hall and Rosillo-Calle, 1998a). Of this, 270 EJ/yr might become available for bioenergy on a sustainable basis (Hall and Rosillo-Calle, 1998a) depending on the economics of production and use as well as the availability of suitable land. In addition to energy crops (Section 3.6.4.3), biomass resources include agricultural and forestry residues, landfill gas and municipal solid wastes. Since biomass is widely distributed it has good potential to provide rural areas with a renewable source of energy (Goldemberg, 2000). The challenge is to provide the sustainable management, conversion and delivery of bioenergy to the market place in the form of modern and competitive energy services (Hall and Rao, 1994).

At the domestic scale in developing countries, the use of firewood in cooking stoves is often inefficient and can lead to health problems. Use of appropriate technology to reduce firewood demand, avoid emissions, and improve health is a no-regrets reduction opportunity (see Section 4.3.2.1).

Agricultural and forest residues such as bagasse, rice husks, and sawdust often have a disposal cost. Therefore, waste-to-energy conversion for heat and power generation and transport fuel production often has good economic and market potential, particularly in rural community applications, and is used widely in countries such as Sweden, the USA, Canada, Austria, and Finland (Hall and Rosillo-Calle, 1998b; Moomaw *et al*., 1999b; Svebio, 1998). Energy crops have less potential because of higher delivered costs in terms of US$/GJ of available energy.

Harvesting operations, transport methods, and distances to the conversion plant significantly impact on the energy balance of the overall biomass system (CEC, 1999; Moreira and Goldemberg, 1999). The generating plant or biorefinery must be located to minimize transport costs of the low energy density biomass as well as to minimize impacts on air and water use. However, economies of scale of the plant are often more sig-

Table 3.31: *Projection of technical energy potential from biomass by 2050*
(Derived from Fischer and Heilig, 1998; D'Apote, 1998; IIASA/WEC, 1998)

Region	**Population in 2050** Billion	**Total land with crop production potential** Gha	**Cultivated Land in 1990** Gha	**Additional cultivated land required in 2050** Gha	**Available area for biomass production in 2050** Gha	**Max. Additional amount of energy from biomass[a]** EJ/yr
***Developed*[b]**	-	0.820	0.670	0.050	0.100	30
Latin America						
Central & Caribbean	0.286	0.087	0.037	0.015	0.035	11
South America	0.524	0.865	0.153	0.082	0.630	189
Africa						
Eastern	0.698	0.251	0.063	0.068	0.120	36
Middle	0.284	0.383	0.043	0.052	0.288	86
Northern	0.317	0.104	0.04	0.014	0.050	15
Southern	0.106	0.044	0.016	0.012	0.016	5
Western	0.639	0.196	0.090	0.096	0.010	3
China[c]	-	-	-	-	-	2
Rest of Asia						
Western	0.387	0.042	0.037	0.010	-0.005	0
South –Central	2.521	0.200	0.205	0.021	-0.026	0
Eastern	1.722	0.175	0.131	0.008	0.036	11
South –East	0.812	0.148	0.082	0.038	0.028	8
Total for regions above	8.296	2.495	0.897	0.416	1.28	396
Total biomass energy potential, EJ/yr						**441[d]**

[a] Assumed 15 odt/ha/yr and 20GJ/odt

[b] Here, OECD and Economies in Transition

[c] For China, the numbers are projected values from D'Apote (1998) and **not** maximum estimates.

[d] Includes 45 EJ/yr of current traditional biomass.

nificant than the additional transport costs involved (Dornburg and Faaij, 2000). The sugar cane industry has experience of harvesting and handling large volumes of biomass (up to 3Mt/yr at any one plant) with the bagasse residues often used for cogeneration on site to improve the efficiency of fuel utilization (Cogen, 1997; Korhonen *et al*., 1999). Excess power is exported. In Denmark about 40% of electricity generated is from biomass cogeneration plants using wood waste and straw. In Finland, about 10% of electricity generated is from biomass cogeneration plants using sawdust, forest residues, and pulp liquors (Pingoud *et al*., 1999; Savolainen, 2000). In other countries biomass cogeneration is utilized to a lesser degree as a result of unfavourable regulatory practices and structures within the electricity industry (Grohnheit, 1999; Lehtilä *et al*., 1997).

Land used for biomass production will have an opportunity cost attributed to it for the production of food or fibre, the value being a valid cost which can then be used in economic analyses. *Table 3.31* shows the technical potential for energy crop production in 2050 to be 396EJ/yr from 1.28Gha of available land[27]. By 2100 the global land requirement for agriculture is estimated to reach about 1.7Gha, whereas 0.69-1.35Gha would then be needed to support future biomass energy requirements in order to meet a high-growth energy scenario (Goldemberg, 2000). Hence, land-use conflicts could then arise.

Several developing countries in Africa (e.g., Kenya) and Asia (e.g., Nepal) derive over 90% of their primary energy supply

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[27] Practical/technical constraints on the use of land for bioenergy such as the distance of a proposed biomass production site from energy demand centres, the power distribution grid, or sources of labour are not considered here. Hence the estimate exceeds the 270EJ of Hall and Rosillo-Calle (1998a).

from traditional biomass. In India it currently provides 45% and in China 30%. Modern bioenergy applications at the village scale are gradually being implemented, leading to better and more efficient utilization which, in many instances, complement the use of the traditional fuels (FAO, 1997) and provide rural development (Hall and Rosillo-Cale, 1998b). For example, production of liquids for cooking, from biomass grown in small-scale plantations, using the Fischer-Tropsch process (modified to co-produce electricity by passing unconverted syngas through a small CCGT), is being evaluated for China using corn husks (Larson and Jin, 1999). Biomass and biofuel were identified by a US Department of Energy study (Interlaboratory Working Group, 1997) as critical technologies for minimizing the costs of reducing carbon emissions. Co-firing in coal-fired boilers, biomass-fuelled integrated gasification combined-cycle units (BIGCC) for the forest industry, and ethanol from the hydrolysis of lignocellulosics were the three areas specifically recognized as having most potential. Estimates of annual carbon offsets from the uptake of these technologies in the USA alone ranged from 16-24Mt, 4.8Mt, and 12.6-16.8Mt, respectively, by 2010. The near term energy savings from use of each of these technologies should cover the associated costs (Moore, 1998), with co-firing giving the lowest cost and technical risk.

Woody biomass blended with pulverized coal at up to 10%–15% of the fuel mix is being implemented, for example, in Denmark and the USA, but may be uneconomic as a consequence of coal being cheaper than biomass together with the costs of combustion plant conversion (Sulilatu, 1998). However, major environmental benefits can result including the reduction of SO_2 and NO_x emissions (van Doorn *et al*., 1996).

Gasification of biomass

Biofuels are generally easier to gasify than coal (see Section 3.8.4.1.3), and development of efficient BIGCC systems is nearing commercial realization. Several pilot and demonstration projects have been evaluated with varying degrees of success (Stahl and Neergaard, 1998; Irving, 1999; Pitcher and Lundberg, 1998). Capital investment for a high pressure, direct gasification combined-cycle plant of this scale is estimated to fall from over US$2,000/kW at present to around US$1,100/kW by 2030, with operating costs, including fuel supply, declining from 3.98c/kWh to 3.12c/kWh (EPRI/DOE, 1997). By way of comparison, capital costs for traditional combustion boiler/steam turbine technology were predicted to fall from the present US$1,965/kW to US$1,100/kW in the same period with current operating costs of 5.50c/kWh (reflecting the poor fuel efficiency compared with gasification) lowering to 3.87c/kWh.

A life cycle assessment of the production of electricity in a BIGCC plant showed 95% of carbon delivered was recycled (Mann and Spath, 1997). From the energy ratio analysis, one unit of fossil fuel input produced approximately 16 units of carbon neutral electricity exported to the grid.

Liquid biofuels

Ethanol production using fermentation techniques is commercially undertaken in Brazil from sugar cane (Moreira and Goldemberg, 1999), and in the USA from maize and other cereals. It is used as a straight fuel and/or as an oxygenate with gasoline at 5%-22% blends. Enzymatic hydrolysis of lignocellulosic feedstocks such as bagasse, rice husks, municipal green waste, wood and straw (EPRI/DOE, 1997) is being evaluated in a 1t/day pilot plant at the National Renewable Energy Laboratory and is nearing the commercial scale-up phase (Overend and Costello, 1998). Research into methanol from woody biomass continues with successful conversion of around 50% of the energy content of the biomass at a cost estimate of around US$0.90/litre (US$34/GJ) (Saller *et al*., 1998). In Sweden production of biofuels from woody biomass (short rotation forests or forest residues) was estimated to cost US$0.22/litre for methanol and US$0.54/litre for ethanol (Elam *et al*., 1994). However, the energy density (MJ/l) of methanol is around only 50% that of petrol and 65% for ethanol. Using the available feedstock for heat and power generation might be a preferable alternative (Rosa and Ribeiro, 1998).

Commercial processing plants for the medium scale production of biodiesel from the inter-esterification of triglycerides have been developed in France, Germany, Italy, Austria, Slovakia, and the USA (Austrian Biofuels Institute, 1997). Around 1.5 million tonnes is produced each year, with the largest plant having a capacity of 120,000 tonnes. Environmental benefits include low sulphur and particulate emissions. A positive energy ratio is claimed with 1 energy unit from fossil fuel inputs giving 3.2 energy units in the biodiesel (Korbitz, 1998). Conversely, other older studies suggest more energy is consumed than produced (Ulgiati *et al*., 1994).

Biodiesel production costs exceed fossil diesel refinery costs by a factor of three to four because of high feedstock costs even when grown on set-aside land (Veenendal *et al*., 1997), and they are unlikely to become more cost effective before 2010 (Scharmer, 1998). Commercial biodiesel has therefore only been implemented in countries where government incentives exist. Biofuels can only become competitive with cheap oil if significant government support is provided by way of fuel tax exemptions, subsidies (such as for use of set-aside surplus land), or if a value is placed on the environmental benefits resulting.

3.8.4.3.3 Wind Power

Wind power supplies around 0.1% of total global electricity but, because of its intermittent nature and relatively recent emergence, accounts for around 0.3% of the global installed generation capacity. This has increased by an average of 25% annually over the past decade reaching 13,000MW by 2000, with estimates of this increasing to over 30,000MW capacity operating by 2005 (EWEA, 1999). The cost of wind turbines

Table 3.32: *Assessment of world wind energy potential on land sites with mean annual wind speeds greater than 5.1m/s* (Grubb and Meyer (1993)

Region	**Percent of land area**	**Population density**	**Gross electric potential**	**Wind energy potential**	**Estimated second order potential**	**Assessed wind energy potential**
	%	**capita/km²**	**TWh ×10³/yr**	**EJ/yr[a)]**	**TWh ×10³ /yr**	**EJ/yr[a]**
Africa	24	20	106	1,272	10.6	127
Australia	17	2	30	360	3.0	36
North America	35	15	139	1,670	14.0	168
Latin America	18	15	54	648	5.4	65
Western Europe	42	102	31	377	4.8	58
EITs	29	13	106	1,272	10.6	127
Asia	9	100	32	384	4.9	59
World	23	-	498	5,976	53.0	636

[a] The energy equivalent in TWh is calculated on the basis of the electricity generation potential of the referenced sources by dividing the electricity generation potential by a factor of 0.3 (a representative value for the efficiency of wind turbines including transmission losses) resulting in a primary energy estimate.

continues to fall as more new capacity is installed. The trend follows the classic learning curve and further reductions are projected (Goldemberg, 2000). In high wind areas, wind power is competitive with other forms of electricity generation.

The global theoretical wind potential is on the order of 480,000TWh/yr, assuming that about 3×10^7 km^2 (27%) of the earth's land surface is exposed to a mean annual wind speed higher than 5.1 m/s at 10 metres above ground (WEC, 1994). Assuming that for practical reasons just 4% of that land area could be used (derived from detailed studies of the potential of wind power in the Netherlands and the USA), wind power production is estimated at some 20,000 TWh/yr, which is 2.5 times lower than the assessment of Grubb and Meyer (1993) (see *Table 3.32*). The *Global Wind Energy Initiative*, presented by the wind energy industry at the 4th Conference of Parties meeting in Buenos Aires (BTM Consult, 1998), demonstrated that a total installed capacity of 844GW by 2010, including offshore installations, would be feasible. A report by Greenpeace and the European Wind Energy Association estimated 1,200GW could be installed by 2020 providing almost 3,000TWh/yr or 10% of the global power demand assumed at that time (Greenpeace, 1999).

Many of the turbines needed to meet future demand will be sited offshore, exceed 2MW maximum output, and have lower operating and maintenance costs, increased reliability, and a greater content of local manufacture. Shallow seas and planning consents may be a constraint.

Various government-enabling initiatives have resulted in the main uptake of wind power to date occurring in Germany, Denmark, the USA, Spain, India, the UK and the Netherlands. Typically turbines in the 250 – 750kW range are being installed (Gipe, 1998). Significant markets are now emerging in China, Canada, South America, and Australia.

Denmark aims to provide 40%-50% of its national electricity generation from wind power by 2030 and remains the main exporter of turbine technology (Krohn, 1997; Flavin and Dunn, 1997). China and India, based on recent wind survey programmes, have a high technical wind potential of 250–260GW and 20–35GW respectively, and are major turbine importers (Wang, 1998; MNES, 1998). However, following various government incentives, both China and India now manufacture their own turbines with export orders in place (Wang, 1998; AWEA, 1998).

Wind power continues to become more competitive, and commercial development is feasible without subsidies or any form of government incentives at good sites. In 1999, for example, a privately owned 32MW wind farm constructed in New Zealand on a site with mean annual wind speed of greater than 10m/s was competing at below US$0.03/kWh in the wholesale electricity market (Walker *et al.*, 1998). The rapidly falling price of wind power is evidenced by the drop in average prices (adjusted for short contract lengths). Over successive rounds of the British NFFO (non-fossil-fuel obligation), average tendered kWh prices declined from 7.95p in 1990 to 2.85p (US$0.043/kWh) in 1999 (Mitchell, 1998; UK DTI, 1999). These confirm the estimate of Krohn (1997) that wind generated electricity costs from projects >10MW would decline to US$0.04/kWh on good sites. The global average price is expected to drop further to US$0.027–0.031/kWh by around 2020 as a result of economies of scale from mass production and improved turbine designs (BTM consult, 1999). EPRI/DOE (1997) predicted the installed costs will fall from US$1,000 to US$635/kW (with uncertainty of +10% -20%), and operating costs will fall from 0.01c/kWh to 0.005c/kWh. However, on poorer sites of around 5m/s mean annual wind speed, the generating costs would remain high at around US$0.10-0.12/kWh (8% discount rate).

Table 3.33a: *Key assumptions for the assessment of the solar energy potential*

Region	**Assumed annual clear sky irradiance**[a] **kW/m²**		**Assumed annual average sky clearance**[b]**, %**	
	Min	Max	Min	Max
NAM (North America)	0.22	0.45	0.44	0.88
LAM (Latin America and the Caribbean)	0.29	0.46	0.48	0.91
AFR (Sub-Saharan Africa)	0.31	0.48	0.55	0.91
MEA (Middle East and North Africa)	0.29	0.47	0.55	0.91
WEU (Western Europe)	0.21	0.42	0.44	0.80
EEU (Central and Eastern Europe)	0.23	0.43	0.44	0.80
FSU (Newly independent states of the former Soviet Union)	0.18	0.43	0.44	0.80
PAO (Pacific OECD)	0.28	0.46	0.48	0.91
PAS (Other Pacific Asia)	0.32	0.48	0.55	0.89
CPA (Centrally planned Asia and China)	0.26	0.45	0.44	0.91
SAS (South Asia)	0.27	0.45	0.44	0.91

[a] The minimum assumes horizontal collector plane; the maximum assumes two-axis tracking collector plane

[b] The maxima and minima are as found for the relevant latitudes in Table 2.2 of WEC (1994).

Since wind power is intermittent the total costs will be higher if back-up capacity has to be provided. In large integrated systems it has been estimated that wind could provide up to 20% of generating capacity without incurring significant penalty. In systems that have large amounts of stored hydropower available, such as in Scandinavia, the contribution could be higher. The Denham wind (690kW)/diesel(1.7MW) system in Western Australia uses a flywheel storage system and new power station controller software to displace around 70% of the diesel used in the mini-grid by wind (Eiszele, 2000).

3.8.4.3.4 Solar Energy

An estimation of solar energy potential based on available land in various regions (*Tables 3.33a* and *3.33b*) gives 1,575 to 49,837 EJ/yr. Even the lowest estimate exceeds current global energy use by a factor of four. The amount of solar radiation intercepted by the earth may be high but the market potential for capture is low because of:

(1) the current relative high costs;
(2) time variation from daily and seasonal fluctuations, and hence the need for energy storage, the maximum solar flux at the surface is about 1 kW/m^2 whereas the annual average for a given point is only 0.2 kW/m^2;
(3) geographical variation, i.e. areas near the equator receive approximately twice the annual solar radiation than at 60° latitudes; and
(4) diffuse character with low power such that large-scale generation from direct solar energy can require significant amounts of equipment and land even with solar concentrating techniques.

Photovoltaics

The costs of photovoltaics are slowly falling from around US$5,000/kW installed as more capacity is installed in line with the classical learning curve (Goldemberg, 2000). Present generating costs are relatively high (20 – 40c/kWh), but solar power is proving competitive in niche markets, and has the potential to make substantially higher contributions in the future as costs fall. Photovoltaics can often be deployed at the point of electricity use, such as buildings, and this can give a competitive advantage over power from central power stations to offset higher costs.

Conversion technology continues to improve but efficiencies are still low. Growing markets for PV power generation systems include grid connected urban building integrated systems; off-grid applications for rural locations and developing countries where 2 billion people still have no electricity; and for independent and utility-owned grid-connected power stations. The size of the annual world market has risen from 60MW in 1994 to 130MW in 1997 with anticipated growth to over 1000MW by 2005 (Varadi, 1998). This remains small compared with hydro, wind, and biomass markets. Industrial investment in PV has increased with Shell and BP-Solarex establishing new PV manufacturing facilities with reductions in the manufacturing costs anticipated (AGO, 1999).

Conversion efficiencies of silicon cells continue to improve with 24.4% efficiency obtained in the laboratory for monocrystalline cells and 19.8% for multicrystalline (Green, 1998; Zhao *et al.*, 1998), though commercial monocrystalline-based mod-

Table 3.33b: *Assessment of the annual solar energy potential*

Region	**Unused land (Gha)**	**Assumed for solar energy**[d] **(Mha)**		**Solar energy potential**[e] **(EJ/yr)**	
	Available[c]	Min	Max	Min	Max
NAM (North America)	0.5940	5.94	59.4	181.1	7,410
LAM (Latin America and the Caribbean)	0.2567	2.57	25.7	112.6	3,385
AFR (Sub-Saharan Africa)	0.6925	6.93	69.3	371.9	9,528
MEA (Middle East and North Africa)	0.8209	8.21	82.1	412.4	11,060
WEU (Western Europe)	0.0864	0.86	8.6	25.1	914
EEU (Central and Eastern Europe)	0.0142	0.14	1.4	4.5	154
FSU (Newly independent states of the former Soviet Union)	0.7987	7.99	79.9	199.3	8,655
PAO (Pacific OECD)	0.1716	1.72	17.2	72.6	2,263
PAS (Other Pacific Asia)	0.0739	0.74	7.4	41.0	994
CPA (Centrally planned Asia and China)	0.3206	3.21	32.1	115.5	4,135
SAS (South Asia)	0.1038	1.04	10.4	38.8	1,339
World total	3.9331	39.33	39.33	1575.0	49,837
Ratio to the current primary energy consumption (425 EJ/yr[f])	-	-	-	3.7	117
Ratio to the primary energy consumption projected[g] for 2050 (590-1,050 EJ/yr)	-	-	-	2.7 - 1.5	84 - 47
Ratio to the primary energy consumption projected[g] for 2100 (880-1,900 EJ/yr)	-	-	-	1.8 - 0.8	57 - 26

[c] The “other land” category from FAO (1999)

[d] The maximum corresponds to 10% of the unused land; the minimum corresponds to 1% of the unused land

[e] The minimum is calculated as (9) = (2)×(4)×(7)× 315 EJ/a, where numbers in parentheses are column numbers in *Tables 3.33a* and *3.33b*, 315 is a coefficient of unit conversion; the maximum (10) is (3)×(5)×(8)× 315 EJ/yr

[f] Source: IEA (1998b)

[g] Source: IIASA/WEC (1998)

ules are obtaining only 13%-17% efficiency and multicrystalline 12%-14%. Modules currently retail for around US$4,000 – 5,000/kW peak with costs reducing as predicted by the Worldwatch Institute (1998) as a result of manufacturing scale-up and mass production techniques. Recent studies showed a US$660M investment in a single factory producing 400MW (5 million panels) a year would reduce manufacturing costs by 75%. KPMG (1999) and Neij (1997) calculated a US$100 billion investment would be needed to reach an acceptable generating level of US$0.05/kWh.

Thin film technologies are less efficient (6%-8%) but cheaper to produce, and can be incorporated into a range of applications including roof tile structures. Further efficiency improvements are proving difficult, whereas both cadmium telluride and copper indium gallium selenide cells have given 16%-18% efficiencies in the laboratory (Green *et al*., 1999) and are close to commercial production. New silicon thin film technology using multilayer cells, which combine buried contact technology with new silicon deposition and recrystallization techniques, enables manufacture to be automated. A commercially viable product now appears to be feasible with an efficiency of around 15% and cost of around US$1500/kW (Green, 1998). Recycling of PV modules is being developed at the pilot scale for both thin film and crystalline silicon modules (Fthenakis *et al*., 1999).

Advances in inverters (including incorporation into the modules to give AC output) and net metering systems have encouraged marketing of PV panels for grid-connected building integration projects either in government sponsored large scale installations (up to 1MW) or on residential buildings (up to 5kW) (IEA, 1998c; Moomaw *et al*., 1999b; IEA, 1999b; Schoen *et al*., 1997). Japan aims to install 400 MW on 70,000 houses by 2000 (Flavin and Dunn, 1997) and 5000MW by 2010. Simple solar home systems with battery storage and designed for use in developing countries are being installed and evaluated in South Africa and elsewhere by Shell International Renewables with funding from the World Bank. Integrated building systems and passive solar design is covered in Section 3.3.4.

A promising low-cost photovoltaic technology is the photosensitization of wide-band-gap semiconductors (Burnside *et al*., 1998). New photosensitizing molecules have been developed in the laboratory, which exhibit an increased spectral response, though at low efficiencies of <1%. Arrays of large synthetic porphyrin molecules, with similar properties to chlorophyll, are being developed for this application (Burrell *et al*., 1999).

Solar Thermal

In Europe 1 million m^2 of flat plate solar collectors were installed in 1997, anticipated to rise to 5 million m^2 by 2005 (ESD, 1996). Combined PV/solar thermal collectors are under development with an anticipated saving in system costs, though these remain high at US$0.18-0.20/kWh at 8% discount rate and 10 year life (Elazari, 1998). High temperature solar thermal power generation systems are being developed to further evaluate technological improvements (Jesch, 1998). The Californian "power tower" pilot project has been successful at the 10 MW scale and is now due to be tested at 30MW with 100MW the ultimate goal (EPRI/DOE, 1997). Dish systems giving concentration ratios up to 2000 and therefore performing at temperatures up to 1,500°C can supply steam directly to a standard turbo-generator (AGO, 1998). Capital costs are projected to fall from US$4,000/kW to US$2,500 by 2030 (Moomaw *et al*., 1999b) with other estimates much lower (AGO, 1998).

3.8.4.3.5 Geothermal

Geothermal energy is a heat resource used for electricity generation, district heating schemes, processing plants, domestic heat pumps, and greenhouse space heating, but is only "renewable" where the rate of depletion does not exceed the heat replenishment.

The geothermal capacity installed in 20 countries was 7,873 MW_e in 1998: this provided 0.3% (40TWh/yr) of the total world power generation (Barbier, 1999). Geothermal direct heat use was an additional 8,700 MW_{th}. This energy resource could be increased by a factor of 10 in the near term with much of the resource being in developing countries such as Indonesia (Nakicenovic *et al*., 1998).

3.8.4.3.6 Marine Energy

The potential for wave, ocean currents, ocean thermal conversion, and tidal is difficult to quantify but a significant resource exists. For example, resources of ocean currents greater than 2 m/s have been identified, and in Europe alone the best sites could supply 48TWh/yr (JOULE, 1993). Technical developments continue but several proposed schemes have met with economic and environmental barriers. Many prototype systems have been evaluated (Duckers, 1998) but none have yet proved to be commercially viable (Thorpe, 1998). Several ocean current prototypes of 5 to 50kW capacity have been evaluated with estimated generating costs of around US$0.06-0.11/kWh (5% discount rate) depending on current speed, though these costs are difficult to predict accurately (EECA, 1996). The economics of tidal power schemes remain non-viable, and there have been environmental concerns raised over protecting wetlands and wading birds on tidal mudflats.

3.8.4.4 Technical CO_2 Removal and Sequestration

Substantial reductions in emissions of CO_2 from fossil fuel combustion for power generation could be achieved by use of technologies for capture and storage of CO_2. These technologies have become much better understood during the past few years, so they can now be seriously considered as mitigation options alongside the more well established options, such as the improvements in fossil fuel systems described in Section 3.8.4.1, and the substitutes for fossil fuels discussed in Sections 3.8.4.2 and 3.8.4.3. Strategies for achieving deep reductions in CO_2 emissions will be most robust if they involve all three types of mitigation option.

The potential for generation of electricity with capture and storage of CO_2 is determined by the availability of resources of fossil fuels plus the capacity for storage of CO_2. Fossil fuel resources are described in Section 3.8.2 and published estimates of CO_2 storage capacity are discussed below. These show that capacity is not likely to be a major constraint on the application of this technology for reducing CO_2 emissions from fossil fuel combustion.

The technology is available now for CO_2 separation, for piping CO_2 over large distances, and for underground storage. This technology is best suited to dealing with the emissions of large point sources of CO_2, such as power plant and energy-intensive industry, rather than small, dispersed sources such as transport and heating. Nevertheless, as is shown below, it could have an important role to play in reducing emissions from all of these sources.

3.8.4.4.1 Technologies for Capture of CO_2

CO_2 can be captured in power stations, either from the flue gas stream (post-combustion capture) or from the fuel gas in, for example, an integrated gasification combined cycle process (pre-combustion capture). At present, the capture of CO_2 from flue gases is done using regenerable amine solvents (Audus, 2000; Williams, 2000). In such processes, the flue gas is scrubbed with the solvent to collect CO_2. The solvent is then regenerated by heating it, driving off the CO_2, which is then compressed and sent to storage. This technology is already in use for removing CO_2 from natural gas, and for separating CO_2 from flue gases for use in the food industry.

The concentration of CO_2 in power station flue gas is between about 4% (for gas turbines) and 14% (for pulverized-coal-fired plant). These low concentrations mean that large volumes of gas have to be handled and powerful solvents have to be used, resulting in high energy consumption for solvent regeneration. Research and development is needed to reduce the energy consumption for solvent regeneration, solvent degradation rates, and costs. Nevertheless, 80%-90% of the CO_2 in a flue gas stream could be captured by use of such techniques.

In pre-combustion capture processes, coal or oil is reacted with oxygen, and in some cases steam, to give a fuel gas consisting mainly of carbon monoxide and hydrogen. The carbon monoxide is reacted with steam in a catalytic shift converter to give CO_2 and more hydrogen. Similar processes can be used with natural gas but then air may be preferred as the oxidant (Audus *et al.*, 1999). The fuel gas produced contains a high concentration of CO_2, making separation easier, so a physical solvent may be better suited for this separation; the hydrogen can be used in a gas turbine or a fuel cell. Similar technology is already in use industrially for producing hydrogen from natural gas (e.g., for ammonia production). The integrated operation of these technologies for generating electricity whilst capturing CO_2 has no major technical barriers but does need to be demonstrated (Audus *et al.*, 1999).

The concentration of CO_2 in a power station flue gas stream can be increased substantially (to more than 90%) by using oxygen for combustion instead of air (Croiset and Thambimuthu, 1999). Then post-combustion capture of CO_2 is a very easy step, but the temperature of combustion must be moderated by recycling CO_2 from the exhaust, something which has been demonstrated for use with boilers but would require major development for use with gas turbines. Currently, the normal method of oxygen production is by cryogenic air separation, which is an energy intensive process. Development of low-energy oxygen separation processes, using membranes, would be very beneficial.

Other CO_2 capture techniques available or under development include cryogenics, membranes, and adsorption (IEA Greenhouse Gas R&D Programme, 1993).

After the CO_2 is captured, it would be pressurized for transportation to storage, typically to a pressure of 100 bar. CO_2 capture and compression imposes a penalty on thermal efficiency of power generation, which is estimated to be between 8 and 13 percentage points (Audus, 2000). Because of the energy required to capture and compress CO_2, the amount of emissions avoided is less than the amount captured. The cost of CO_2 capture in power stations is estimated to be approximately US$30-50/t CO_2 emissions avoided (US$110-180/tC), equivalent to an increase of about 50% in the cost of electricity generation.

3.8.4.4.2 Transmission and Storage of CO_2

CO_2 can be transported to storage sites using high-pressure pipelines or by ship. Pipelines are used routinely today to transport CO_2 long distances for use in enhanced oil recovery (Stevens *et al.*, 2000). Although CO_2 is not transported by ship at present, tankers similar to those currently used for liquefied petroleum gas (LPG) could be used for this purpose (Ozaki, 1997).

CO_2 exists in natural underground reservoirs in various parts of the world. Potential sites for storage of captured CO_2 are underground reservoirs, such as depleted oil and gas fields or deep saline reservoirs. CO_2 injected into coal beds may be preferentially absorbed, displacing methane from the coal; sequestration would be achieved providing the coal is never mined. Another possible storage location for captured CO_2 is the deep ocean, but this option is at an earlier stage of development than underground reservoirs; so far only small-scale experiments for preliminary investigation have been carried out (Herzog *et al.*, 2000); the deep ocean is chemically able to dissolve up to 1800GtC (Sato, 1999). An indication of the global capacities of the major storage options is given in *Table 3.34*. The capacities of these reservoirs are subject to substantial uncertainty, as purposeful exploration has only been conducted in some parts of the world so far. Other published estimates of the global capacity for storage in underground aquifers range up to 14,000GtC (Hendriks, 1994). Other methods of CO_2 storage have been suggested but none are competitive with underground storage (Freund, 2000).

Substantial amounts of CO_2 are already being stored in underground reservoirs:

- Nearly 1Mt/yr of CO_2 is being stored in a deep saline reservoir about 800m beneath the bed of the North Sea as part of the Sleipner Vest gas production project (Baklid and Korbol, 1996). This is the first time CO_2 has been stored purely for reasons of climate protection.
- About 33Mt/yr of CO_2 is used at more than 74 enhanced oil recovery (EOR) projects in the USA. Most of this CO_2 is extracted from natural CO_2 reservoirs but some is captured from gas processing plants. Much of this CO_2 remains in the reservoir at the completion of oil production; any CO_2 produced with the oil is separated and reinjected. An example of an EOR scheme which will use anthropogenic CO_2 is the Weyburn project in Canada (Wilson *et al.*, 2000). In this project, 5,000 t/d of CO_2 captured in a coal gasification plant in North Dakota, USA will be piped to the Weyburn field in Saskatchewan, Canada.
- At the Allison unit in New Mexico, USA, (Stevens *et al.*, 1999), over 100,000 tonnes of CO_2 has been injected over a three-year period to enhance production of coal bed methane. The injected CO_2 is sequestered in the coal (providing it is never mined). This is the first example of CO_2-enhanced coal bed methane production.

The cost of CO_2 transport and storage depends greatly on the transport distance and the capacity of the pipeline. The cost of transporting large quantities of CO_2 is approximately US$1-3/t

Table 3.34: *Some natural reservoirs which may be suitable for storage of carbon dioxide*
(Freund, 1998; Turkenburg, 1997)

Reservoir type	Storage option	Global capacity (GtC)
Below ground		
	Disused oil fields	100
	Disused gas fields	400
	Deep saline reservoirs	>1000
	Unminable coal measures	40
Above ground		
	Forestry	1.2 GtC/yr
Ocean		
	Deep ocean	>1000

per 100km (Ormerod, 1994; Doctor *et al*., 2000). The cost of underground storage, excluding compression and transport, would be approximately US\$1-2/tCO_2 stored (Ormerod, 1994). The overall cost of transport and storage for a transport distance of 300 km would therefore be about US\$8/tCO_2 stored, equivalent to about US\$10/t of emissions avoided (US\$37/tC).

If the CO_2 is used for enhanced oil recovery (EOR) or enhanced coal bed methane production (ECBM), there is a valuable product (oil or methane, respectively) which would help to offset the cost of CO_2 capture and transport. In some EOR or ECBM projects, the net cost of CO_2 capture and storage might be negative. Other ideas for utilizing CO_2 to make valuable products have not proved to be as useful as sequestration measures, because of the amount of energy consumed in the process and the relatively insignificant quantities of CO_2 which would be used.

If no valuable products were produced, the overall cost of CO_2 capture and storage would be about US\$40-60/t CO_2 emissions avoided (150-220/tC). As with most new technologies, there is scope to reduce these costs in the future through technical developments and wider application.

3.8.4.4.3 Other Aspects

If CO_2 is to be stored for mitigation purposes, it is important that the retention time is sufficient to avoid any adverse effect on the climate. It is also important to avoid large-scale accidental releases of CO_2. It is expected that these goals will be achievable with underground storage of CO_2 and may be achievable with ocean storage. Oil and gas fields have remained secure for millions of years, so they should be able to retain CO_2 for similar timescales, providing extraction of oil or gas or injection of CO_2 does not disrupt the seal. Deep saline reservoirs are generally less well characterized than oil and gas reservoirs because of their lack of commercial importance to date. Their ability to contain CO_2 for the necessary timescales is less certain, but research is underway to improve understanding of this aspect (Williams, 2000).

If CO_2 storage were to be used as a basis for emissions trading or to meet national commitments under the UNFCCC, it would be necessary to establish the quantities of CO_2 stored in a verifiable manner. Most verification requirements for geologically stored CO_2 can be achieved with technology available today. Validation of CO_2 storage in the ocean would be more difficult, but it should be possible to verify quantities of CO_2 stored in concentrated deposits on the seabed.

3.8.4.4.4 Applicability of Capture and Storage in Other Industries

The possibility of using CO_2 capture and storage in the manufacturing industry is described in Section 3.5.3.4, including capture of CO_2 during production of hydrogen from fossil fuels. Hydrogen is widely used for ammonia production and in oil refineries, but it can also be used as an energy carrier. Applications would be for small, dispersed, and/or mobile energy users where capture of CO_2 after combustion would not be feasible. Particular examples are in transport e.g., cars and aircraft, and small-scale heat and power production. Production of hydrogen from fossil fuels with CO_2 storage could be an attractive transition strategy to enable the wide-scale introduction of hydrogen as an energy carrier (Turkenburg, 1997; Williams, 1999).

3.8.4.4.5 The Role of CO_2 Capture and Storage in Mitigation of Climate Change

Some CO_2 could be captured from anthropogenic sources and stored underground at little or no overall cost, for example where the CO_2 is already available in concentrated form, such as in natural gas treatment plants or in hydrogen or ammonia manufacture. If the captured CO_2 were to be stored in depleted hydrocarbon reservoirs, such as in enhanced oil recovery schemes, or through enhanced production of coal bed methane, the income produced would also help to offset the costs. Such opportunities are available for early action to combat climate change using technology which is available today.

Substantial quantities of CO_2 from fossil fuel combustion could be captured in the future and sequestered in natural reservoirs (Williams, 2000). Potentially, this approach could achieve deep reductions in emissions of CO_2. Edmonds *et al.* (2000) have considered various possible strategies to achieve stabilization of CO_2 concentrations around 550-750 ppmv. It has been shown that inclusion of the option of capture and storage of CO_2 offers significant reduction in overall cost compared with strategies which do not include this option.

3.8.4.5 Emissions from Production, Transport, Conversion, and Distribution

Methane can be released during the production, transport and use of coal, oil, and gas. Various techniques can be used to reduce these emissions, some of which can be captured for use as an energy resource (Williams, 1993; IEA Greenhouse Gas R&D Programme, 1996, 1997; IGU, 1997, 2000; US EPA, 1993, 1999a).

With coal, methane is trapped in coal seams and surrounding strata in varying amounts and is released as a result of mining. Coal mines are ventilated to dilute the methane as it is released to prevent an explosive build up of the gas. The diluted methane is then normally released to the atmosphere. The emissions can be reduced substantially by capturing some of the methane in a more concentrated form in areas of old workings in a mine or by drilling into the coal seams to release the methane prior to mining, then using it as an energy source. Around 50% of emissions from coal mining could be prevented at costs in the range US$1-4/$tC_{eq}$ (IEA Greenhouse Gas R&D Programme, 1996).

With natural gas, leakage of methane occurs at exploration, through transportation to final use. In North America and Europe, the major source is from fugitive emissions, often leaked from above ground installations or old cast iron or steel pipelines that were originally installed for coal- and oil-derived town gas. Vulnerable networks can be replaced with polyethylene pipes. In Russia, the main sources of leakage are from exploration, compressors, pneumatic devices, and fugitive emissions. Techniques are being applied to reduce emissions including replacing seals, increasing compressor efficiencies, and replacing gas-operated pneumatic devices. Around 45% of global emissions from gas could be eliminated and produce a saving of US$5 billion (IEA Greenhouse Gas R&D Programme, 1997). A further 10% of gas emissions could be reduced at costs up to US$108/$tC_{eq}$, and a further 15% at costs up to US$135/$tC_{eq}$. However, the cost of emission reduction for old distribution systems remains very high, and the reduction potential will be reached mainly as networks are replaced.

Methane and other gases often occur with oil in the ground and are brought to the surface during extraction. If there was no market for the gas, it was normally vented to the air, but since the1960s methane has increasingly been utilized, compressed and reinjected into the oil field to aid oil production or flared rather than vented. Emissions can be reduced typically by 98% by such methods and these are now common. In Nigeria, where venting is still practised, Shell has made a commitment to end continuous venting by 2003 and continuous flaring by 2008, and has started to liquefy the gas for export.

Sulphur hexafluoride, SF_6, used as an insulator in electrical transmission equipment, is covered in Section 3.5.

3.8.5 Regional Differences

3.8.5.1 Privatization and Deregulation of the Electricity Sector

In many countries, state owned or state regulated electricity supply monopolies have been privatized and broken up to deregulate markets such that companies compete to generate electricity and to supply customers. These moves affect the types of power station favoured. Traditional, large power stations (> 600MW) have had high capital costs and construction periods of 4-7 years, which have led to high interest payments during construction and the need for higher planning margins. Under the new circumstances, the new power generators use higher discount rates, seek lower overall costs, and try to minimize project risks by preferring plants of smaller unit size. They thus favour projects with low capital costs, rapid construction times, use of proven technology, high plant reliability/availability, and low operating costs. CCGTs meet all of these new criteria, and are favoured by generators where gas is available at acceptable costs. This could point the way for the development of new designs for other types of power station, which need to be smaller with modular designs that are largely factory built rather than site built. Economies of scale then come from replication on an assembly line rather than through size (see also Section 6.2.1.3).

Community ownership of distributed renewable energy projects, particularly wind turbines and biogas plants, is becoming common in Denmark (Tranaes, 1997) and more recently in the UK (UK DTI, 1999). The trend towards privately owned distributed power supply systems, either independent or grid connected, is likely to continue as a result of growing public interest in sustainability and technical improvements in controls and asynchronous grid connections.

In countries where privatization of transmission line companies is occurring, there is no longer any commercial rationale to construct and maintain lines only to service a small demand. This has historically often been a social investment by governments and aid agencies. Where grid connections are already in place, it is possible that disconnections may occur in the future where the lines are uneconomic. Then existing residents will have to choose between installing independent domestic-scale systems or establishing community-owned co-operative schemes.

State owned utilities have been able to cross-subsidize otherwise non-competitive projects including nuclear and renewable technologies. Privatization of these utilities requires new methods of supporting technology implementation objectives.

In some cases, electricity tariffs and regulatory systems may need to be amended to include the benefits and costs of embedded generation. This would enable renewable energy projects to be sited on the distribution network at nodes where they would bring most benefit to quality of supply (see Mitchell, 1998, 1999; and Chapter 6). One detrimental impact could be an increase of fossil fuel electricity generation caused by the increased need to operate in load-following mode.

3.8.5.2 Developing Country Issues

In the past there has been little incentive to explore for gas in developing countries unless there was an existing infrastructure to utilize it. The development of CCGT technology now means that, if electricity generation is required, an initial market for the gas can be developed quite rapidly and this market extended to other sectors as the infrastructure is built.

Developing countries have a large need for capital to meet the development of hospitals, schools, and transport and not just for energy in general or electricity in particular. In such circumstances, cheaper power stations are often built at lower efficiency than might otherwise be the case, for example 30%-35% efficiency for an old coal-fired design rather than 40%+ for a modern design. The low price of fuel in some of these countries can also make a cheaper, less efficient design economically more attractive. In India, coal-fired power station design has been standardized at 37.5% efficiency and capacity of 250 and 500MW. Capital costs are US$884/kW whereas a 40% efficiency station would cost around US$977/kW. The coal price is US$25 - US$37/t, depending on location. Even at the higher price, the increased capital costs for the higher efficiency power station outweigh the economic benefits from its lower fuel demand and hence lower emissions.

Technology transfer of advanced power generation technologies including CCGT, nuclear, clean coal, and renewable energy would lead to emission reduction and could be encouraged through the Kyoto mechanisms (see Chapter 6). In addition to limited capital resources that can make advanced technologies unaffordable, many developing countries face skill shortages that can impede the construction and operation of such technology. This is discussed more fully in Chapter 5.

Electricity plants and boilers are sometimes not operated as efficiently as possible in developing countries. In some cases, incremental investment in such a plant will yield benefits but, more often, it is investment in training the operators that is lacking and that will yield substantial gains. The extension of grids in regions such as India and Africa could allow better use to be made of efficient power stations in order to displace less efficient local units. In India, one trading scheme by three electricity companies resulted in an emissions reduction of 2MtC (Zhou, 1998), and there are similar possibilities in southern and east Africa (Batidzirai and Zhou, 1998). The same study shows that there is a large scope in the subregion for exploiting hydropower, sharing of natural gas resources for power generation, and utilization of wind power along the coastal areas. These measures can displace coal-based generation which currently emits 30–40MtC in southern Africa alone.

An alternative to the extension of grids in developing countries is to increase development of efficiently distributed power generation. This is discussed further in the section below.

3.8.5.3 Distributed Systems

Distributed power comprises small power generation or storage systems located close to the point of use and/or controllable load. Worldwide, these include more than 100MW of existing compressed ignition and natural gas-fired spark ignition engines, small combustion turbines, smaller steam turbines, and renewables. Emerging distributed power technologies include cleaner natural gas or biodiesel engines, microturbines, Stirling engines and fuel cells, small modular biopower and geopower packaged as cogeneration units, and wind, photovoltaics and solar dish engine renewable generation. Increased integration of distributed power with other distributed energy resources could further enhance technology improvement in this sector.

Interest is growing in generating power at point of use using independent or grid-connected systems, often based on renewable energy. These could be developed, owned, and operated by small communities. The European "Campaign for Take-off" target for 100 communities to be supplied by 100% renewable energy and become independent of the grid by 2010 will require a hybrid mix of technologies to be used depending on local resources (Egger, 1999). Local employment opportunities should result and the experience should aid uptake in developing countries.

For small grid-connected embedded generation systems, power supply companies could benefit from improved power quality where the distributed sites are located towards the end of long and inefficient transmission lines (Ackermann *et al.*, 1999). Expensive storage would be avoided where a grid system can provide back-up generation.

3.8.6 Technological and Economic Potential

Several studies have attempted to express the costs of power generation technologies on a comparable basis (US DOE/EIA, 2000; Audus, 2000; Freund, 2000; Davison, 2000; Goldemberg, 2000; OECD, 1998b). The OECD data are for power stations that are mainly due for completion in 2000 to 2005 in a wide cross section of countries, and these show that costs can vary considerably between projects, because of national and regional differences and other circumstances. These include the need for additional infrastructure, the trade-off between capital costs and efficiency, the ability to run on baseload, and the cost and availability of fuels. The costs of reducing greenhouse gas emissions will similarly vary both because of variability in the costs of the alternative technology and because of the variability in the costs of the baseline technology. Because of this large variation in local circumstances, the generating costs of studies can rarely be generalized even within the boundaries of one country. Consequently, costs (and mitigation potentials) are highly location dependent. The analysis in this section uses two principle sources of data, the OECD (1998b) data and the US DOE/EIA (2000) data. The latter data are for a single country and may reduce some of the variability in costs seen in multi-country studies.

Tables 3.35a-d are derived from the OECD (1998b) survey which gives data on actual power station projects due to come on stream in 2000 to 2005 from 19 countries including Brazil, China, India, and Russia, together with a few projects for 2006 to 2010 based on more advanced technologies. Data from other sources have been added where necessary and these are identified in the footnote to the tables. The tables present typical costs per kWh and CO_2 emissions of alternative types of generation expected for 2010. *Tables 3.35a* and *3.35b* use a baseline pulverized coal technology for comparative purposes. *Table 3.35a* contains data for Annex I countries (as defined in the UN Framework Convention on Climate Change) in the OECD dataset, and *Table 3.35b* contains data for non-Annex I countries. In addition to coal, the table gives projected costs for gas, nuclear, CO_2 capture and storage, PV and solar thermal, hydro, wind, and biomass. In the baseline, costs and carbon emissions are an average of the coal-fired projects in the OECD database for Annex I/non-Annex I countries respectively, with flue gas desulphurization (FGD) included in all Annex I cases and in around 20% of the non-Annex I cases. Other technologies are then compared to the coal baseline using cost data from the OECD database and other sources. In *Tables 3.35c* and *3.35d*, the baseline technology is assumed to be CCGT burning natural gas, and costs and emissions are similarly calculated for Annex I and non-Annex I countries.

In the tables, the first column of data gives the generation costs in USc/kWh and the emissions of CO_2 in grams of carbon per kWh (gC/kWh) for the baseline technology and fuel, coal, and gas, respectively. The subsequent columns give a range of possible generation options, and the costs and emissions for alternative technologies that could be used to reduce C emissions over the next 20 years and beyond. Additionally, it might be noted that the non-Annex I baseline coal technology is cheaper than that for Annex I countries (both based on the costs of power stations under construction) and that CO_2 emissions (expressed as gC/kWh) are higher. This reflects the lower efficiencies of power stations currently being built in non-Annex I countries. The costs of reducing greenhouse gas emissions in the mitigation options varies both because of variability in the costs of the alternative technology and because of the variability in the costs of the baseline technology.

Tables 3.35a-d also present estimates of the CO_2 reduction potential in 2010 and 2020 for the alternative mitigation options. Baseline emissions of CO_2 are used, derived from projections of world electricity generation from different energy sources (IEA, 1998b). The IEA projections essentially are enveloped by the range of SRES marker scenarios for the period up to 2020. The IEA projections were used as the baseline because of their shorter time horizon and higher technology resolution. In the tables, it is assumed that a maximum of 20% of new coal baseline capacity could be replaced by either gas or nuclear technologies during 2006 to 2010 and 50% during 2011 to 2020. Similarly, it is assumed that a maximum of 20% of new gas capacity in 2006 to 2010 and 50% in 2011 to 2020 could be displaced by mitigation options. These assumptions would allow a five-year lead-time (from the publication of this report) for decisions on the alternatives to be made and construction to be undertaken. It is assumed that the programme would build up over several years and hence the maximum capacity that could be replaced to 2010 is limited. After 2010 it is assumed that there will be practical reasons why half the new coal capacity could not be displaced. The rate of building gas or nuclear power stations that would be required using these assumptions should not present problems. For nuclear power, the rate of building between 2011 and 2020 would be less than that seen at the peak for constructing new nuclear plants. For gas, the gas turbines are factory made, so no problems should arise from increasing capacity, and less would be required in terms of boilers, steam turbines, and cooling towers than the coal capacity being replaced. For renewables such as wind, photovoltaics (PV) and biomass, maximum penetration rates were derived from the Shell sustainable growth scenario (Shell, 1996) and applied to replace new coal or gas capacities. For wind and PV, these penetration rates imply substantial growth, but are less than what could be achieved if the industries continued to expand at the current rate of 25% per year until 2020. For biomass, most of the fuel would be wood process or forest waste. Some non-food crops would also be used. The introduction of CO_2 capture and storage technology would require similar construction processes as for a conventional power plant. The CO_2 separation facilities would need additional equipment but, in terms of physical construction, involve no more effort than, say, the establishment of a similar scale of biomass gasification plant. CO_2 storage facilities would be constructed using available oil/gas industry technology and this is not seen to be a limiting factor. Storage would be in saline aquifers of depleted oil and gas fields. For CO_2 capture and storage, it is assumed that pilot plants could be operational before 2010, and the mitigation potential is put at 2–10MtC each for coal and gas technologies. It is assumed, arbitrarily, that these would be in Annex I countries. For 2020, the total mitigation potential is put at 40–200MtC, split equally between coal and gas, and between Annex I and non-Annex I countries. Again, this is somewhat arbitrary, but reflects, on the one hand, the potential to move forward with the technology if no major problems are encountered, and, on the other, the potential for more extended pilot schemes. It is assumed, for simplicity, that fuel switching, from coal to gas or vice versa, would not occur in addition to CO_2 capture and storage, although this would be an extra option.

The tables show that the reduction potential in 2020 is substantially higher than in 2010, which follows from the assumptions used and reflects the time taken to take decisions and, especially in the case of renewables and CO_2 capture and storage, to build up manufacturing capacity, to learn from experience, and to reduce costs. The tables show that each of the mitigation technologies can contribute to reducing emissions, with nuclear, if socio-politically desirable, having the greatest potential. Replacement of coal by gas can make a substantial contribution as can CO_2 capture and storage. Each of the renewables can contribute significantly, although the potential contribution of solar power is more limited. The potential reductions within each table are not addable. The alternative mitigation technologies will be competing with each other to displace new coal and gas power stations. On the assumption about the maximum displacement of new coal and gas power stations (20% for 2006 to 2010, 50% for 2011 to 2020), the maximum mitigation that could be achieved would be around 140MtC in 2010 and 660MtC in 2020. These can be compared with estimated and projected global CO_2 emissions from power stations of around 2400MtC in 2000, 3150MtC in 2010 and 4000MtC in 2020 (IEA, 1998b).

In practice, a combination of technologies could be used to displace coal and natural gas fired generation and the choice will often depend on local circumstances. In addition to the description in the tables, oil-fired generation could also be displaced and, on similar assumptions, there is a further mitigation potential of 10MtC by 2010 and 40MtC by 2020. Furthermore, in practice not all of the mitigation options are likely to achieve their potential for a variety of reasons – unforeseen technical difficulties, cost limitations, and socio-political barriers in some countries. The total mitigation potential for all three fossil fuels from power generation, allowing for potential problems, is therefore estimated at about 50-150MtC by 2010 and 350-700MtC by 2020.

In contrast to the OECD data which span a wide range reflecting local circumstances, *Table 3.35e* presents costs for the USA, mainly based on data used in the *Annual Energy Outlook* of the US Energy Information Agency (US DOE/EIA, 2000). By and large, the mitigation costs fall in the range of costs given in *Tables 3.35a-d*. The electricity generating costs are based on national projections of utility prices for coal and natural gas, while capital costs and generating efficiencies are dynamically improving depending on their respective rates of market penetration. The table indicates that once sufficient capacities have been adopted in the market place, coal-fired integrated gasification combined cycle power stations would have similar costs but lower emissions than the pulverized fuel (pf) power station (because of its higher efficiency). In many places, gas-fired CCGT power stations offer lower cost generation than coal at current gas prices and produce around only half the emissions of CO_2. Data on CO_2 capture and storage have been taken from IEA Greenhouse Gas R & D Programme studies (Audus, 2000; Freund, 2000; Davison, 2000). This could reduce emissions by about 80% with additional costs of around 1.5c/kWh for gas and 3c/kWh for coal pf and 2.5c/kWh for coal IGCC. In the EIA study, nuclear power is more expensive than coal-fired generation, but generally less than coal with carbon capture and storage. Wind turbines can be competitive with conventional coal and gas power generation at wind farm sites with high mean annual speeds. Biomass can also contribute to GHG mitigation, especially where forestry residues are available at very low costs (municipal solid waste even at negative costs). Where biofuel is more costly, either because the in-forest residue material used requires collection and is more expensive or because purpose grown crops are used, or where wind conditions are poorer, the technologies may still be competitive for reducing emissions. Photovoltaics and solar thermal technologies appear expensive against large-scale power generation, but will be increasingly attractive in niche markets or for off-grid generation as costs fall.

Table 3.35e also gives estimated CO_2 emissions and mitigation costs compared to either a coal-fired pf power station or a gas-fired CCGT. For the coal base-case, it is projected that in 2010 under assumptions of improved fossil fuel technologies, an IGCC would offer a small reduction in emissions at positive or negative cost. A gas-fired CCGT has generally negative mitigation costs against a coal-fired pf baseline, reflecting the lower costs of CCGT in the example used. CO_2 capture and storage would enable deep reductions in emissions from coal-fired generation but the cost would be about US$100-150/tC depending on the technology used. Gas-fired CCGT with CO_2 capture and storage appears attractive, but this is principally because switching to CCGT is attractive in itself. Nuclear power mitigation costs are in the range US$50-100/tC when coal is used as the base for comparison. It is uncertain whether there would be sufficient capacity available for wind or biomass to deliver as much electricity as could be produced by fossil fuel-fired plants, but certainly not at the low costs shown in *Table 3.35e*.

If a gas-fired baseline is assumed, most of the mitigation options are found to be more expensive. CO_2 capture and storage appears relatively attractive, achieving deep reductions in emissions at around US$150/tC avoided. Wind, biomass, and nuclear could be attractive options in some circumstances. Other options show higher costs. PV and solar thermal are again expensive mitigation options, and, as noted above, are more suited to niche markets and off-grid generation.

Table 3.35a: *Estimated costs of alternative mitigation technologies in the power generation sector compared to baseline coal-fired power stations and potential reductions in carbon emissions to 2010 and 2020 for Annex I countries*

Technology	**pf+FGD, NO_x, etc**	**IGCC and Super-critical**	**CCGT**	**pf+FGD+ CO_2 capture**	**CCGT+ CO_2 capture**	**Nuclear**	**PV and thermal solar**	**Hydro**	**Wind turbines**	**BIGCC**
Energy source	Coal	Coal	Gas	Coal	Gas	Uranium	Solar radiation	Water	Wind	Biofuel
Generating costs (c/kWh)	4.90	3.6-6.0	4.9-6.9	7.9	6.4-8.4	3.9-8.0	8.7-40.0	4.2-7.8	3.0-8	2.8-7.6
Emissions (gC/kWh)	229	190-198	103-122	40	17	0	0	0	0	0
Cost of carbon reduction (US$/tC)	Baseline	-10 to 40	0 to 156	159	71 to 165	-38 to 135	175 to 1400	-31 to 127	-82 to 135	-92 to 117
Reduction potential to 2010 (MtC/yr)	Baseline	13	18	2-10	-	30	2	6	51	9
Reduction potential to 2020 (MtC/yr)	Baseline	55	103	5-50	-	191	20	37	128	77

see notes on page 258

Table 3.35b: *Estimated costs of alternative mitigation technologies in the power generation sector compared to baseline coal-fired power stations and potential reductions in carbon emissions to 2010 and 2020 for non-Annex I countries*

Technology	**pf+FGD, NO_x, etc**	**IGCC and Super-critical**	**CCGT**	**pf+FGD+ CO_2 capture**	**CCGT+ CO_2 capture**	**Nuclear**	**PV and thermal solar**	**Hydro**	**Wind turbines**	**BIGCC**
Energy source	Coal	Coal	Gas	Coal	Gas	Uranium	Solar radiation	Water	Wind	Biofuel
Generating costs (c/kWh)	4.45	3.6-6.0	4.45-6.9	7.45	5.95-8.4	3.9-8.0	8.7-40.0	4.2-7.8	3.0-8	2.8-7.6
Emissions (gC/kWh)	260	190-198	103-122	40	17	0	0	0	0	0
Cost of carbon reduction (US$/tC)	Baseline	-10 to 200	0 to 17	136	62 to 163	-20 to 77	164 to 1370	-10 to 129	-56 to 137	-63 to 121
Reduction potential to 2010 (MtC/yr)	Baseline	36	20	0		36	0.5	20	12	5
Reduction potential to 2020 (MtC/yr)	Baseline	85	137	5-50		220	8	55	45	13

see notes on page 258

Table 3.35c: *Estimated costs of alternative mitigation technologies in the power generation sector compared to gas-fired CCGT power stations and the potential reductions in carbon emissions to 2010 and 2020 for Annex I countries*

Technology	**CCGT**	**pf+FGD+ CO_2 capture**	**CCGT+ CO_2 capture**	**Nuclear**	**PV and thermal solar**	**Hydro**	**Wind turbines**	**BIGCC**
Energy source	Gas	Coal	Gas	Uranium	Solar	Water	Wind radiation	Biofuel
Generation costs (c/kWh)	3.45	7.6-10.6	4.95	3.9-8.0	8.7-40.0	4.2-7.8	3.0-8	2.8-7.6
Emissions (gC/kWh)	108	40	17	0	0	0	0	0
Cost of carbon reduction (US$/tC)	Baseline	610 to 1050	165	46 to 421	500 to 3800	66 to 400	-43 to 92	-60 to 224
Reduction potential to 2010 (MtC/yr)	Baseline	-	2-10	62	0.8	3	23	4
Reduction potential to 2020 (MtC/yr)	Baseline	-	5-50	181	9	18	61	36

see notes on page 258

Table 3.35d: *Estimated costs of alternative mitigation technologies in the power generation sector compared to gas-fired CCGT power stations and the potential reductions in carbon emissions to 2010 and 2020 for non-Annex I countries*

Technology	**CCGT**	**pf+FGD+ CO_2 capture**	**CCGT+ CO_2 capture**	**Nuclear**	**PV and thermal solar**	**Hydro**	**Wind turbines**	**BIGCC**
Energy source	Gas	Coal	Gas	Uranium	Solar	Water	Wind radiation	Biofuel
Generation costs (c/kWh)	3.45	6.9-8.7	4.95	3.9-8.0	8.7-40.0	4.2-7.8	3.0-8	2.8-7.6
Emissions (gC/kWh)	108	40	17	0	0	0	0	0
Cost of C reduction (US$/t)	Baseline	507-772	165	46 to 421	500 to 3800	66 to 400	-43 to 92	-60 to 224
Reduction potential to 2010 (MtC/yr)	Baseline	-	0	10	0.2	9	5	1
Reduction potential to 2020 (MtC/yr)	Baseline	-	5-50	70	4	26	21	6

Notes to Tables 3.35a-d

Costs are derived from OECD (1998b) for coal, gas and nuclear. The additional costs of CO_2 capture and storage are derived from IEA Greenhouse Gas R & D Programme (Audus, 2000; Freund, 2000; Davison, 2000). For coal, the costs for CO_2 capture and storage are given for pf power stations. Photovoltaic costs are taken from the World Energy Assessment (Goldemberg, 2000) and are based on today's costs of US$5,000 per peak kilowatt capacity at the high end, and US$1,000 per peak kilowatt capacity projected after 2015 at the low end. Data for hydropower are taken from Goldemberg (2000) and Ishitani and Johansson (1996) in IPCC (1996). Data on wind power are based on today's costs (Walker *et al*., 1998) and projected future costs are also given in Ishitani and Johansson (1996). Finally, for biofuels, the technology used is BIGCC with capital and operating costs assumed to be similar to those for coal IGCC. Fuel costs are set at US$0-2.8/GJ, based on either wood process and forest residues or specially grown crops (from *Table 3.35e*). A 10% discount rate was used throughout. IEA (1998b) projections of electricity generation were used to estimate the potential CO_2 reductions for each mitigation technology.

For *Tables 3.35a* and *3.35b*, if gas infrastructures are in place and CCGT is a lower cost option than coal, it is assumed that natural gas is the fuel of choice. Hence no negative cost reduction options exist for natural gas to displace coal.

In estimating the maximum CO_2 mitigation each technology could achieve, it was assumed that only newly planned or replacement of end-of-life coal or gas power stations could be displaced – no early retirements of existing plant and equipment were assumed.

As a general rule, increasing the amount of abatement to be achieved will require moving to higher cost options. This will apply particularly to renewables as additional capacity might require moving to sites with less favourable conditions.

pf+FGD: pulverized fuel + flue gas desulphurization.

Table 3.35e: *Estimated costs of coal and gas baselines and alternative mitigation technologies in the US power generation sector*

Technology	**pf+FGD, NO_x, *etc.***	**IGCC**	**CCGT**	**pf+FGD+ CO_2 capture**	**IGCC + CO_2 capture**	**CCGT+ CO_2 capture**	**Nuclear**	**PV and thermal solar**	**Wind turbines**	**Biomass**	**Biomass**
Energy source	Coal	Coal	Gas	Coal	Coal	Gas	Uranium	Solar radiation	Wind	Forestry residues	Energy crops
Generating costs (c/kWh)	3.3-3.7	3.2 – 3.9	2.9-3.4	6.3-6.7	5.7-6.4	4.4-4.9	5.0-6.0	9.0 – 25.0	3.3-5.4	4.0-6.7	6.4-7.5
Emissions (gC/kWh)	247 - 252	190-210	102-129	40	37	17	0	0	0	0	0
Cost of C reduction compared to coal pf (US$/tC)	Baseline	-80 to 168	-53 to 8	141-145	93-148	30-70	52-102	210 – 880	-16 to 85	12-138	107-170
Cost of C reduction compared to gas CCGT (US$/tC)			Baseline	326-613	250-538	134-176	124-304	434 –2167	-8 to 245	47-373	233-450

Notes to *Table 3.35e*: Data derived from US DOE/EIA (2000) except for additional costs of CO_2 capture and disposal which are from IEA Greenhouse Gas R & D Programme (Audus, 2000; Freund, 2000; Davison, 2000). Additionally, coal costs of US$1.07/GJ were used for coal-fired power stations; and gas costs of US$3.07/GJ were used for gas-fired power stations (from US DOE/EIA, 1999a). The alternative wind costs come from high and low cases in the US DOE/EIA (2000) study. The costs of biomass-derived electricity used a fuel cost of US$2.8/GJ for purpose grown crops, whereas the fuel costs for biofuel wastes were US$0-2/GJ. A 10% discount rate was used. It should be noted that the costs of renewables given in the table apply to specific conditions of availability of sunlight, wind, or crops. As production from renewables increases, it may be necessary to move to sites with less favourable conditions and higher costs. The large-scale reliance on intermittent renewables may require the construction of back-up capacity or energy storage at additional costs.

3.8.7 Conclusions

The section on energy sources indicates that there are many alternative technological ways to reduce GHG emissions, including more efficient power generation from fossil fuels, greater use of renewables or nuclear power, and the capture and disposal of CO_2. There are also opportunities to reduce emissions of methane and other non-CO_2 gases associated with energy supply. In general, this new review reinforces the conclusions reached in the SAR, as discussed in Section 3.8.2.

3.9 Summary and Conclusions

The analysis in this chapter is based upon a review of existing and emerging technologies, and the technological and economic potential that they have for reducing GHG emissions. In many areas, technical progress relevant to GHG emission reduction since the SAR has been significant and faster than anticipated. A broad array of technological options have the combined potential to reduce annual global greenhouse gas emission levels close to or below those of 2000 by 2010 and even lower by 2020.

Estimates of the technical potential, an assessment of the range of potential costs per metric tonne of carbon equivalent (tC_{eq}), and the probability that a technology will be adopted are presented in *Table 3.36* by sector. Specific examples and the estimation methodologies are discussed more fully in the chapter for each sector.

Available estimates of the technological potential to reduce greenhouse gas emissions and its costs suffer from several important limitations:

- There are no consistent estimates of technological and economic potential covering all the major regions of the world;
- Country- and region-specific studies employ different assumptions about the future progress of technologies and other key factors;
- Studies make different assumptions about the difficulty of overcoming barriers to the market penetration of advanced technologies and the willingness of consumers to accept low-carbon technologies;
- Most studies do not describe a range of costs over a domain of carbon reduction levels, and many report average rather than marginal mitigation costs; and
- Social discount rates of 5%-12% are commonly used in studies of the economic potential for specific technologies which are lower than those typically used by individuals and in industry.

A summary of the estimates of the potential for worldwide emission reductions is given in *Table 3.37*. Overall, the total potential for worldwide greenhouse gas emissions reductions resulting from technological developments and their adoption are estimated to amount to 1,900-2,600MtC/yr by 2010[28] and 3,600–5,050MtC/yr by 2020.

In the scenarios that were constructed within the SRES emissions of the six Kyoto Protocol greenhouse gases develop as follows (in MtC_{eq}, rounded numbers):

1990:	9,500
2000:	10,500
2010:	11,500 – 13,800
2020:	12,000 – 15,900

It was not possible to calculate the emission reduction potential of the short-term mitigation options presented in this Chapter on the basis of the SRES scenarios, mainly because of lack of technological detail in the SRES. In order to come to a comprehensive emission reduction estimate, it has been ensured that for all the sectors the estimates are compatible with one of the scenarios, i.e. the B2-Message (standardized) scenario. The emission reductions presented in *Table 3.37* total 14% - 23% of baseline emissions in the year 2010 and to 23% - 42% of baseline emissions in the year 2020.[29] If these percentages also apply to the other scenarios - there is no obvious reason why this would not be the case – it is concluded that *in most situations* the annual global greenhouse gas emission levels can be reduced to a level close to or below those of 2000 by 2010 and even lower by 2020.

The evidence on which this conclusion is based is extensive, but is subject to the limitations outlined above. Therefore, the estimates as presented in the table should be considered to be indicative only. Nevertheless, the main conclusion presented above can be drawn with a high degree of confidence.

Costs of options vary by technology, sector and region (see cost discussion in *Table 3.37*). Based upon the costs in a majority of the studies, approximately half of the potential for emissions reductions cited above for 2010 and 2020 can be achieved at net negative costs (value of energy saved exceeds capital, operating and maintenance costs) using the social discount rates cited. Most of the remainder can be achieved at a cost of less than US\$100/tC_{eq}.

The overall rate of diffusion of low emission technologies is insufficient to offset the societal trend of increasing consumption of energy-intensive goods and services, which results in increased emissions. Nevertheless, substantial technical progress has been made in many areas, including the market introduction of efficient hybrid engine cars, the demonstration of underground carbon dioxide storage, the rapid advancement of wind turbine design, and the near elimination of N_2O emissions from adipic acid production.

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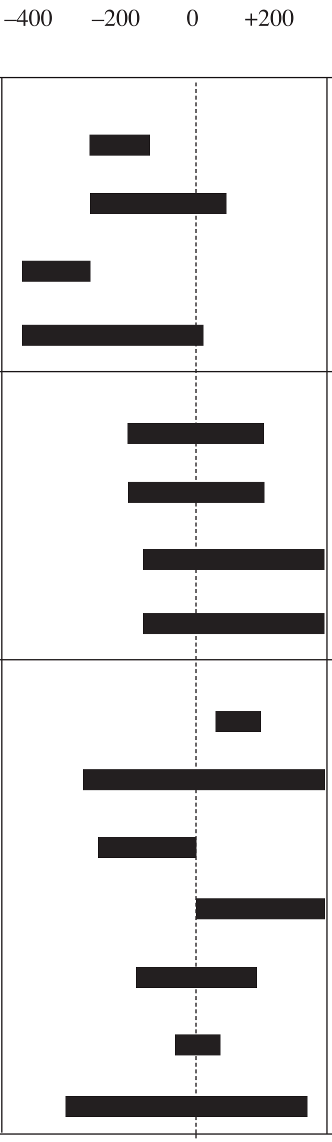
[28] For comparison: the total commitment of Annex I countries according to the Kyoto Protocol is estimated to be 500MtC (SRES-scenario B2 as reference).

[29] Some double-counting in the emission reduction estimates occur, especially between electricity saving options and options in the electricity production sector. However, further analysis shows that the effect of double-counting is just noise within the uncertainty range.

Table 3.36: *Estimations of greenhouse gas emission reductions and cost per tonne of carbon equivalent avoided following the anticipated socio-economic potential uptake by 2010 and 2020 of selected energy efficiency and supply technologies, either globally or by region and with varying degrees of uncertainty*



	Region	**US$/tC avoided**	**2010**		**2020**		**References; comments; relevant section of report**
			Potential[a]	Probability[b]	**Potential**[a]	Probability[b]	
Buildings / appliances							
Residential sector	OECD/EIT		◆◆◆◆◆	◊◊◊◊◊	◆◆◆◆◆	◊◊◊◊◊	Acosta Moreno *et al*., 1996 Brown *et al*., 1998 Wang and Smith, 1999
	Dev. cos.		◆◆◆◆	◊◊◊	◆◆◆◆	◊◊◊◊◊	
Commercial sector	OECD/EIT		◆◆◆◆	◊◊◊◊	◆◆◆◆◆	◊◊◊◊◊	
	Dev. cos.		◆◆◆	◊◊◊	◆◆◆◆	◊◊◊◊◊	
Transport							
Automobile efficiency improvements	USA		◆◆◆◆◆	◊◊◊◊	◆◆◆◆◆	◊◊◊	Interlab. Working Group, 1997 Brown *et al*, 1998 US DOE/EIA, 1998 ECMT, 1997 (8 countries only) Kashiwagi *et al*, 1999 Denis and Koopman, 1998 Worrell *et al*., 1997b
	Europe		◆◆◆◆◆	◊◊	◆◆◆◆◆	◊◊	
	Japan		◆◆◆◆	◊◊	◆◆◆◆◆	◊◊	
	Dev. cos.		◆◆◆◆	◊◊	◆◆◆◆◆	◊◊	
Manufacturing							
CO_2 removal – fertilizer; refineries	Global		◆	◊◊◊◊	◆	◊◊◊◊	*Table 3.21*
Material efficiency improvement	Global		◆◆◆◆	◊◊◊	◆◆◆◆	◊◊◊	*Table 3.21*
Blended cements	Global		◆	◊◊◊	◆	◊◊◊	*Table 3.21*
N_2O reduction by chem. indus.	Global		◆	◊◊◊◊	◆	◊◊◊	*Table 3.21*
PFC reduction by Al industry	Global		◆	◊◊◊	◆	◊◊◊	*Table 3.21*
HFC-23 reduction by chem. industry	Global		◆◆	◊◊◊	◆◆	◊◊◊	*Table 3.21*
Energy efficient improvements	Global		◆◆◆◆◆	◊◊◊◊◊	◆◆◆◆◆	◊◊◊◊	*Table 3.19*

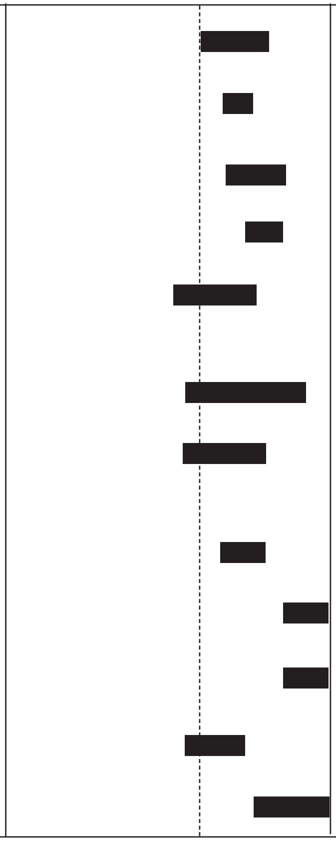
(continued)

Table 3.36: continued

	Region	US $/tC avoided –400 –200 0 +200	2010		2020		References; comments; relevant section of report
			Potential[a]	Probability[b]	**Potential**[a]	Probability[b]	
Agriculture							
Increased uptake of conservation tillage and cropland management	Dev. cos.		◆	◊◊	◆	◊◊	Zhou, 1998; *Table 3.27* Dick *et al.*, 1998
	Global		◆◆◆	◊◊	◆◆◆◆	◊◊◊	IPCC, 2000
Soil carbon sequestration	Global		◆◆◆	◊◊	◆◆◆◆	◊◊◊	Lal and Bruce, 1999 *Table 3.27*
Nitrogenous fertilizer management	OECD		◆	◊◊◊	◆	◊◊◊	Kroeze & Mosier, 1999 *Table 3.27*
	Global		◆	◊◊◊	◆◆◆	◊◊◊◊	OECD, 1999; IPCC, 2000
Enteric methane reduction	OECD		◆◆	◊◊	◆◆	◊◊◊	Kroeze & Mosier, 1999 *Table 3.27*
	USA		◆	◊◊	◆	◊◊◊	OECD, 1998 Reimer & Freund, 1999
	Dev. cos.		◆	◊	◆	◊◊	Chipato, 1999
Rice paddy irrigation and fertilizers	Global		◆◆◆	◊◊	◆◆◆◆	◊◊◊	Riemer &Freund, 1999 IPCC, 2000
Wastes							
Landfill methane capture	OECD		◆◆◆◆	◊◊◊	◆◆◆◆	◊◊◊◊	Landfill methane USEPA, 1999
Energy supply							
Nuclear for coal	Global		◆◆◆◆	◊◊	◆◆◆◆◆	◊◊◊◊	[c]**Totals** – See Section 3.8.6
	Annex I		◆◆	◊◊	◆◆◆◆	◊◊	*Table 3.35a*
	Non-Annex I		◆◆	◊◊◊	◆◆◆◆◆	◊◊◊	*Table 3.35b*
Nuclear for gas	Annex I		◆◆◆	◊	◆◆◆◆	◊	*Table 3.35c*
	Non-Annex I		◆	◊	◆◆◆	◊	*Table 3.35d*

(continued)

Table 3.36: continued

	Region	**US$/tC avoided**	**2010**		**2020**		**References; comments; relevant section of report**
		–400 –200 0 +200 	**Potential**[a]	Probability[b]	**Potential**[a]	Probability[b]	
Gas for coal	Annex I		◆	◊◊◊	◆◆◆◆	◊◊◊◊	*Table 3.35a*
	Non-Annex I		◆	◊◊◊◊	◆◆◆◆	◊◊◊◊	*Tables 3.35b*
CO_2 capture from coal	Global		◆	◊◊	◆◆	◊◊	*Tables 3.35a + b*
CO_2 capture from gas	Global		◆	◊◊	◆◆	◊◊	*Tables 3.35c + d*
Biomass for coal	Global		◆	◊◊◊◊	◆◆◆	◊◊◊◊	*Tables 3.35a + b* Moore, 1998; Interlab w. gp. 1997
Biomass for gas	Global		◆	◊	◆	◊◊◊	*Tables 3.35c + d*
Wind for coal or gas	Global		◆◆◆	◊◊◊	◆◆◆◆◆	◊◊◊◊	*Tables 3.35a - d* BTM Cons 1999;Greenpeace, 1999
Co-fire coal with 10% biomass	USA		◆	◊◊◊	◆◆	◊◊◊	Sulilatu, 1998
Solar for coal	Annex I		◆	◊	◆	◊	*Table 3.35a*
	Non-Annex I		◆	◊	◆	◊	*Table 3.35b*
Hydro for coal	Global		◆◆	◊	◆◆◆	◊◊	*Tables 3.35a + b*
Hydro for gas	Global		◆	◊	◆◆	◊◊	*Tables 3.35c + d*

Notes:

[a] Potential in terms of tonnes of carbon equivalent avoided for the cost range of US$/tC given.

◆ = <20 MtC/yr ◆◆ = 20-50 MtC/yr ◆◆◆ = 50-100MtC/yr ◆◆◆◆ = 100-200MtC/yr ◆◆◆◆◆ = >200 MtC/yr

[b] Probability of realizing this level of potential based on the costs as indicated from the literature.

◊ = Very unlikely ◊◊ = Unlikely ◊◊◊ = Possible ◊◊◊◊ = Probable ◊◊◊◊◊ = Highly probable

[c] Energy supply total mitigation options assumes that not all the potential will be realized for various reasons including competition between the individual technologies as listed below the totals.

Table 3.37: Estimates of potential global greenhouse gas emission reductions in 2010 and in 2020.

Sector		Historic emissions in 1990 (MtC_{eq}/yr)	Historic C_{eq} annual growth rate in 1990-1995 (%)	Potential emission reductions in 2010 (MtC_{eq}/yr)	Potential emission reductions in 2020 (MtC_{eq}/yr)	Net direct costs per tonne of carbon avoided
Buildings[a]	CO_2 only	1650	1.0	700-750	1000-1100	Most reductions are available at negative net direct costs.
Transport	CO_2 only	1080	2.4	100-300	300-700	Most studies indicate net direct costs less than US$25/tC but two suggest net direct costs will exceed US$50/tC.
Industry	CO_2 only	2300	0.4			
-energy efficiency				300-500	700-900	More than half available at net negative direct costs.
-material efficiency				~200	~600	Costs are uncertain.
Industry	Non-CO_2 gases	170		~100	~100	N_2O emissions reduction costs are US$0-$10/tC_{eq}.
Agriculture[b]	CO_2 only	210				Most reductions will cost between US$0-100/$tC_{eq}$ with limited opportunities for negative net direct cost options.
	Non-CO_2 gases	1250-2800		150-300	350-750	
Waste[b]	CH_4 only	240	1.0	~200	~200	About 75% of the savings as methane recovery from landfills at net negative direct cost; 25% at a cost of US$20/$tC_{eq}$.
Montreal Protocol replacement applications	Non-CO_2 gases	0		~100		About half of reductions due to difference in study baseline and SRES baseline values. Remaining half of the reductions available at net direct costs below US$200/$tC_{eq}$.
Energy supply and conversion[c]	CO_2 only	(1620)	1.5	50-150	350-700	Limited net negative direct cost options exist; many options are available for less than US$100/$tC_{eq}$.
Total		**6,900-8,400**[d]		**1,900-2,600**[e]	**3,600-5,050**[e]	

[a] Buildings include appliances, buildings, and the building shell.

[b] The range for agriculture is mainly caused by large uncertainties about CH_4, N_2O, and soil-related emissions of CO_2. Waste is dominated by landfill methane and the other sectors could be estimated with more precision as they are dominated by fossil CO_2.

[c] Included in sector values above. Reductions include electricity generation options only (fuel switching to gas/nuclear, CO_2 capture and storage, improved power station efficiencies, and renewables).

[d] Total includes all sectors reviewed in Chapter 3 for all six gases. It excludes non-energy related sources of CO_2 (cement production, 160MtC; gas flaring, 60MtC; and land use change, 600-1400MtC) and energy used for conversion of fuels in the end-use sector totals (630MtC). Note that forestry emissions and their carbon sink mitigation options are not included.

[e] The baseline SRES scenarios (for six gases included in the Kyoto Protocol) project a range of emissions of 11,500-14,000MtC_{eq} for 2010 and of 12,000-16,000MtC_{eq} for 2020. The emissions reduction estimates are most compatible with baseline emissions trends in the SRES-B2 scenario. The potential reductions take into account regular turnover of capital stock. They are not limited to cost-effective options, but exclude options with costs above US$100/$tC_{eq}$ (except for Montreal Protocol gases) or options that will not be adopted through the use of generally accepted policies.

Hundreds of technologies and practices exist to reduce greenhouse gas emissions from the buildings, transport, and industrial sectors. These energy efficiency options are responsible for more than half of the total emission reduction potential of these sectors. Efficiency improvements in material use (including recycling) will also become more important in the longer term.

The energy supply and conversion sector will remain dominated by cheap and abundant fossil fuels but with potential for reduction in emission caused by the shift from coal to natural gas, conversion efficiency improvement of power plants, the adoption of distributedcogeneration plants, and carbon dioxide recovery and sequestration. The continued use of nuclear power plants (including their lifetime extension) and the application of renewable energy sources will avoid emissions from fossil fuel use. Biomass from by-products, wastes, and methane from landfills is a potentially important energy source which can be supplemented by energy crop production where suitable land and water are available. Wind energy and hydropower will also contribute, more so than solar energy because of the latter's relatively high costs.

N_2O and some fluorinated greenhouse gas reductions have already been achieved through major technological advances. Process changes, improved containment, recovery and recycling, and the use of alternative compounds and technologies have been implemented. Potential for future reductions exists, including process-related emissions from insulated foam and semiconductor production, and by-product emissions from aluminium and HCFC-22. The potential for energy efficiency improvements connected to the use of fluorinated gases is of a similar magnitude to reductions of direct emissions.

Agriculture contributes 20% of total global anthropogenic emissions, but although there are a number of technology mitigation options available, such as soil carbon sequestration, enteric methane control, and conservation tillage, the widely diverse nature of the sector makes capture of emission reductions difficult.

Appropriate policies are required to realize these potentials. Furthermore, on-going research and development is expected to significantly widen the portfolio of technologies to provide emission reduction options. Maintaining these R&D activities together with technology transfer actions will be necessary if the longer term potential as outlined in *Table 3.37* is to be realized. Balancing mitigation activities in the various sectors with other goals such as those related to development, equity, and sustainability is the key to ensuring they are effective.

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Chapter 3 Appendix

Options to Reduce Global Warming Contributions from Substitutes for Ozone-Depleting Substances

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CONTENTS

EXECUTIVE SUMMARY

Hydrofluorocarbons (HFCs) and to a lesser extent perfluorocarbons (PFCs) have been introduced to replace ozone-depleting substances (ODSs) that are being phased out under the Montreal Protocol on Substances that Deplete the Ozone Layer. HFCs and PFCs have a significant global warming potential (GWP) and are listed in the Kyoto Protocol. This Appendix estimates consumption and emissions and assesses alternative practices and technologies to reduce emissions. Emissions as by-products of manufacturing are treated in the main part of Chapter 3.

In the absence of the Montreal Protocol the use of chlorine-containing compounds and especially CFCs would have expanded significantly. However, because of this treaty, developed countries replaced about 8% of projected chlorofluorocarbon use with HFCs, 12% with HCFCs, and eliminated the remaining 80% by controlling emissions, specific use reductions, or by using alternative technologies and fluids including ammonia, hydrocarbons, carbon dioxide, water, and not-in-kind options.

In 1997, the production of HFCs was about 125 kilotons ($50MtC_{eq}$), and the production of PFCs amounted to 5 kilotons ($12MtC_{eq}$). The production of HFCs in 2010 is projected to be about 370 kilotons or $170MtC_{eq}$ and less than $12MtC_{eq}$ for PFCs, assuming current trends in use and regulations, substantial investment in new HFC production capacity, and success of voluntary agreements. Since most of the HFCs and some of the PFCs are contained in equipment or products, annual emissions lag production when use is growing.

Refrigeration, air conditioning, and heat pumps are the largest source of emissions of HFCs. Improved design, tighter components, and recovery and recycling during servicing and disposal can reduce lifetime HFC emissions at moderate to low costs. Non-HFC alternatives include hydrocarbons, ammonia, and carbon dioxide, or alternative technologies. Lifecycle climate performance (LCCP) analysis of the entire system, including direct fluid emissions and indirect emissions from carbon dioxide resulting from energy use by the device, provides a means of assessing the net contribution of a system to global climate change. The LCCP calculations are very system specific and can be used to make relative rankings. However, since the LCCP approach involves regional climate conditions and local energy sources, the results cannot be generalized in order to make globally valid comparisons.

Insulating foams are anticipated to become the second largest source of HFC emissions and HFC use is expected to grow rapidly as CFCs and HCFCs are replaced with HFC-134a, HFC-245fa, and HFC-365mfc. Alternative blowing agents including the different pentanes and carbon dioxide have lower direct climate impact from direct emissions. However, they also have lower insulating values than CFCs and HCFCs, and hence may have higher indirect emissions from energy use if the foam thickness is not increased to offset the higher conductivity. Non-foam insulation alternatives such as mineral fibres are also used, and vacuum panels may play a role in the future.

Other sources of HFC and PFC emissions are industrial solvent applications, medical aerosol products, other aerosol products, fire protection, and non-insulating foams. A variety of options are available to reduce emissions including increased containment, recovery, destruction, and substitution by non-fluorocarbon fluids and not-in-kind technologies. There are no zero- or low-GWP alternatives for some medical and fire protection applications.

A3.1 Introduction

Alternatives and substitutes for HFCs, perfluorocarbons (PFCs), and ozone depleting substances (ODSs) have recently been extensively evaluated. The Montreal Protocol Technology and Economic Assessment Panel (TEAP) and its technical committees published a comprehensive assessment (UNEP, 1999b). Furthermore, reports were published within the framework of the joint IPCC/TEAP workshop (IPCC/TEAP, 1999) and the second non-CO_2 greenhouse gases conference (van Ham *et al.*, 2000).

The HFCs that are projected for large volume use have global warming potentials (GWPs) which are generally lower than those of the ODSs they replace. The GWP of HFCs replacing ODSs range from 140 to 11,700. HFC-23 with a GWP of 11,700 is used as a replacement for ODSs to only a very minor extent. However, there are relatively large emissions of HFC-23 from the HCFC-22 manufacturing process. The majority of HFCs have GWPs much lower than that of HFC-23. PFCs have GWPs that are generally higher than those of the ODSs they replace, ranging from 7,000 to 9,200 (IPCC, 1996). *Table A3.1* lists the atmospheric properties of the HFCs and HFC blends considered in this Appendix.

Most HFCs are used for energy-consuming applications such as refrigeration, air conditioning and heat pumps, and building and appliance insulation. Life cycle climate performance (LCCP) analysis is being used to estimate the net contribution to climate change. It includes all direct greenhouse gas emissions and indirect emissions related to energy consumption associated with the design and the operational modes of systems (UNEP, 1999b; Papasavva and Moomaw, 1998). The LCCP is a very system specific parameter that can be used to make relative rankings. However, LCCP analysis involves regional differences – including different fuel sources – and the related equipment operating conditions; the results can therefore not be generalized in order to make globally valid comparisons.

Table A3.1: *Atmospheric properties (lifetime, global warming potential (GWP)) for the HFC chemicals described in the Appendix (IPCC, 1996; WMO, 1999)*

Compound	Chemical formula	Lifetime (yr) (IPCC, 1996)	GWP (100 yr) (IPCC, 1996)	Lifetime (yr) (IPCC, 2000)	GWP (100 yr) (IPCC, 2000)
HFC-23	CHF_3	264	11,700	260	12,000
HFC-32	CH_2F_2	5.6	650	5.0	550
HFC-125	CHF_2CF_3	32.6	2,800	29	3,400
HFC-134a	CH_2FCF_3	14.6	1,300	13.8	1,300
HFC-143a	CH_3CF_3	48.3	3,800	52	4,300
HFC-152a		1.5	140	1.4	120
HFC-227ea	CF_3CHFCF_3	36.5	2,900	33	3,500
HFC-245fa[a]	$CF_3CH_2CHF_2$	-	-	7.2	950
HFC-365mfc[a]	$CF_3CH_2CF_2CH_3$	-	-	9.9	890
HFC-43-10mee	$CF_3CHFCHFCF_2CF_3$	17.1	1,300	15	1,500
R-404A (44% HFC-125, 4% HFC-134a, 52% HFC-143a)			3,260		
R-407C (23% HFC-32, 25% HFC-125, 52% HFC-134a)			1,525		
R-410A (50% HFC-32, 50% HFC-125)			1,725		
R-507 (50% HFC-125, 50% HFC-143a)			3,300		

[a] No lifetime or GWP listed in IPCC (1996)

Note: GWP values to be used by Parties for reporting any emissions and for any other commitments under the Kyoto Protocol are the 100 year GWP values from IPCC (1996) (decision taken at CoP 3, 1997)

The energy efficiency of equipment and products can be expressed in at least three ways: theoretical maximum efficiency, maximum efficiency achievable with current technology, and actual efficiency for commercial scale production (often expressed as a range of values). Systems optimized for a new refrigerant have been compared to sub-optimum systems with other refrigerants. Furthermore, appliance sizes and features that influence energy performance vary between studies and test conditions, and methodologies are often significantly different. These factors have led to a wide range of energy efficiency claims in technical reports and commercial publications. Ultimately, the performance and cost effectiveness of specific products from commercial scale production must be directly compared. Furthermore, costs reported in this appendix might not always be comparable because of differing estimation methods, including estimates based on both consumer and producer costs.

A3.1.1 Past Trends

Unlike anthropogenic greenhouse gases emitted as an immediate consequence of the burning of fossil fuels to generate energy, most HFCs and PFCs are contained within equipment or products for periods ranging from a few months (e.g., in aerosol propellants) to years (e.g., in refrigeration equipment) to decades (e.g., in insulating foams). Thus, emissions significantly lag consumption and, because HFC systems are relatively new, emissions will continue to grow after 2010.

Both the quantities used and patterns of use of ODSs, HFCs, and PFCs are changing (see *Figure A3.1*) as ODSs are phased out under the Montreal Protocol (IPCC/TEAP, 1999; McFarland, 1999). In 1986, less than half of total ODS use was in insulating foams, fire protection, refrigeration, air conditioning, and heat pumps, with more than half as aerosol product propellants, non-insulating foam, solvent, and specialized applications. However, by 1997, the global consumption of fluorocarbons (CFCs, HCFCs and HFCs) had decreased by about 50% as solvent, aerosol product, and non-insulating foam applications switched to alternatives other than fluorocarbons. Refrigeration, air conditioning, and insulating foam accounted for about 85% of the remaining total fluorocarbon use. 80% of projected chlorofluorocarbon demand was avoided by reducing emissions, redesign, and use of non-fluorocarbon technologies. As CFCs, halons, and HCFCs are phased out globally, the quantities of fluorocarbons are expected to continue to decline in the short term, but are expected to grow in the longer term.

A3.1.2 Projections

Future global HFC and PFC consumption and/or emissions as substitutes for ODSs have been separately estimated by IPCC (1995), Midgley and McCulloch (1999), and UNEP (1998a). Midgley and McCulloch (1999) projected carbon-equivalent emissions of HFCs and PFCs (excluding unintended chemical by-product emissions) at $60MtC_{eq}$ in 2000, $150MtC_{eq}$ in 2010 and $280MtC_{eq}$ in 2020. Projected consumption data for 2000 and 2010 are primarily based on UNEP reports (UNEP, 1998f, 1999b) and are shown in *Table A3.2*. Considering that emissions lag consumption by many years, the Midgley and McCulloch figures are much larger than the UNEP figures. This discrepancy is consistent with the Midgley and McCulloch scenario which was constructed to represent plausible upper limits to future emissions (McFarland, 1999). HFC emissions in the SRES scenarios (IPCC, 2000) are $54MtC_{eq}$ in

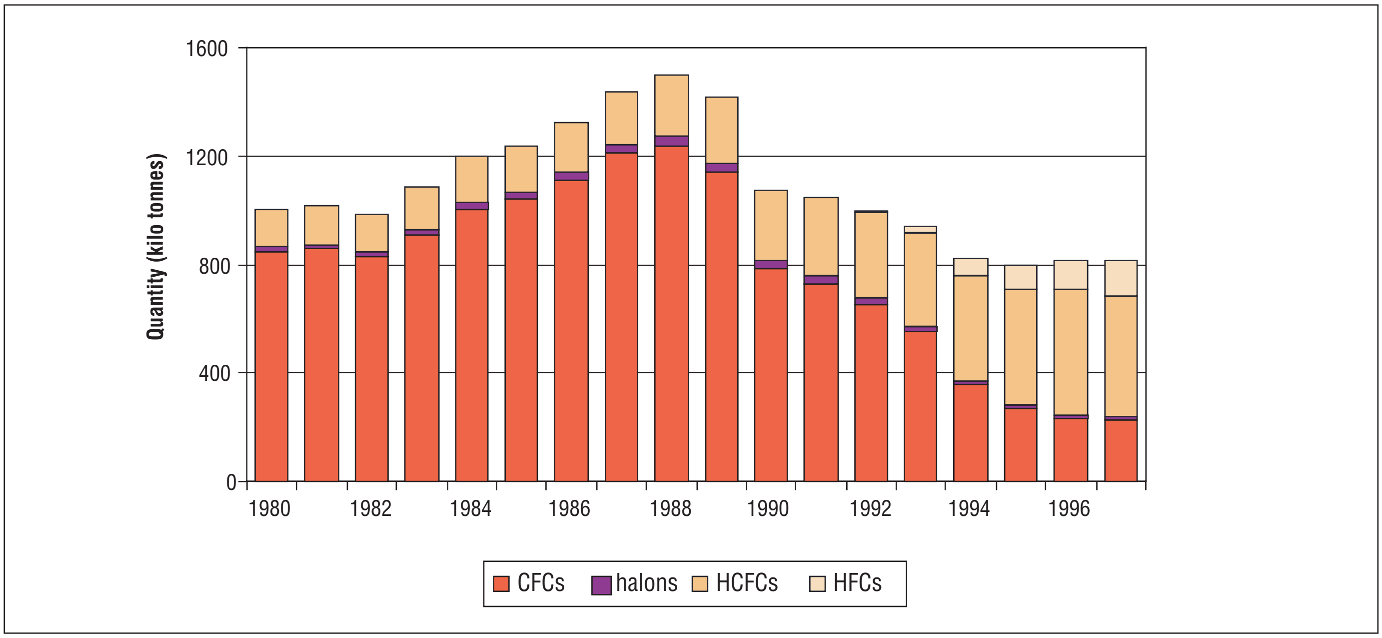

Figure A3.1: *Estimated global consumption of CFCs, halons, HCFCs, and HFCs (McFarland, 1999).*

Table A3.2: *Estimated and projected global HFC consumption and emission for different sub-sectors for 2000 and 2010*

Sub-sector	**2000**				**2010**			
	HFC consumption	**HFC consumption**	**HFC emission**	**HFC emission**	**HFC eonsumption**	**HFC consumption**	**HFC emission**	**HFC emission**
	kt/yr	**MtC_{eq}/yr**	**kt/yr**	**MtC_{eq}/yr**	**kt/yr**	**MtC_{eq}/yr**	**kt/yr**	**MtC_{eq}/yr**
Refrigeration & A/C[a,b]	*102-112*	*47-50*	*40-44*	*18-19*	*195-255*	*106-139*	*82-124*	*42-64*
Mobile A/C[c]	64-74	23-26	31-35	11-12	58-79	21-28	37-54	13-19
Domestic refrigeration[f]	7	2.5	0.9	0.3	15-17	5.5-6.4	3.5-4.5	1.3-1.7
Comm. refrigeration[d, e, f]	19	15	5	4.5	46.5-64	39-54	19.5-31	16-26
Cold storage[d]	4.5	3	1.2	0.8	9-12	6-8	3-4	2-2.5
Industrial refrigeration[d]	1.5	1	0.3	0.2	3-4	2-2.7	0.6-0.8	0.4-0.5
Chiller A/C	2.5	1	0.2	0.1	3.5-4.5	2.3-3	0.5-0.7	0.3-0.5
Transport refrigeration[d, e, f]	3.3	1	1.3	0.7	17-23.5	8.5-12	10-14.5	5-7
Unitary air conditioning	-	-	-	-	43-51	22-25	8-14	4-7
Insulating foams[g]	*4+*	*1.5+*	*<1*	*<0.5*	*115*	*29.5*	*20-40*	*5-10*
Solvents/ cleaning[h]	*<2*	*<9*	*<2*	*<9*	*>2*	*<9*	*>2*	*<9*
Med. aerosol[h]	*1*	*<1*	*1*	*<1*	*<9*	*<4*	*<9*	*<4*
Other aerosol[h]	*<15*	*<4*	*<15*	*<4*	*<20*	*<5*	*<20*	*<5*
Fire protection[a,b,i]	*1.0 - 1.6*	*0.8 - 1.3*	*0.2-0.4*	*0.2 - 0.3*	*1.6 - 2.0*	*1.3 - 1.7*		
	0.6 - 0.9	*0.5 - 0.8*						
TOTAL	125-136	63-66	59-62	32-33	343-403	155-189	134-196	66-93

[a] Consumption and emission estimates are based on information contained in (UNEP, 1998a, 1999b); A/C = Air Conditioning

[b] The average growth has been estimated as 2.5% annually over the period 2000-2010

[c] See text and *Table A3.3* for explanations

[d] The mix of refrigerants (both pure HFCs and HFC blends) is estimated based on information in (UNEP, 1998a, 1999b) for commercial, cold storage, industrial and transport applications

[e] 2010 emission factors have been defined as 7%-10% for commercial refrigeration, 12%-18% for transport refrigeration;

[f] Equipment life for domestic refrigeration is assumed to be 15 years or longer implying that no emissions at disposal will occur by the year 2010. Equipment life for commercial and transport refrigeration is assumed to be 10 years with between 60% and 80% emitted (20%-40% recovery) at disposal

[g] Emissions for insulating foam were based on a methodology described in Gamlen *et al.*, 1986

[h] Emissions of HFCs used as solvents and medical and other aerosol propellants occurs within one year of consumption (Gamlen *et al.*, 1986)

[i] Emissions for the fire protection sector for 2000 are estimated to be 5% of the installed base (the same level as the average halon emission in the recent decade); for the year 2010 they are assumed to be 2.5% of the installed base, as a result of improved design and service practices (IPCC/TEAP, 1999; UNEP, 1999b).

2000 and 130-136MtC$_{eq}$ in 2010. These values are higher than those presented in *Table A3.2* because of the top-down approach used in SRES that does not adequately account for delay between use and emissions in the 2000 to 2010 timeframe. Considering this fact and given the options for substitution, containment, etc., it is estimated that emissions in 2010 could well be about 100MtC$_{eq}$ below the SRES forecast at a marginal cost lower than US$200/tC$_{eq}$. None of the scenarios have considered the implications of new uses of HFCs or PFCs other than as substitutes for ODSs.

Projected consumption and emission estimates for HFCs by sub-sector for 2000 and 2010 are summarized in *Table A3.2*.

A3.2 Refrigeration, Air Conditioning, and Heat Pumps

Most current and projected HFC consumption and emissions is in this sector. HFC consumption in refrigeration and mobile and stationary air conditioning in 1997 was, on a mass basis, about 30% of projected developed country CFC consumption in the absence of the Montreal Protocol (McFarland, 1999). Most of the remaining 70% of projected consumption has been eliminated by reducing leaks, reduced charge per application, and improved service practices; the substitution by other fluids and new technologies played a lesser role (some substitution – a few per cent – by HCFCs also took place). Globally, there is still a huge potential to further reduce HFC emissions. Estimated consumption and emissions of HFCs for this sector for 2000 and 2010 are shown in *Table A3.2*. Emissions significantly lag consumption because HFC systems are relatively new so emissions will occur well after 2010.

The primary options for limiting HFC emissions are the use of alternative refrigerants and technologies, reduced refrigerant charge, improved containment, recovery with recycling, and/or destruction. There are no globally representative estimates of the cost effectiveness of improved containment and recovery. In developed countries, recovery during servicing of small domestic refrigerators captures a relatively insignificant proportion of HFCs, while end-of-life recovery is significant. For medium-sized devices such as commercial units with substantial leakage rates, recovery during both multiple servicing and at the end of useful life is both significant. For very large units recovery both during servicing and at end of life is frequently done already because of the high economic value associated with the large quantities of recovered fluids.

In developing countries, where low cost is important, the quality of equipment is often poor, resulting in high failure rates. Since the service sector in developing countries is normally not equipped with the tools for recycling, the emissions of refrigerants during servicing and product disposal form a significant portion of the overall emissions.

Recovery at theend of equipment life is likely to exhibit a poor cost-effectiveness for smaller units. For these units, the introduction of economic incentives will be necessary, probably together with voluntary agreements and/or government regulations (as already exist in some countries) to achieve significant reductions in this sector.

Carbon dioxide emissions associated with energy consumption by refrigeration, air conditioning, and heat pump equipment are usually the largest contributions to global warming associated with cooling equipment (AFEAS, 1991; Papasavva and Moomaw, 1998). Japanese manufacturers estimate that energy-related CO_2 emissions represent an even larger fraction of lifetime emissions for their low leakage rate, small charge appliances. Thus, improvements in equipment energy efficiency are often a cost-effective way to reduce greenhouse gas emissions and to lower costs to consumers (March, 1998). Proper equipment design, component performance, and the selection of the most appropriate refrigerant fluid are the most important factors contributing to energy efficiency. Examination of the LCCP of the system will determine which combination of operating efficiency and fluid choice yields the lowest overall contribution to global warming.

Hydrocarbons, carbon dioxide, and to a lesser extent, ammonia are the most likely alternatives to HFC refrigerants. No ammonia vapour compression units have capacity less than 50kW. Since both hydrocarbons and ammonia are flammable and ammonia is toxic, their acceptance will depend on cultural norms and specific regulations in each country. Hydrocarbons are currently being used in about 50% of the refrigerators manufactured in Europe and in some manufactured in Asia and Latin America; their use in these products as well as in other refrigeration and air conditioning systems could increase. Large charges can present a safety concern, and globally standardized mechanical and electrical safety standards are being established.

If safety is a concern, secondary loops containing a heat transfer fluid can be used. For modest cooling, such as water chilling for residential air conditioning or industrial process chilling, there is no energy penalty from using a secondary loop. For medium temperature applications in food processing and commercial refrigeration, secondary loops permit the safe use of ammonia and hydrocarbons, or enable minimization of an HFC refrigerant charge, generally with a modest energy penalty. If safety concerns require a secondary loop for low temperature applications in food processing and cold storage, in which normally the refrigerant is used as the direct heat transfer fluid, a substantial energy penalty may ensue.

Where they are required, the estimated cost of utilizing secondary loops with ammonia and hydrocarbons to replace HFCs is estimated to exceed US$100/tC$_{eq}$ (Harnisch and Hendriks, 2000). Secondary loop systems designed to achieve comparable efficiency and demonstrated in Europe have up to a 15% higher cost.

An optimal transition strategy from ODSs to alternatives can substantially lower costs and better meet development goals

Table A3.3: *Estimated global HFC-134a emissions for vehicle air conditioning*
Source: Baker (1999).

Year	**Vehicles w/134a A/C (million)**	**Recycle at service/disposal (%)**	**HFC-134a use (kt)**	**HFC-134a emissions (kt)**
2000	214-247	60	64-74	31-35
2010	464-530	60	58-79	37-54

for developing countries, especially in the refrigeration and air conditioning sectors (Papasavva and Moomaw, 1997). The Montreal Protocol Multilateral Fund (MLF) and the Global Environment Facility (GEF) have just begun to coordinate financing of ozone and climate protection (IPCC/TEAP, 1999). To date, one project has been jointly funded by the MLF and the GEF, which addresses energy efficiency in the replacement of CFCs. Energy use forms a major problem for the stressed energy supply system of capital-strapped developing countries. Since the greatest growth in refrigeration and air conditioning is projected to occur in developing countries, it is important that they select the most effective (in terms of costs and energy efficiency) non-ODS technology. Currently, customers in developing countries make purchase decisions based on initial cost with little consideration of energy consumption.

A3.2.1 Mobile Air Conditioning

HFC-134a replaced CFC-12 in virtually all vehicle air conditioners produced after 1993/94. Motor vehicle air conditioning uses HFC-134a refrigerant in an integrated system of components that provide cooling, heating, defrosting, demisting, air filtering, and humidity control. It is technically and economically feasible to significantly reduce emissions of HFC-134a refrigerants: by recovery and recycling of refrigerant during servicing and vehicle disposal; by using high quality components with low leakage rates, hoses with lower permeation rates, and improved connections; and by minimizing refrigerant charge. Efficiency improvements and smaller, lighter units can further reduce energy-related CO_2 emissions. New systems using alternative refrigerants –carbon dioxide or hydrocarbons– are being developed as described below (see Section A3.2.1.3).

A3.2.1.1 Estimates of Global HFC-134a Emissions

Globally, 65%–75% of air-conditioned vehicles in service in 2000 have HFC-134a air conditioners and it is predicted that between 2000 and 2010, 70%–80% of all new vehicles will have HFC-134a air conditioners. This projection assumes a continuation of current trends of mobile air conditioning installed in vehicles in normally cool climates where air conditioning may not be necessary. When air conditioning systems were redesigned to use HFC-134a, vehicle manufacturers used a smaller refrigerant charge and reduced leakage rates. Typical direct HFC emissions over a 10-year period in the USA are 1.4 kg if recycling is undertaken during service and disposal and 3.2 kg without recycling (Baker, 2000). Estimates for HFC-134a air conditioner emissions are included in *Table A3.3*.

A3.2.1.2 Strategies for Reducing Emissions and Improving Energy Efficiency of HFC-134a Systems

Vehicle manufacturers and their suppliers are working to increase the energy efficiency and reduce the emissions of HFC-134a systems. Typical CO_2 exhaust emissions resulting from air-conditioner operation are in the range of 2% to 10% of total vehicle CO_2 emissions (SAE, 2000). Comparison of reduced emissions HFC-134 systems and CO_2 systems have been published (Petitjean *et al*., 2000; March, 1998). HFC-134a systems can be redesigned for higher energy efficiency and smaller refrigerant charge within 2–4 years, and manufacturers of replacement parts could supply high-quality components within 2–4 years (SAE, 2000). SAE (2000) estimates that improved HFC-134a systems can be introduced faster and at lower incremental cost than carbon dioxide, hydrocarbon, and HFC-152a systems.

Lowering the demand for cooling and humidity control can reduce indirect emissions from fuel consumption and could allow smaller air conditioning systems having reduced refrigerant charges. This is accomplished by increasing thermal insulation and decreasing thermal mass in the passenger compartment, by sealing the vehicle body against unwanted air infiltration, by minimizing heat transfer through window glass, and by controlling the compressor to minimize over-cooling and subsequent re-heating of air.

A3.2.1.3 Strategies for Developing Efficient Alternative Air Conditioning Systems

Considerable activity is underway to develop alternatives to HFC-134a air conditioning systems for vehicles. Prominent efforts are the European "Refrigeration and Automotive Climate Systems under Environmental Aspects (RACE) Project" (Gentner, 1998), and the Society of Automotive Engineers/US EPA/Mobile Air Conditioning Society Worldwide "Mobile Air Conditioning Climate Protection Partnership" (SAE, 1999, 2000).

Two categories of alternative refrigerant candidates have emerged for new systems: 1) transcritical carbon dioxide systems and 2) hydrocarbon or HFC-152a systems.

1. Transcritical CO_2 systems require substantial new engineering, reliability, and testing efforts. These carbon dioxide systems have potential energy efficiency that is comparable or better than HFC-134a systems and the lowest direct global warming emissions of any candidate refrigerant. Prototype systems from several European vehicle manufacturers provided comparable passenger cooling comfort in medium-sized vehicles, and one reported improved efficiency over HFC systems at the Scottsdale Symposium (SAE, 1999). A CO_2 system in a small vehicle was less efficient, especially during idling (Kobayashi *et al*., 1998). With a higher heat rejection temperature compared to HFC-134a cycles, carbon dioxide systems can also efficiently operate in reverse mode to heat vehicle interiors. New equipment and technician training will be required to safely repair systems with operating pressures up to 6 times higher than systems with HFC-134a. The first CO_2 systems could be commercially available within 4-7 years (SAE, 2000).

2. Hydrocarbon and HFC-152a systems, with secondary cooling loops to mitigate flammability risk, are under study and development by several manufacturers in co-operation with suppliers (Baker, 2000; Ghodbane 1999; Dentis *et al*., 1999; SAE, 1999a). One prototype achieved a cooling performance at the 1999 Phoenix Forum comparable to HFC-134a systems (Baker, 2000; Gentner, 1998; Ghodbane, 1999; SAE, 2000). Systems using flammable refrigerants will require additional engineering and testing, development of safety standards and service procedures, and training of manufacturing and service technicians before commercialization, but would require fewer technical breakthroughs than carbon dioxide systems. If proven safe to Original Equipment Manufactures (OEMs), it is estimated that systems with flammable refrigerants could be commercially implemented in the first vehicles in as little as 4-5 years (SAE, 2000).

Highly efficient air conditioning and heating systems are particularly important to the commercial success of electric, hybrid, fuel cell, and other low-emission vehicles to help overcome the limited power of such vehicles.

A3.2.1.4 Cost-Effectiveness of Reducing Emissions from Vehicle Air Conditioning

Recovery and Recycle

It is estimated that recycling rates can be increased from 60% to 90% within one to two years in developed countries (SAE, 2000). Recovery and recycling of HFCs can reduce emissions by more than 10 kt annually (Baker, 1999). About 50% of the global fleet of HFC-134a air conditioned vehicles are in the USA where recycling is mandatory, and 25% are in Japan, where voluntary programme achieve a substantial recycling rate. The remainder are in Europe where recycling ranges from zero in some countries to near 100% participation in others, and in developing countries, where a wide range of recovery practices is found. A UNDP survey of 1300 Brazilian garages found one-quarter of garages recycling HFC-134a (UNDP, 1999).

The current market value of HFC-134a recovered during service or disposal in the USA more than pays for the cost of labour, equipment, and maintenance for shops servicing more than 6 vehicle air-conditioning systems per week. By 2002 to 2003 it is technically feasible to reduce system charge and leakage rates significantly. Recovery of 0.33 kg of HFC-134a will cost US$0.70 in large shops and US$1.50 in small shops. For large shops, recovery costs for improved, low-charge vehicles are estimated at less than US$3.50/$tC_{eq}$. Even for small shops, the cost-effectiveness per tonne of carbon equivalent can then be calculated in the range of US$1.18-12.81/$tC_{eq}$ depending upon the size of the charge (EPA, 1998).

Reduced Charge and Improved Containment

By 2002 to 2003, it is technically feasible to reduce system charge and leakage rates worldwide. It is estimated that the vehicle charge in the US can be reduced from 0.9kg to 0.8kg and that annual vehicle leakage could be reduced from 0.07 kg/yr to 0.04kg/yr (UNEP, 1998a; Baker, 1998; Sand *et al*., 1997; Wertenbach and Caesar, 1998). In Europe, refrigerant charges average about 0.7 kg per vehicle (Clodic, 1999). For the USA it is estimated (Baker, 2000) that emissions can be reduced from 8% to 5% per year for a 10-year reduction of 1.2 kg/vehicle without recovery and recycling or 1.0kg with recovery and recycling. Two studies (Harnisch and Hendriks, 2000; March, 1998) estimate that, in Europe, the cost per vehicle to reduce leakage rates from 10% to 4%-5%/yr is only US$11-US$13.

Alternative Systems

Three authors have published estimates of the cost of emission reductions achieved through alternative vehicle air conditioning using carbon dioxide as the refrigerant (March, 1998; Baker, 1999, 2000; Harnisch and Hendriks, 2000). These studies reported widely diverging results on the specific abatement costs of HFC emissions for the use of transcritical CO_2 systems (from US$90 to >US$1000/tC_{eq}). Differences in cost estimates can be traced back to a number of factors among which two are most important: (1) the use of producer-costs versus consumer costs and (2) differing assumptions about the existing degree of recovery of HFC-134a during servicing and at the end of life. Of lesser importance were differing assumptions on the average fluid charge of an HFC air conditioning system, annual leakage rates, relative differential costs, and applied discount rates. Once the results are normalized to common assumptions on the major factors, the abatement costs differ by only a factor of two or less (see *Table A3.4*).

As reported in *Table A3.4*, costs of avoiding HFC emissions through alternative air conditioning systems vary between US$20 and US$2100/tC_{eq} depending on the emission characteristics of the reference HFC system (and on whether consumer or producer prices are used). Consequently in countries

Table A3.4: *Abatement costs*[a] *of avoiding HFC emissions by using alternative systems (based on* CO_2 *or secondary hydrocarbons) relative to different baseline HFC emission scenarios*

Alternative system compared against current HFC-134a systems				Alternative system compared against improved HFC-134a systems with reduced leakage rate			
With recycling, 1.4 kg 10-year emission baseline[b] (US\$/tC$_{eq}$)		without recycling, 3.2 kg 10-year emission baseline (US\$/tC$_{eq}$)		With recycling, 0.4 kg 10-year emission baseline[b] (US\$/tC$_{eq}$)		without recycling 2.0 kg 10-year emission baseline (US\$/tC$_{eq}$)	
Producer cost	Consumer cost	Producer cost	Consumer cost	Producer cost	Consumer cost	Producer cost	Consumer cost
102-173	306-519	21-53	63-159	460-711	1380-2133	59-109	177-327

[a] Assuming:(i) equivalent energy efficiency for conventional and alternative systems, (ii) an increase of producer cost by US$60-90 per vehicle relative to current HFC-systems, (iii) a discount rate of 4% per year, and (iv) a factor of 3 between consumer cost and producer cost (Crain, 1999).

[b] Incremental costs for the improved HFC system and for establishing and enforcing a recovery system are not included but assumed to be small compared to additional costs of alternative systems.

where systems already exist to ensure HFC recycling during servicing and at the end of life, alternative air conditioning systems will need to exhibit significantly reduced indirect emissions in order to be cost-effective in abating greenhouse gas emissions.

A3.2.2 Domestic Appliances

In developed countries, the only replacements for the fluid CFC-12 in refrigerators and freezers have been HFC-134a and isobutane (R-600a). Developing countries have chosen the same replacements, but some still utilize CFC-12; here, the complete conversion of new equipment from CFC-12 is not expected until 2001-2002. Globally, in 1996 to isobutane was used in about 8% of new appliances (UNEP, 1998a). Isobutane accounts for a much higher and growing percentage in Northern European countries such as Germany, where it is used in virtually all new domestic appliances. It is estimated that isobutane currently is the coolant used in 45%-50% of domestic refrigerator and freezer sold in Western Europe. Projected use and emissions of HFC-134a are shown in *Table A3.2*.

HFC emission reductions achieved during servicing and through recovery of the refrigerant upon disposal of appliances are costly. Next to economic incentives, regulations (as already exist for CFC-containing appliances in several countries) would probably be required to obtain significant emissions reductions through HFC recovery (March, 1998). One study (Harnisch and Hendriks, 2000) reports a value of US\$334/tC$_{eq}$ for the recovery of HFCs from refrigerators; the larger part of this is the cost for the transport and collection scheme.

Product liability, export market opportunities, and regulatory differences among regions are likely to be significant factors in determining the choice between isobutane and HFC-134a systems. Isobutane may well account for over 20% of domestic appliances globally by the year 2010. Published estimates suggest that isobutane systems are US\$15 to US\$35 more expensive than HFC-134a systems (Juergensen, 1995; Dieckmann *et al*., 1999). These costs would translate into a cost effectiveness of US\$600/tC$_{eq}$ due to the relatively small refrigerant charge (about 120 g of HFC-134a).

A3.2.3 Commercial Refrigeration

The primary refrigerants used in this sector are R-404A and HFC-134a; usage of R-407C and R-507 is relatively small. Hydrocarbons are being applied in smaller direct expansion systems and in both small and large systems with a secondary loop, whereas ammonia is mainly applied in larger systems with secondary loops (UNEP, 1998a). Projected consumption and emissions of HFCs are shown in *Table A3.2*.

Historical emission rates of CFC refrigerants from the commercial refrigeration sector were 30% or more of the system charge per year. Regulations have resulted in improved system designs and service practices with significantly lower emissions in many countries (UNEP, 1998a; IEA, 1998). These practices are being carried over to HFC systems and the emissions savings are reflected in the projections shown in *Table A3.2* (UNEP, 1999b). March (1998) estimated that refrigerant emissions could be further reduced through better containment and recovery by an additional 30% to 50% in 2010 for Europe. In many developing countries, the supermarket refrigeration units are often produced by small and medium enterprises to lower quality standards, leading to considerable emissions of HFCs. The existing stock of supermarket refrigerators continues to operate with CFC-12 and HCFC-22.

The use of hydrocarbons and ammonia as refrigerants in this sector is growing from a small base. Several large commercial refrigeration manufacturers are developing systems using carbon dioxide which are expected to enter the market shortly. The HFC projections shown in *Table A3.2* are based upon the assumption that less than 10% of the systems will use ammonia, hydrocarbons, and carbon dioxide in 2010.

A3.2.4 Residential and Commercial Air Conditioning and Heating

Most existing residential air conditioning and heating systems (unitary systems) currently use HCFC-22 as the refrigerant; in the manufacturing of new systems HCFC-22 is being displaced by HFC blends, and to a lesser extent, by propane in some systems. In developed countries, the Montreal Protocol and more stringent national regulations are leading to a replacement of HCFC-22 in virtually all new equipment, ultimately by 2010. The leading HFC alternatives are R-407C and R-410A (UNEP, 1998a), the latter particularly for smaller units in the developed countries at present. In developing countries, HCFC-22 will be available for many more years and the use of HFC blends may remain small. Split HC based air conditioning equipment is produced by some smaller European manufacturers; production of these units is being announced by others. Estimated consumption and emission amounts for 2010 are shown in *Table A3.2*.

In small water chillers, applying a variety of compressor types, there is emphasis on the use of R-407C. For large water chillers that apply centrifugal compressors, the primary alternatives to CFCs are HFC-134a and HCFC-123. HCFC-123 is used in virtually all low-pressure chillers since it has a very high energy-efficiency and so far no highly efficient, low-pressure non-ODS alternative has become available (Wuebbles and Calm, 1997). Certain existing high-pressure HFC equipment or new low pressure HFCs may take over the low-pressure market gradually in the near future (IEA, 1998). Ammonia chillers form an important replacement and they are already in use in some regions. In large chillers, there is some use of water as a refrigerant, particularly in Northern Europe, where the water can also be used – in ice slurry form – as the cooling agent in the secondary loop. Use of hydrocarbon refrigerants for chillers is growing from a small base. Estimated consumption and emissions of HFCs are shown in *Table A3.2*.

Continued improvement in emissions reductions is anticipated. In 1994, the annual emission rates from low-pressure CFC chillers were estimated at 7% and for high pressure CFC-12 chillers at 17% (UNEP 1998a); for current new low (HCFC-123) and high pressure chillers the emissions are estimated at less than 2% and 8%, respectively.

A3.2.5 Food Processing, Cold Storage, and Other Industrial Refrigeration Equipment

Owing to their long lifetime, three out of four CFC systems are still in use in cold storage and food processing. The main non-CFC refrigerants used are ammonia, HCFC-22, HFC-134a, HFC blends, and hydrocarbons, with significant regional differences (see Section A3.4).

In the industrial sub-sector all types of refrigerants are used, with HCFCs and ammonia currently representing the majority of the refrigerant volume. Hydrocarbons hold a significant market share in industrial sub-sectors that handle flammable fluids. Since industrial refrigeration does not pose risks to the public, efficient ammonia and hydrocarbon systems are often used. The majority of the larger CFC systems used for cold storage and food processing are still in operation and may keep operating until 2010 to 2015.

Ammonia has traditionally been used in the cold storage sector because of its low cost and high efficiency. It has increased its importance in Europe and Australia. In the USA it is estimated to have a 90% market share in systems of 100kW cooling capacity and above; however, the market share of ammonia in industrial systems is much lower. In the developing countries, ammonia and HCFC-22 are expected to remain the most important alternatives. Unfortunately, many of these systems exhibit low efficiency due to poor system design.

HFC-134a has not been used much since the use of CFC-12 was traditionally small relative to HCFC-22. R-404A and R-507 are currently the most commonly used HFCs in these sub-sectors. However, their efficiencies are low compared to ammonia and HCFC-22 if the equipment is not very well designed. R-410A is well suited for industrial applications, with an insignificant market share at present, but it is estimated to grow significantly during the next decade (UNEP, 1998a). The HFCs are currently used in about 10% of new systems in Europe and in 20% in other developed countries. The demand for HFCs is expected to grow by about 40% between 2000 and 2010. It is expected that recovery and re-use will be cost effective in this sector. Rough estimates are that the emission rates are currently 6% per annum for new HFC systems, and are expected to decrease further over the next decade.

A3.2.6 Transport Refrigeration

Transport refrigeration relates to reefer ships, containers, railcars, and road transport. The majority of reefer ships currently use HCFC-22; the vast majority of new containers are equipped with HFC-134a or R-404A, and also R-410A.

For road transport, new equipment uses HFC-134a, R-404A, and still a considerable amount (estimated 25%) of HCFC-22. Owing to the mechanically and thermally harsh operating envi-

Table A3.5: *Alternative refrigerant options for the specific refrigeration and air conditioning sub-sectors: buildings (domestic and commercial refrigeration, residential and commercial air conditioners, chillers), industry (food processing and cold storage, other industrial processes), transport (transport refrigeration and mobile air conditioning)*

Refrigerant options	HFC-134a	R-404A	HFC blends	HCs	NH_3	Absorption	HCFC	CO_2	H_2O
Domestic refrigeration	*			*					
Comm. refrigeration									
Small (< 5 kW)	*	*	*	*			*		
Other (> 5 kW)		*	*	* S	* S		*	P	
Residential A/C									
Unitary A/C (<20 kW)	*		*	*			*	P	
Commercial A/C									
Unitary A/C (>20 kW)			*	O/S					O
Chillers									
Centrifugal	*			O	*	*	*		O
Industrial									
Food processing	*	*	*	*	*		*		
Cold storage		*	*		*		*	P	
Other industrial	*	*		*	*	*	*		P
Transport refrigeration	*	*	*	*			*	O/P	
Mobile A/C	*			P				P	

Note: (*) indicates current practice, (O) small number installed, (P) prototype installed, (S) includes secondary loop.

ronment, the emissions estimated from transport refrigeration are significant and exceed 25% of the charge annually in many applications. One German manufacturer produces trucks equipped with refrigeration systems using propane.

Although the use of ammonia on ships has a reasonable potential, its proliferation has not been significant. Carbon dioxide has been tested for cooling containers; however, its future market share is difficult to predict and cost indications are lacking.

HFC-134a and, in the near future, R-410A are forecast to be the most important refrigerants for transport refrigeration. It is almost certain that all reefer ships will utilize R-410A. The fraction of equipment using HFCs in the mid-1990s was about 15% (UNEP, 1998a) and that fraction is expected to grow, e.g. one study (Harnisch and Hendriks, 2000) estimates the fraction in Europe to be 70% by 2010 and 100% by 2030.

In the developing countries, the use of HCFC-22 could continue until phase-out is required in 2040, after which HFC-134a or other options developed by then may take over the market.

A3.2.7 Summary of Alternative Refrigerant Use

An overview of the current pattern of refrigerant fluids by sub-sector and technology is provided in *Table A3.5*.

A3.3 Foams

A3.3.1 Insulating Foams

The global market for thermal insulation materials is large, complex, and has substantial regional variation. Since the prime purpose of insulation in addition to energy conservation is to maintain appropriate ambient conditions within a defined space, insulation use is affected most by external climatic conditions. However, in developing countries per-capita use is often lower than local climatic conditions would predict. Increasing insulation use can therefore often go towards improving comfort levels as well as saving energy use and resultant carbon dioxide emissions.

Climatic conditions, space constraints, local building code requirements, and construction costs can all influence the choice of insulation material. In mass markets polymeric foams offer the best insulation performance at higher unit cost. The thermal efficiency of foam is influenced by the choice of blowing agent, and HFCs promise to yield a performance similar to that of previously used HCFCs (UNEP, 1998d).

In Europe, where construction applications dominate, the market for insulation foams, polyurethane, extruded polystyrene, and phenolic resins accounts for about 13% of the total insulation market. Mineral fibres and expanded polystyrene have historically been the dominant materials in terms of volume and mass (roughly 80%), primarily on grounds of lower unit cost. However, performance characteristics are becoming an increasingly important factor in material selection to meet the demands of greater prefabrication.

In North America, the timber frame method of construction has contributed to a more widespread use of polyurethane (PU), polyisocyanurate (PIR), and extruded polystyrene foams. The PU and PIR systems also have better production economics than in Europe because of higher line speeds and less stringent thickness tolerance criteria. In Japan, the market is shaped by strict fire codes and much of the construction is based around concrete. PU spray foams have done particularly well in enclosed spaces and use of phenolic foam is preferred in some exposed applications because of its lower flammability compared to other alternatives. In developing countries, the use of foam for cold storage applications predominates.

Where HFCs are used, they will be emitted during the manufacturing and over the life of the foam (25–50 years). Retention in the foam at end-of-life will generally depend on the thickness of the foam and the facings used.

A3.3.2 Insulating Foams in Appliances

Appliance foams are currently produced with either hydrocarbons or HCFC-141b. Foams produced with HCFC-141b generally provide 5%-15% more insulation per unit of thickness than those produced with other blowing agents. HFCs (primarily "liquid" HFCs such as HFC-245fa and HFC-365mfc) are anticipated to partly replace HCFCs because they produce foams with similar insulating properties. The contribution of the foam to the overall energy efficiency of the appliance is important since the energy used to operate the appliance accounts for the majority of the global warming impacts in most cases.

Where HFCs are selected, options to reduce emissions include the use of formulations that minimize the amount and GWP of the blowing agent used, and the end-life destruction of the HFC. The latter is particularly important, since it is technically possible to recover and destroy over 90% of the HFC blowing agent at an estimated cost-effectiveness of between US$30 and US$100/tC_{eq} (AFEAS, 2000).

A recent study for the European Commission (Harnisch and Hendriks, 2000) estimates that in Europe about 70% of all polyurethane foams for appliances will be blown with hydrocarbons and about 30% with HFCs by 2010. HFCs are more likely to be selected where more stringent energy standards exist. In contrast, the investment related to the introduction of a new blowing agent might play a determining role in developing countries. However, in practice, this effect has been broadly offset by the supporting activities of the multilateral fund. Significant concern about hydrocarbon use exists in North America and Japan, related to product liability and process safety costs.

Vacuum panels may partly replace insulation foam in the future but the cost-effectiveness of this option is uncertain. A few domestic and commercial applications already use vacuum insulation panels in combination with polyurethane foams. These systems have up to 20% lower energy consumption than those using CFC or HCFC blown foam insulation systems (UNEP, 1998d).

A3.3.3 Insulating Foams in Residential Buildings

The use of HFC blown foams in the residential sector is expected to be relatively limited because of the high cost-sensitivity of this market. However, it is preferable to base the choice of insulation for all buildings on a proper consideration of the LCCP, including the comparative energy saving impacts of alternative insulation materials, the potential emissions of blowing agents, and the embodied energies of the insulating materials themselves. Where HFCs are used, the cost to destroy the HFC will be determined primarily by the cost of separating the construction materials. There are trends towards prefabricated construction and requirements for recycling of building materials in some regions that could lower these costs in time. Emissions of HFCs partially offset the benefits of low energy consumption arising from their use.

The use of hydrocarbon and carbon dioxide as blowing agents for polyurethane and extruded polystyrene insulation foams is expanding. A recent European study (Harnisch and Hendriks, 2000) estimated that by 2010 about 50% of all polyurethane and extruded polystyrene foams in this sector will be blown by hydrocarbons and carbon dioxide, respectively. It is estimated that substituting the remaining HFCs by hydrocarbon use in the mass markets of polyurethane foam production would cost between US$90 and US$125/tC_{eq}. There is some concern about the use of flammable hydrocarbons in the residential environment and indoor air quality could also be affected. The replacement of HFCs by CO_2/water blown polyurethane spray systems is estimated to be available at a cost-effectiveness of about US$80/t$C_{eq}$ (Harnisch and Hendriks, 2000). In Europe, one major producer is converting its extruded polystyrene production lines to use CO_2 as the blowing agent. The cost-effectiveness of the use of CO_2 as the blowing agent for extruded polystyrene is estimated at US$40/t$C_{eq}$ (March, 1998) and at US$25/t$C_{eq}$ (Harnisch and Hendriks, 2000) for the remaining manufacturers in Europe.

Fibrous insulation materials and expanded polystyrene are used extensively for residential construction in most parts of the world. The increased thickness required to achieve a desired energy efficiency can cost more; however, builders have been willing to increase the cavity wall size substantially since the 1970s to comply with increasing insulation standards in some regions.

A3.3.4 Insulating Foams in Commercial Buildings

For commercial buildings, the choice of foam type and facings is more likely to be based on lifetime costs (performance related) than on initial cost. An additional factor is the increased use of prefabricated building techniques, particularly in Europe. Both aspects suggest that HFC blown foams could penetrate the commercial and industrial sectors to a greater extent than the residential sector previously discussed. Harnisch and Hendriks (2000) estimate that avoiding HFCs in most mass applications by switching to hydrocarbon systems would cost in the region of US\$90 to US\$125/tC$_{eq}$. For the switch from HFC to CO_2 use in extruded polystyrene, one study estimates US\$40/tC$_{eq}$ (March, 1998), whilst another (Harnisch and Hendriks, 2000) estimates US\$25/tC$_{eq}$ for the remaining European manufacturers.

Fibrous insulation materials and expanded polystyrene are used extensively for commercial construction and are expected to play a significant role in the future. However, whether this role will expand technically seems in doubt.

A3.3.5 Insulating Foams in Transportation

Hydrocarbon blown foams and vacuum insulation panels are alternative options. Hydrocarbon blown foams have a somewhat lower insulating value per unit of thickness than HFC blown foams, and the vacuum insulating panels currently cost substantially more. Insulating performance is crucial in this sub-sector and serious thickness constraints exist, limiting the available options.

A3.3.6 Other Insulating Foams

Another application of HFCs for insulating foams will be in industrial process applications, where an estimated 2500 tonnes will be used – primarily in process pipework. Owing to high foam densities in this sector the differences in insulation performance between different blowing agents are small. For Europe it is estimated (Harnisch and Hendriks, 2000) that in 2010 hydrocarbons will have a market share of 50% of the pipe insulation production.

Both the building industry and the do-it-yourself market use one-component foams in a variety of applications, including sound and thermal insulation applications. The thermal conductivity of the foam, however, is not a critical requirement. HFC-134a and HFC-152a, hydrocarbons, propane, butane, and dimethyl ether (DME) are all technically suitable and in use. These are frequently used in blends; for example, a blend of HFC-134a/DME/propane/butane is widely used in Europe (UNEP, 1998d). Some replacement of HFC use in this sector is likely although concerns over the flammability of mixtures may delay this process in some regions.

A3.3.7 Non-Insulating Foams

Non-insulation HFC blown foams are expected to be used only in those applications where product or process safety are paramount, for example, integral skin foams for safety applications. Harnisch and Hendriks (2000) project that HFCs will not be required for the production of non-insulation foams in Europe. However, in view of different product specifications elsewhere in the world, liquid HFCs could replace a significant part of the current small use of HCFCs.

A3.4 Solvents and Cleaning Agents

Less than 3% of projected demand for CFCs solvents has been replaced by HFCs and PFCs (McFarland, 1999).The high cost of fluorocarbons, regulatory prohibitions on HFC and hydrofluoroethers and hydrofluoroesters (HFE) solvents, and investment in emission reduction measures are expected to maintain carbon equivalent use and emissions in 2010 to current baseline levels. Annual PFC solvent emissions are estimated at 3,000–4,000 tonnes (UNEP, 1999b; Harnisch *et al*., 1999) and HFC emissions are estimated to be 1,000–2,000 tonnes (UNEP, 1999b). These values convert to less than 7.5MtC$_{eq}$ for PFCs and less than 1 MtC$_{eq}$ for HFCs.

Perfluorocarbons (PFCs such as C_5F_{12}, C_6F_{14}, C_7F_{16}, and C_8F_{18}) were introduced in the early 1990s as substitutes for ozone-depleting CFC-113 solvents and are also used in some applications where ODS solvents were never used. HFC-43-10mee and its azeotropic blends with alcohol, hydrochlorocarbons, and hydrocarbons were introduced in the mid-1990s to replace CFC-113 and PFCs. HFE solvents became commercially available in the late 1990s to replace PFCs, CFCs, HCFCs, and HFCs.

HFCs and HFEs are used in specialized cleaning of delicate materials, oxygen systems, and precision parts; as a flush fluid for particulate removal in precision cleaning; as a rinsing agent in a co-solvent process for cleaning printed circuit boards and mechanical components; and to dry electronics and precision parts after aqueous or semi-aqueous processing. In some circumstances, HFC drying may have a lower LCCP than thermal drying. HFCs and HFEs are also replacing PFCs and CFC-113 as carrier fluids for specialized fluorocarbon lubricants, as dielectric and heat transfer fluids, in developing latent fingerprints off porous surfaces, in rain repellent sprays for aircraft windshields, and in other applications demanding unique solvency properties (UNEP, 1998e, 1999b).

The four emission reduction options are: (1) changing production processes and product designs to avoid the need for fluorocarbon solvents (e.g., "no-clean" soldering and aqueous cleaning); (2) switching to lower GWP fluorocarbon or non-fluorocarbon solvents; (3) reducing emissions through process improvements (UNEP, 1999b); and (4) utilizing solvent recovery and recycling where possible. Progress is being made in each of these options.

One source estimates that process improvements could reduce fluorocarbon solvent emissions in the European Union by 20% by 2010 at a cost effectiveness of about US\$160/tC_{eq} and that an 80% reduction could be achieved at about US\$330/tC_{eq} (March, 1998).

A3.5 Aerosol Products

A3.5.1 Medical Applications

Metered dose inhalers (MDIs) form a reliable and effective therapy for asthma and chronic obstructive pulmonary disease (COPD).

There are estimated to be 300 million patients with asthma and COPD worldwide. Approximately 450-500 million MDIs are used annually worldwide with asthma prevalence increasing as urbanization of developing countries continues. It is estimated that 10,000 metric tons (tonnes) of CFC and 1000 tonnes of HFCs were used in MDIs worldwide in 1998 (UNEP, 1998b, 1999b). HFC-based MDIs are essential for the near-term CFC phaseout, because other available options, including dry powder inhalers (DPIs) (single or multi-dose), nebulizers (hand held or stationary), orally administered drugs (tablets, capsules, or oral liquids), and injectable drugs, which are alternatives for not using CFCs or HFCs, cannot currently replace CFC products for all patients (UNEP, 1999b). The transition to HFC MDIs began in 1995, and approximately 5% in 1998 and 10% in 1999 contain HFC (UNEP, 1999b). HFC-based MDIs and DPIs are expected to help minimize the use of CFCs by 2005 in developed countries, while providing essential medication for patients. Important factors in the conversion to DPIs will include their acceptance by doctors, patients, insurance companies, and medical authorities.

Assuming the complete phase-out of CFC MDIs and a continued growth rate in demand for asthma and COPD treatment of 1.5%–3.0%/yr, it is estimated that HFC consumption and emissions will be 7,500 to 9,000/yr – about 3–3.6MtC_{eq} in 2010 (UNEP, 1999b).

DPIs have been formulated successfully for many anti-asthma drugs. Dry powder inhalers are an immediately available alternative free of CFCs and HFCs; however, they are not a satisfactory alternative to the pressurized MDIs for some patients with very low inspiratory flow (e.g., some small children and elderly people, patients) with acute asthma attacks or with severe respiratory diseases, and emergency-room patients. Use is likely to accelerate, particularly as they may be more suitable for young children than the older DPIs (UNEP, 1999b). In Scandinavian countries, government policies have led to greater use of DPIs than of MDIs (IPCC/TEAP, 1999; UNEP, 1999b; March, 1998).

The abatement cost estimates to reduce future HFC emissions by replacing MDIs with DPIs depend on the price of DPIs. The cost per equivalent dose varies between products and countries, with some CFC-free MDIs being more expensive than CFC-based MDIs and some DPIs more expensive than both CFC- and HFC-based MDIs (ARCF, 2000). In Europe, prices are less as much as US\$4 higher for a DPI than for a comparable MDI (Harnisch and Hendriks, 2000). It is estimated that, by 2010, the EU can reduce HFC emissions by 30% at a cost of about US\$460/tC_{eq} and 50% at about US\$490/tC_{eq} (March, 1998), which translates to a differential cost of US\$4 over MDIs; for one country in Europe there is no differential cost (Harnisch and Hendriks, 2000). It is not currently medically feasible to replace MDIs by DPIs completely because approximately 25% of MDI use is for patients who require medication be forced into their respiratory system (Öko-Recherche, 1999).

A3.5.2 Cosmetic, Convenience, and Technical Aerosol Propellants

Global 1998 consumption and emissions of HFCs in non-medical aerosol products was less than 15,000 tonnes (UNEP, 1998d) with two-thirds HFC-134a and one-third HFC-152a – less than 4MtC_{eq}. Emissions of HFCs are projected to not exceed 20,000 tonnes in 2010 (IPCC/TEAP, 1999) or about 5MtC_{eq} (calculated assuming equal emissions of HFC-134a and HFC-152a). HFCs have replaced only about 2% of the aerosol product market that would have used CFCs had there not been the Montreal Protocol (McFarland, 1999). Hydrocarbon, dimethyl ether (DME), carbon dioxide, nitrogen propellants, and not-in-kind alternative products have replaced the remaining 98% of projected demand.

HFCs are used in aerosol products primarily to comply with technical requirements or environmental regulations. HFC-134a is the propellant of choice for products that must be completely non-flammable. An example of HFC use based on a technical requirement is non-flammable, far-reaching insecticide products used on high-voltage power lines and transformers where workers cannot escape from wasps and hornets. HFC-152a is the propellant of choice to replace hydrocarbon aerosol propellants restricted in Southern California and in some applications where hydrocarbons and dimethyl ether are too flammable but the flammability of HFC-152a is acceptable. HFC-134a and HFC-152a are the propellants of choice for laboratory, analytical, and experimental uses where chemical properties are important and flammability may be a concern.

One source estimates that about 45% of HFC emissions from cosmetic and convenience applications where flammability is an issue could be eliminated at a cost of US\$70/tC_{eq} and about 70% could be eliminated at a cost of about US\$130/tC_{eq} (March, 1998).

The aerosol product industry has every incentive to minimize HFC use. HFCs cost more than other propellants and unnecessary HFC use has the potential to re-ignite consumer boycotts like the CFC boycotts in the early 1970s that led to national bans on certain cosmetic products. Boycotts could threaten sales of all aerosol products because consumers may not be able to distinguish targetted HFC products from acceptable hydrocarbon products (UNEP, 1999b).

A "self-chilling beverage can" was designed to achieve refrigeration through the physics of expanding and emitting approximately 35–75g of HFC-134a directly to the atmosphere for every beverage can chilled. The inventing company pledged not to manufacture or license the technology and to discourage its use, the US government banned the use of HFCs in self-chilling beverage cans (US Federal Register, 1999), and a number of HFC producers have stated publicly that they will not supply such an application. However, self-chilling cans using HFC-134a are marketed in at least one country and it is estimated that even a small market penetration could substantially increase emissions of greenhouse gases (US Federal Register, 1999).

The UNEP/TEAP HFC and PFC Task Force (UNEP, 1999b) developed principles to guide the use of HFCs for aerosol products:

- recommend HFCs be used only in applications where they provide technical, safety, energy, or environmental advantage that are not achieved by not-in-kind alternatives; and
- select the HFC compound with the smallest GWP that still meets the application requirements.

Application of these principles justifies the use of HFCs for some products in some circumstances but these "responsible use" criteria are not satisfied when not-in-kind alternatives are technically and economically suitable. The above-mentioned study (UNEP, 1999b) includes detailed evaluation of alternatives and substitutes for aerosol safety products (insecticides, boat horns, noise-makers), cosmetic products (deodorants, hair sprays, shaving creams), convenience products (room fresheners, dust blowers, tyre inflators, foam caulk, and insulation), and novelty products (foam party streamers, pneumatic pellet and bait guns).

A3.6 Fire Protection

A range of alternatives to halon with no or low GWP, such as water-based technologies, dry powders, inert gases, and carbon dioxide, have displaced about 75% of previous halon use in countries classified as developed under the Montreal Protocol. About 5% of the existing and new halon applications are considered critical, with no technically or economically feasible alternatives. These critical uses include military vehicles, civil and military aircraft, and other high-risk explosion scenarios involving unacceptable threat to humans, the environment, or national security. Recovered and recycled halon is being used to meet these needs (IPCC/TEAP, 1999).

Relatively small, but important, quantities of HFCs and PFCs are being used as substitutes for halon in fire protection. About 20% of the systems that would have used halons in the absence of the Montreal Protocol currently use HFCs and only about 1% use PFCs (UNEP, 1998c, 1999b).

Growth in HFC use is limited by high cost compared to other choices. PFCs are not technically necessary as halon replacements except in rare and special circumstances (UNEP, 1999b). However, relatively strong growth of HFC/PFC use in developing countries and countries with economies in transition is being driven by aggressive marketing, and is producing a new dependency that could lead to a rapidly growing market in applications where other alternatives are available. Awareness campaigns involving fire protection experts and their customers could help limit uses that are not technically justified (UNEP, 1999b).

The Montreal Protocol prompted various improvements in the management of halons and their replacements, resulting in a fourfold decrease in annual emissions. Testing and training with halon and HFC was eliminated and the unintended discharges of systems were greatly reduced through intensified maintenance and operational improvements. With only 20% of new fire protection systems using HFCs and with the fourfold decrease in emissions, HFC emissions are 5% compared to those from halon systems before the Montreal Protocol (UNEP, 1999b; McFarland, 1999).

Emissions of HFC from the installed bank of fire protection equipment, including necessary emissions to suppress fires, are estimated to be about 4%–6% per year (UNEP, 1999b). These emissions could be reduced by up to 50% through continued improvements to eliminate unnecessary discharges and by increased recycling of the HFCs (IPCC/TEAP, 1999). There are no estimates of the cost-effectiveness of such measures.

A3.7 Developing Countries and Countries with Economies in Transition

Developing countries have until 2010 to phase out CFCs, whereas some countries with economies in transition (EIT) have largely met the more stringent schedules of the developed countries. However, both country groups are concerned that any potential future restrictions on the use of HFCs in the developed countries might reduce the availability of these substances to developing countries and EITs. This could limit the possibilities for them to comply with their Montreal

Protocol obligations. Possible impacts are anticipated in the refrigeration, air conditioning, and foam sectors. It will be clear that the availability of HFC supplies to those developing countries and EITs that have selected HFC technologies is essential for manufacturing if supplies and service to customers are to be maintained.

It will be advantageous for both developing countries and countries with economies in transition if they develop and prioritize consistent strategies that simultaneously address the protection of the ozone layer and the mitigation of climate change. Such strategies utilized to date include emission reductions, the selection of zero ODP and low GWP solutions wherever possible, as well as the optimization of the energy efficiency of products in conversion projects by the Multilateral Fund (MLF) and the Global Environment Facility (GEF). The mechanisms that have guided developing countries towards a successful implementation of the Montreal Protocol should be studied within the framework of mechanisms that are being negotiated for the Kyoto Protocol. It can be emphasized here that capacity building is seen as at least as important for the implementation of the Kyoto Protocol as it is for the Montreal Protocol.

A3.7.1 Technology Selection

Certain non-ODP substitutes and alternative technologies to CFCs and HCFCs have become available in recent years for many applications. The selection of the substitute or alternative technology is based on a balance of maturity, availability, cost-effectiveness, energy-efficiency, safety, and safety costs. The selection is also influenced by local circumstances, preferences of enterprises, accessibility and cost-effectiveness of certain technologies, joint venture partners and customers, availability of training, and regulatory compliance. This implies that developing countries need access to the newest information and need to be part of an adequate technical review process so that they can assess the choice of the most appropriate and integrated environmental solutions. In addition, those developing countries that receive financial assistance from the MLF for the conversion process and select HCFC-based technologies must submit a thorough justification as to why these are preferred. This is because the countries have to take into account the decisions by the Montreal Protocol Parties that state that certain fluorocarbon-based technologies should be avoided if more environmentally friendly and acceptable technologies are available, as well as the guidelines developed by the MLF Executive Committee for the implementation of these technologies.

A3.7.2 Impact of Replacement Technology Options in Montreal Protocol MLF Projects

HCFC- and HFC-based technologies have not been significant alternative choices in the phase-out of ODSs in aerosols and in solvent applications, or in the fire extinguishing sector. However, HCFCs and HFCs have been selected as significant alternatives to ODSs in the foam, refrigeration, and air conditioning sectors. *Table A3.6* shows the quantities of controlled substances (CFCs) that have been (or are in the process of being) phased out in developing countries through projects approved under the Montreal Protocol's multilateral fund (to date, over US$1 billion has been used to support these phase-out activities). *Table A3.6* also shows the replacement technology selected in the different refrigeration and foam sectors and sub-sectors. *Table A3.6* presents data for projects, approved by the Executive Committee of the MLF and listed under the Inventory of Approved Projects of the MLF Secretariat as of March 1999, see UNEP (1999b).

A3.7.2.1 Foams Sector

The present contribution of HFCs as a direct replacement technology for ODSs in projects approved under the MLF in the foam sector is much less than 1% of the total tonnage of ODS replaced in this sector. *Table A3.6* presents the breakdown of ODS replaced in each of the foam sub-sectors. The contribution of hydrocarbons is significant. The overall contribution of zero-ODP and low-GWP technologies selected to replace ODSs is close to 27,000 ODP tonnes or about 75% (see *Table A3.6*).

Wherever application of zero-ODP technologies was not feasible because of availability, safety, and safety-related costs, or for energy-efficiency reasons, HCFCs (HCFC-22, -141b, and -142b) have been selected as a transitional replacement in all foam sub-sectors. In the medium term HCFCs are expected to be replaced by zero-ODP and low-GWP substitutes, such as water, carbon dioxide or hydrocarbons, except in certain parts of the rigid polyurethane foam sub-sector where HFC alternatives are expected to play an important role in the medium to long term. *Table A3.6* also presents the HCFC contribution; it amounts to about 25% of the total tonnage of ODSs replaced.

While several mid-size and large domestic and commercial refrigeration companies have switched to hydrocarbons in the rigid foam sector, most small and medium-sized enterprises (SMEs) in the developing countries have had more difficulties in this selection of hydrocarbons because of safety concerns and related higher manufacturing costs. Next to large companies, many of these SMEs have selected HCFC-141b as a transitional substance. All these companies will have to switch to the use of other, non-ODP substances when HCFC availability cannot be guaranteed or HCFCs will be phased out according to Montreal Protocol schedules. It is expected that a large part of this SME sector will convert to HFC alternatives in the medium to long term. With regard to HCFCs, questions on HCFC availability after 2003 are of serious concern to developing countries; these will be evaluated by the Technology and Economic Assessment Panel, at the request of the Parties to the Montreal Protocol. With regard to HFCs, it should be mentioned that enterprises are uncertain whether their businesses

Table A3.6: Replacement technology options in multilateral Fund-approved projects in developing countries (UNEP, 1999b)

Use sector (# projects)	ODS	Impact (ODP t)	ODP tonnes to be eliminated according to technology selected							
			HCFC		HFC		Hydrocarbons		Other	
			Type	(t)	Type	(t)	Type	(t)	Type	(t)
1-Refrigeration										
a-Domestic (168)										
Foam	CFC-11	16,589	HCFC-141b	4,379		0	Cyclopentane	12,188		0
Refrigerant	CFC-12	5,241		0	HFC-134a/152a/blends	4,553	Isobutane	688		0
b-Commercial (161)										
Foam	CFC-11	2,432	HCFC-141b	1,648		0	Cyclopentane	784		0
Refrig (plus chillers)	CFC-12	1,136	HCFC-22	4	HFC-134a	1,132		0		0
	R-502	1	HCFC-22	1						
c-Insulation foam (34)	CFC-11	1,998	HCFC-141b/blends	636		0	Cyclopentane	849	H_2O/CO_2	513
	CFC-12	8	HCFC-141b	8		0		0		0
2-Foam										
a-Flexible molded (12)	CFC-11	450	HCFC-141b	66		0		0	H_2O/CO_2/Me-Cl	384
b-Flexible slabstock (159)	CFC-11	11,934	HCFC-141b	35		0		0	H_2O/CO_2/Me-Cl	11,899
c-Integral skin (84)	CFC-11	2,573	HCFC-141b	597		0	Hexane/pentane	345	H_2O/CO_2	1,631
d-Polystyr./polyethyl. (63)	CFC-11	1,204		0		0	Butane/ isobutane/ LPG/ Pentane / isopentane	980	CO_2/CO_2-butane blend	224
	CFC-12	6,280	HCFC-22/-142b	196		0	Butane/LPG/pentane	6,084		0
	CFC-114	40		0		0	LPG	40		0
e-Rigid foam (238)	CFC-11	10,938	HCFC-141b/-22/-142b	7,144	HFC-134a	58	Cyclopentane	3,003	H_2O/CO_2	733
f-Multiple sub-sector (30)	CFC-11	1,829	HCFC-141b	556		0	Butane	200	H_2O/ CO_2/ Me-Cl/ LCD	1,073

Note: Data have been reproduced from the data presented in UNEP (1999b) which were directly taken from the internal report "Inventory of Approved Projects", as published by the Multilateral Fund Secretariat, Montreal, March 1999.

will be impacted if, in the near future, certain developed countries decide to put certain (national) restrictions on the use of HFCs, influencing their availability for the developing countries.

A3.7.2.2 Refrigeration Sector

There are only a limited number of options to replace ODSs in this sector. HCFCs have been selected as an interim replacement technology for ODSs, where non-ODP alternatives could not be applied, and their share represents about 24% of the total tonnage of ODSs replaced in the sector as a whole (see *Table A3.6*).

In refrigeration products the foam considered is exclusively rigid polyurethane foam. As a direct replacement for ODS blowing agents in the foam, the contribution of HFCs is negligible in the projects approved by the Multilateral Fund. In contrast to this very small contribution, hydrocarbons have accounted for 53% of the total ODS replacement in the sector, which includes both the refrigeration and the foam part; their share is about 66% in the replacement of ODS foam blowing agents. In these projects, zero-ODP and low-GWP alternatives could meet the requirements on availability, safety and safety related costs, and the stringent energy efficiency.

As shown in *Table A3.6*, the contribution of HFC-based technology as a direct refrigerant replacement technology is close to 21% of the total ODS replacement in the sector, if both the refrigeration and the insulating foam part are included. Where it concerns the refrigeration part, for both domestic and commercial refrigeration, HFCs constitute about 89% of the refrigerant replacement. The conversion of refrigeration components and the refrigeration manufacturing plants is to a large extent determined by market availability and by market forces (compressor suppliers); of course, there is also a direct relation to manufacturing and safety costs.

A3.7.3 General Concerns and Opportunities

For the developing countries, financial assistance is available for agreed incremental costs associated with the ODS phase-out through the multilateral fund under the Montreal Protocol. Likewise, financial assistance from the GEF is available for countries with economies in transition. GEF financing is currently available to improve energy efficiency and other reductions of greenhouse gas emissions. The Clean Development Mechanism (CDM), guidelines of which are still being negotiated within the Kyoto Protocol framework, might also provide opportunities to reduce HFC emissions.

Further opportunities exist in those parts of the refrigeration and air conditioning sector in which large emissions of HFCs occur, and for equipment that will need thorough maintenance; this particularly applies to mobile air conditioning, commercial, and transport refrigeration. Where emission reductions are possible, best-practices training is needed (UNDP *et al*., 1999).

Under the Multilateral Fund, enterprises are eligible for financial assistance for only one conversion. This makes it crucial for an enterprise to choose a technology that is cost effective, environmentally acceptable, and globally sustainable. It is very important that developing countries and countries with economies in transition examine opportunities for consistent strategies to simultaneously protect the ozone layer and to mitigate climate change. Such opportunities, *inter alia*, may be in the field of emission reductions, the direct transition to non-fluorocarbon low GWP alternatives where possible, as well as in the field of enhancing energy efficiencies. It would be advantageous if assistance given by the multilateral fund could be expanded to extra assistance from the GEF in terms of addressing the energy efficiency optimization aspect.

To date, when funds were available, manufacturers in the developing countries have responded rapidly to the goals of the Montreal Protocol, and to regulations in the developed countries that prohibited import of products made with or containing ODSs. Uncertainties regarding the availability of HCFCs and regarding the impact of possible restrictions on the use of HFCs in certain developed countries may delay the implementation of the Montreal Protocol in EITs and developing countries; this aspect can be considered as an interlinkage between the Montreal and Kyoto Protocols and it is the subject of further study.

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