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Sources of CO_2

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EXECUTIVE SUMMARY

Assessing CO_2 capture and storage calls for a comprehensive delineation of CO_2 sources. The attractiveness of a particular CO_2 source for capture depends on its volume, concentration and partial pressure, integrated system aspects, and its proximity to a suitable reservoir. Emissions of CO_2 arise from a number of sources, mainly fossil fuel combustion in the power generation, industrial, residential and transport sectors. In the power generation and industrial sectors, many sources have large emission volumes that make them amenable to the addition of CO_2 capture technology. Large numbers of small point sources and, in the case of transport, mobile sources characterize the other sectors, making them less amenable for capture at present. Technological changes in the production and nature of transport fuels, however, may eventually allow the capture of CO_2 from energy use in this sector.

Over 7,500 large CO_2 emission sources (above 0.1 $MtCO_2$ yr^{-1}) have been identified. These sources are distributed geographically around the world but four clusters of emissions can be observed: in North America (the Midwest and the eastern freeboard of the USA), North West Europe, South East Asia (eastern coast) and Southern Asia (the Indian sub-continent). Projections for the future (up to 2050) indicate that the number of emission sources from the power and industry sectors is likely to increase, predominantly in Southern and South East Asia, while the number of emission sources suitable for capture and storage in regions like Europe may decrease slightly.

Comparing the geographical distribution of the emission sources with geological storage opportunities, it can be seen that there is a good match between sources and opportunities. A substantial proportion of the emission sources are either on top of, or within 300 km from, a site with potential for geological storage. Detailed studies are, however, needed to confirm the suitability of such sites for CO_2 storage. In the case of ocean storage, related research suggests that only a small proportion of large emission sources will be close to potential ocean storage sites.

The majority of the emissions sources have concentrations of CO_2 that are typically lower than 15%. However, a small proportion (less than 2%) have concentrations that exceed 95%, making them more suitable for CO_2 capture. The high-content sources open up the possibility of lower capture costs compared to low-content sources because only dehydration and compression are required. The future proportion of high- and low-content CO_2 sources will largely depend on the rate of introduction of hydrogen, biofuels, and the gasification or liquefaction of fossil fuels, as well as future developments in plant sizes.

Technological changes, such as the centralized production of liquid or gaseous energy carriers (e.g., methanol, ethanol or hydrogen) from fossil sources or the centralized production of those energy carriers or electricity from biomass, may allow for CO_2 capture and storage. Under these conditions, power generation and industrial emission sources would largely remain unaffected but CO_2 emissions from transport and distributed energy-supply systems would be replaced by additional point sources that would be amenable to capture. The CO_2 could then be stored either in geological formations or in the oceans. Given the scarcity of data, it is not possible to project the likely numbers of such additional point sources, or their geographical distribution, with confidence (estimates range from 0 to 1,400 $GtCO_2$ (0–380 GtC) for 2050).

According to six illustrative SRES scenarios, global CO_2 emissions could range from 29.3 to 44.2 $GtCO_2$ (8–12 GtC) in 2020 and from 22.5 to 83.7 $GtCO_2$ (6–23 GtC) in 2050. The technical potential of CO_2 capture associated with these emission ranges has been estimated recently at 2.6–4.9 $GtCO_2$ for 2020 (0.7–1.3 GtC) and 4.9–37.5 $GtCO_2$ for 2050 (1.3–10 GtC). These emission and capture ranges reflect the inherent uncertainties of scenario and modelling analyses. However, there is one trend common to all of the six illustrative SRES scenarios: the general increase of future CO_2 emissions in the developing countries relative to the industrialized countries.

2.1 Sources of CO_2

This chapter aims to consider the emission sources of CO_2 and their suitability for capture and subsequent storage, both now and in the future. In addition, it will look at alternative energy carriers for fossil fuels and at how the future development of this technology might affect the global emission sources of CO_2 and the prospects for capturing these emissions.

Chapter 1 showed that the power and industry sectors combined dominate current global CO_2 emissions, accounting for about 60% of total CO_2 emissions (see Section 1.2.2). Future projections indicate that the share of these sectoral emissions will decline to around 50% of global CO_2 emissions by 2050 (IEA, 2002). The CO_2 emissions in these sectors are generated by boilers and furnaces burning fossil fuels and are typically emitted from large exhaust stacks. These stacks can be described as large stationary sources, to distinguish them from mobile sources such as those in the transport sector and from smaller stationary sources such as small heating boilers used in the residential sector. The large stationary sources represent potential opportunities for the addition of CO_2 capture plants. The volumes produced from these sources are usually large and the plants can be equipped with a capture plant to produce a source of high-purity CO_2 for subsequent storage. Of course, not all power generation and industrial sites produce their emissions from a single point source. At large industrial complexes like refineries there will be multiple exhaust stacks, which present an additional technical challenge in terms of integrating an exhaust-gas gathering system in an already congested complex, undoubtedly adding to capture costs (Simmonds *et al.*, 2003).

Coal is currently the dominant fuel in the power sector, accounting for 38% of electricity generated in 2000, with hydro power accounting for 17.5%, natural gas for 17.3%, nuclear for 16.8%, oil for 9%, and non-hydro renewables for 1.6%. Coal is projected to remain the dominant fuel for power generation in 2020 (about 36%), whilst natural-gas generation will become the second largest source, surpassing hydro. The use of biomass as a fuel in the power sector is currently limited. Fuel selection in the industrial sector is largely sector-specific. For example, the use of blast furnaces dominates primary steel production in the iron and steel sector, which primarily uses coal and coke (IEA GHG, 2000b; IPCC, 2001). In the refining and chemical sectors, oil and gas are the primary fuels. For industries like cement manufacture, all fossil fuels are used, with coal dominating in areas like the USA, China and India (IEA GHG, 1999), and oil and gas in countries like Mexico (Sheinbaum and Ozawa, 1998). However, the current trend in European cement manufacture is to use non-fossil fuels: these consist principally of wastes like tyres, sewage sludge and chemical-waste mixtures (IEA GHG, 1999). In global terms, biomass is not usually a significant fuel source in the large manufacturing industries. However, in certain regions of the world, like Scandinavia and Brazil, it is acknowledged that biomass use can be significant (Möllersten *et al*., 2003).

To reduce the CO_2 emissions from the power and industry sectors through the use of CO_2 capture and storage, it is important to understand where these emissions arise and what their geographical relationship is with respect to potential storage opportunities (Gale, 2002). If there is a good geographical relationship between the large stationary emission sources and potential geological storage sites then it is possible that a significant proportion of the emissions from these sources can be reduced using CO_2 capture and storage. If, however, they are not well matched geographically, then there will be implications for the length and size of the transmission infrastructure that is required, and this could impact significantly on the cost of CO_2 capture and storage, and on the potential to achieve deep reductions in global CO_2 emissions. It may be the case that there are regions of the world that have greater potential for the application of CO_2 capture and storage than others given their source/storage opportunity relationship. Understanding the regional differences will be an important factor in assessing how much of an impact CO_2 capture and storage can have on global emissions reduction and which of the portfolio of mitigation options is most important in a regional context.

Other sectors of the economy, such as the residential and transport sectors, contribute around 30% of global CO_2 emissions and also produce a large number of point source emissions. However, the emission volumes from the individual sources in these sectors tend to be small in comparison to those from the power and industry sectors and are much more widely distributed, or even mobile rather than stationary. It is currently not considered to be technically possible to capture emissions from these other small stationary sources, because there are still substantial technical and economic issues that need to be resolved (IPCC, 2001). However, in the future, the use of low-carbon energy carriers, such as electricity or hydrogen produced from fossil fuels, may allow CO_2 emissions to be captured from the residential and transport sectors as well. Such fuels would most probably be produced in large centralized plants and would be accompanied by capture and storage of the CO_2 co-product. The distributed fuels could then be used for distributed generation in either heaters or fuels cells and in vehicles in the transport sector. In this scenario, power generation and industrial sources would be unaffected but additional point sources would be generated that would also require storage. In the medium to long term therefore, the development and commercial deployment of such technology, combined with an accelerated shift to low- or zero-carbon fuels in the transport sector, could lead to a significant change in the geographical pattern of CO_2 emissions compared to that currently observed.

2.2 Characterization of CO_2 emission sources

This section presents information on the characteristics of the CO_2 emission sources. It is considered necessary to review the different CO_2 contents and volumes of CO_2 from these sources as these factors can influence the technical suitability of these emissions for storage, and the costs of capture and storage.

2.2.1 Present

2.2.1.1 Source types

The emission sources considered in this chapter include all large stationary sources (>0.1 $MtCO_2\ yr^{-1}$) involving fossil fuel and biomass use. These sources are present in three main areas: fuel combustion activities, industrial processes and natural-gas processing. The largest CO_2 emissions by far result from the oxidation of carbon when fossil fuels are burned. These emissions are associated with fossil fuel combustion in power plants, oil refineries and large industrial facilities.

For the purposes of this report, large stationary sources are considered to be those emitting over 0.1 $MtCO_2\ yr^{-1}$. This threshold was selected because the sources emitting less than 0.1 $MtCO_2\ yr^{-1}$ together account for less than 1% of the emissions from all the stationary sources under consideration (see Table 2.1). However, this threshold does not exclude emissions capture at smaller CO_2 sources, even though this is more costly and technically challenging.

Carbon dioxide not related to combustion is emitted from a variety of industrial production processes which transform materials chemically, physically or biologically. Such processes include:

- the use of fuels as feedstocks in petrochemical processes (Chauvel and Lefebvre, 1989; Christensen and Primdahl, 1994);
- the use of carbon as a reducing agent in the commercial production of metals from ores (IEA GHG, 2000; IPCC, 2001);
- the thermal decomposition (calcination) of limestone and dolomite in cement or lime production (IEA GHG, 1999, IPCC 2001);
- the fermentation of biomass (e.g., to convert sugar to alcohol).

In some instances these industrial-process emissions are produced in combination with fuel combustion emissions, a typical example being aluminium production (IEA GHG, 2000).

Table 2.1 Properties of candidate gas streams that can be inputted to a capture process (Sources: Campbell et al., 2000; Gielen and Moriguchi, 2003; Foster Wheeler, 1998; IEA GHG, 1999; IEA GHG, 2002a).

Source	CO_2 concentration % vol (dry)	Pressure of gas stream MPa[a]	CO_2 partial pressure MPa
CO_2 from fuel combustion			
• Power station flue gas:			
Natural gas fired boilers	7 - 10	0.1	0.007 - 0.010
Gas turbines	3 - 4	0.1	0.003 - 0.004
Oil fired boilers	11 - 13	0.1	0.011 - 0.013
Coal fired boilers	12 - 14	0.1	0.012 - 0.014
IGCC[b]: after combustion	12 - 14	0.1	0.012 - 0.014
• Oil refinery and petrochemical plant fired heaters	8	0.1	0.008
CO_2 from chemical transformations + fuel combustion			
• Blast furnace gas:			
Before combustion[c]	20	0.2 - 0.3	0.040 - 0.060
After combustion	27	0.1	0.027
• Cement kiln off-gas	14 - 33	0.1	0.014 - 0.033
CO_2 from chemical transformations before combustion			
• IGCC: synthesis gas after gasification	8 - 20	2 - 7	0.16 - 1.4

[a] 0.1 MPa = 1 bar.
[b] IGCC: Integrated gasification combined cycle.
[c] Blast furnace gas also contains significant amounts of carbon monoxide that could be converted to CO_2 using the so-called shift reaction.

A third type of source occurs in natural-gas processing installations. CO_2 is a common impurity in natural gas, and it must be removed to improve the heating value of the gas or to meet pipeline specifications (Maddox and Morgan, 1998).

2.2.1.2 CO_2 content

The properties of those streams that can be inputted to a CO_2 capture process are discussed in this section. In CO_2 capture, the CO_2 partial pressure of the gas stream to be treated is important as well as the concentration of the stream. For practical purposes, this partial pressure can be defined as the product of the total pressure of the gas stream times the CO_2 mole fraction. It is a key variable in the selection of the separation method (this is discussed further in Chapter 3). As a rule of thumb, it can be said that the lower the CO_2 partial pressure of a gas stream, the more stringent the conditions for the separation process.

Typical CO_2 concentrations and their corresponding partial pressures for large stationary combustion sources are shown in Table 2.1, which also includes the newer Integrated Gasification Combined Cycle technology (IGCC). Typically, the majority of emission sources from the power sector and from industrial processes have low CO_2 partial pressures; hence the focus of the discussion in this section. Where emission sources with high partial pressure are generated, for example in ammonia or hydrogen production, these sources require only dehydration and some compression, and therefore they have lower capture costs.

Table 2.1 also provides a summary of the properties of CO_2 streams originating from cement and metal production in which chemical transformations and combustion are combined. Flue gases found in power plants, furnaces in industries, blast furnaces and cement kilns are typically generated at atmospheric pressure and temperatures ranging between 100°C and 200°C, depending on the heat recovery conditions.

Carbon dioxide levels in flue gases vary depending on the type of fuel used and the excess air level used for optimal combustion conditions. Flue gas volumes also depend on these two variables. Natural-gas-fired power generation plants are typically combined cycle gas turbines which generate flue gases with low CO_2 concentrations, typically 3–4% by volume (IEA GHG, 2002a). Coal for power generation is primarily burnt in pulverized-fuel boilers producing an atmospheric pressure flue gas stream with a CO_2 content of up to 14% by volume (IEA GHG, 2002a). The newer and potentially more efficient IGCC technology has been developed for generating electricity from coal, heavy fuel oil and process carbonaceous residues. In this process the feedstock is first gasified to generate a synthesis gas (often referred to as 'syngas'), which is burnt in a gas turbine after exhaustive gas cleaning (Campbell *et al*., 2000). Current IGCC plants where the synthesis gas is directly combusted in the turbine, like conventional thermal power plants, produce a flue gas with low CO_2 concentrations (up to 14% by volume). At present, there are only fifteen coal- and oil-fired IGCC plants, ranging in size from 40 to 550 MW. They were started up in the 1980s and 1990s in Europe and the USA (Giuffrida *et al*., 2003). It should be noted that there are conceptual designs in which the CO_2 can be removed before the synthesis gas is combusted, producing a high-concentration, high-pressure CO_2 exhaust gas stream that could be more suitable for storage (see Chapter 3 for more details). However, no such plants have been built or are under construction.

Fossil fuel consumption in boilers, furnaces and in process operations in the manufacturing industry also typically produces flue gases with low CO_2 levels comparable to those in the power

Table 2.2 Typical properties of gas streams that are already input to a capture process (Sources: Chauvel and Lefebvre, 1989; Maddox and Morgan, 1998; IEA GHG, 2002a).

Source	CO_2 concentration % vol	Pressure of gas stream MPa[a]	CO_2 partial pressure MPa
Chemical reaction(s)			
• Ammonia production[b]	18	2.8	0.5
• Ethylene oxide	8	2.5	0.2
• Hydrogen production[b]	15 - 20	2.2 - 2.7	0.3 - 0.5
• Methanol production[b]	10	2.7	0.27
Other processes			
• Natural gas processing	2 - 65	0.9 - 8	0.05 - 4.4

[a] 0.1 MPa = 1 bar

[b] The concentration corresponds to high operating pressure for the steam methane reformer.

sector. CO_2 concentrations in the flue gas from cement kilns depend on the production process and type of cement produced and are usually higher than in power generation processes (IEA GHG, 1999). Existing cement kilns in developing countries such as China and India are often relatively small. However, the quantity of CO_2 produced by a new large cement kiln can be similar to that of a power station boiler. Integrated steel mills globally account for over 80% of CO_2 emissions from steel production (IEA GHG, 2000b). About 70% of the carbon input to an integrated steel mill is present in the blast furnace gas, which is used as a fuel gas within the steel mill. CO_2 could be captured before or after combustion of this gas. The CO_2 concentration after combustion in air would be about 27% by volume, significantly higher than in the flue gas from power stations. Other process streams within a steel mill may also be suitable candidates for CO_2 capture before or after combustion. For example, the off-gas from an oxygen-steel furnace typically contains 16% CO_2 and 70% carbon monoxide.

The off-gases produced during the fermentation of sugars to ethanol consist of almost pure CO_2 with a few impurities. This gas stream is generated at a rate of 0.76 kg CO_2^{-1} and is typically available at atmospheric pressure (0.1 MPa) (Kheshgi and Prince, 2005).

CO_2 also occurs as an undesirable product that must be removed in some petrochemical processes, particularly those using synthesis gas as an intermediate or as an impurity in natural gas. The properties of the raw gas streams from which CO_2 is customarily removed in some of these industries are shown in Table 2.2. It can be seen from Table 2.1 that the CO_2 partial pressures of flue gases are at least one order of magnitude less than the CO_2 partial pressures of the streams arising from the processes listed in Table 2.2. This implies that CO_2 recovery from fuel combustion streams will be comparatively much more difficult.

2.2.1.3 *Scale of emissions*

A specific detailed dataset has been developed for CO_2 stationary sources for 2000, giving their geographical distribution by process type and country (IEA GHG, 2002a). The stationary sources of CO_2 in this database comprise power plants, oil refineries, gas-processing plants, cement plants, iron and steel plants and those industrial facilities where fossil fuels are used as feedstock, namely ammonia, ethylene, ethylene oxide and hydrogen. This global inventory contains over 14 thousand emission sources with individual CO_2 emissions ranging from 2.5 tCO_2 yr^{-1} to 55.2 $MtCO_2$ yr^{-1}. The information for each single source includes location (city, country and region), annual CO_2 emissions and CO_2 emission concentrations. The coordinates (latitude/longitude) of 74% of the sources are also provided. The total emissions from these 14 thousand sources amount to over 13 $GtCO_2$ yr^{-1}. Almost 7,900 stationary sources with individual emissions greater than or equal to 0.1 $MtCO_2$ per year have been identified globally. These emissions included over 90% of the total CO_2 emissions from large point sources in 2000. Some 6,000 emission sources with emissions below 0.1 $MtCO_2$ yr^{-1} were also identified, but they represent only a small fraction of the total emissions volume and were therefore excluded from further discussion in this chapter. There are also a number of regional and country-specific CO_2 emission estimates for large sources covering China, Japan, India, North West Europe and Australia (Hibino, 2003; Garg *et al.*, 2002; Christensen *et al.*, 2001, Bradshaw *et al.*, 2002) that can be drawn upon. Table 2.3 summarizes the information concerning large stationary sources according to the type of emission generating process. In the case of the petrochemical and gas-processing industries, the CO_2 concentration listed in this table refers to the stream leaving the capture process. The largest amount of CO_2 emitted from large stationary sources originates from fossil fuel combustion for power generation, with an average annual emission of 3.9 $MtCO_2$ per source. Substantial amounts of CO_2 arise in the oil and gas processing industries while cement production is the largest emitter from the industrial sector.

In the USA, 12 ethanol plants with a total productive capacity of 5.3 billion litres yr^{-1} each produce CO_2 at rates in excess of 0.1 $MtCO_2$ yr^{-1} (Kheshgi and Prince, 2005); in Brazil, where ethanol production totalled over 14 billion litres per year during 2003-2004, the average distillery productive capacity is 180 million litres yr^{-1}. The corresponding average fermentation CO_2 production rate is 0.14 $MtCO_2$ yr^{-1}, with the largest distillery producing nearly 10 times the average.

Table 2.3 Profile of worldwide large CO_2 stationary sources emitting more than 0.1 Mt CO_2 per year (Source: IEA GHG, 2002a).

Process	**CO_2 concentration in gas stream % by vol.**	**Number of sources**	**Emissions (MtCO$_2$)**	**% of total CO_2 emissions**	**Cumulative total CO_2 emissions (%)**	**Average emissions/source (MtCO$_2$ per source)**
CO_2 from fossil fuels or minerals						
Power						
Coal	12 to 15	2,025	7,984	59.69	59.69	3.94
Natural gas	3	985	759	5.68	65.37	0.77
Natural gas	7 to 10	743	752	5.62	70.99	1.01
Fuel oil	8	515	654	4.89	75.88	1.27
Fuel oil	3	593	326	2.43	78.31	0.55
Other fuels[a]	NA	79	61	0.45	78.77	0.77
Hydrogen	NA	2	3	0.02	78.79	1.27
Natural-gas sweetening						
	NA[b]	NA	50[c]	0.37	79.16	
Cement production						
Combined	20	1175	932	6.97	86.13	0.79
Refineries						
	3 to 13	638	798	5.97	92.09	1.25
Iron and steel industry						
Integrated steel mills	15	180	630[d]	4.71	96.81	3.50
Other processes[d]	NA	89	16	0.12	96.92	0.17
Petrochemical industry						
Ethylene	12	240	258	1.93	98.85	1.08
Ammonia: process	100	194	113	0.84	99.70	0.58
Ammonia: fuel combustion	8	19	5	0.04	99.73	0.26
Ethylene oxide	100	17	3	0.02	99.75	0.15
Other sources						
Non-specified	NA	90	33	0.25	100.00	0.37
		7,584	**13,375**	**100**		**1.76**
CO_2 from biomass[e]						
Bioenergy	3 to 8	213	73			0.34
Fermentation	100	90	17.6			**0.2**

[a] Other gas, other oil, digester gas, landfill gas.

[b] A relatively small fraction of these sources has a high concentration of CO_2. In Canada, only two plants out of a total of 24 have high CO_2 concentrations.

[c] Based on an estimate that about half of the annual worldwide natural-gas production contains CO_2 at concentrations of about 4% mol and that this CO_2 content is normally reduced from 4% to 2% mol (see Section 3.2.2).

[d] This amount corresponds to the emissions of those sources that have been individually identified in the reference database. The worldwide CO_2 emissions, estimated by a top-down approach, are larger than this amount and exceed 1 Gt (Gielen and Moriguchi, 2003).

[e] For North America and Brazil only. All numbers are for 2003, except for power generation from biomass and waste in North America, which is for 2000.

The top 25% of all large stationary CO_2 emission sources (those emitting more than 1 MtCO$_2$ per year) listed in Table 2.3 account for over 85% of the cumulative emissions from these types of sources. At the other end of the scale, the lowest 41% (in the 0.1 to 0.5 MtCO$_2$ range) contribute less than 10% (Figure 2.1). There are 330 sources with individual emissions above 10 MtCO$_2$ per year. Of their cumulative emissions, 78% come from power plants, 20% from gas processing and the remainder from iron and steel plants (IEA GHG, 2000b). High-concentration/high-partial-pressure sources (e.g., from ammonia/hydrogen production and gas processing operations) contribute a relatively low share (<2%) of the emissions from large stationary sources (van Bergen *et al*., 2004). However, these high-concentration sources could represent early prospects for the implementation of CO_2 capture and storage. The costs for capture are lower than for low-concentration/low-partial-pressure sources. If these sources can then be linked to enhanced production schemes in the vicinity (<50km), like CO_2-enhanced oil recovery, they could be low-cost options for CO_2 capture and storage (van Bergen *et al.*, 2004). Such sources emit 0.36 $GtCO_2$ yr^{-1} (0.1 GtC yr^{-1}), which equates to 3% of emissions from point sources larger than 0.1 $MtCO_2$ yr^{-1} (IEA GHG, 2002b). The geographical relationship between these high-concentration sources and prospective storage opportunities is discussed in Section 2.4.3. A small number of source streams with high CO_2 concentrations are already used in CO_2-EOR operations in the USA and Canada (Stevens and Gale, 2000).

2.2.2 Future

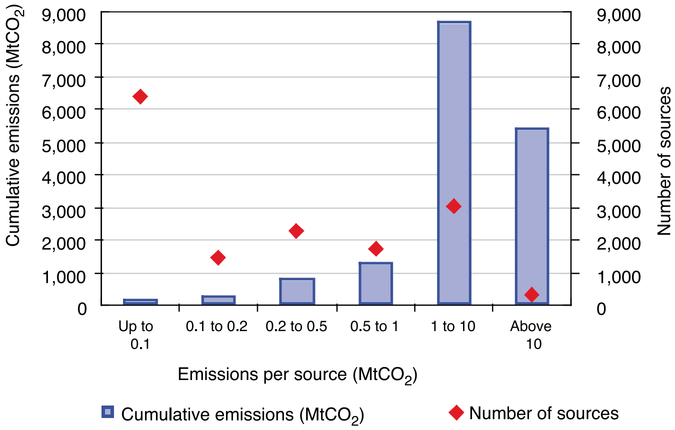

Figure 2.1 Relationship between large stationary source emissions and number of emission sources (Source: IEA GHG, 2002a).

Future anthropogenic CO_2 emissions will be the product of different drivers such as demographic development, socio-economic development, and technological changes (see Chapter 1, Section 1.2.4). Because their future evolution is inherently uncertain and because numerous combinations of different rates of change are quite plausible, analysts resort to scenarios as a way of describing internally consistent, alternative images of how the future might unfold. The IPCC developed a set of greenhouse gas emission scenarios for the period until 2100 (IPCC, 2000). The scenarios show a wide range of possible future worlds and CO_2 emissions (see Figure 2.2), consistent with the full uncertainty range of the underlying literature reported by Morita and Lee (1998). The scenarios are important as they provide a backdrop for determining the baseline for emission reductions that may be achieved with new technologies, including CO_2 capture and storage implemented specially for such purposes.

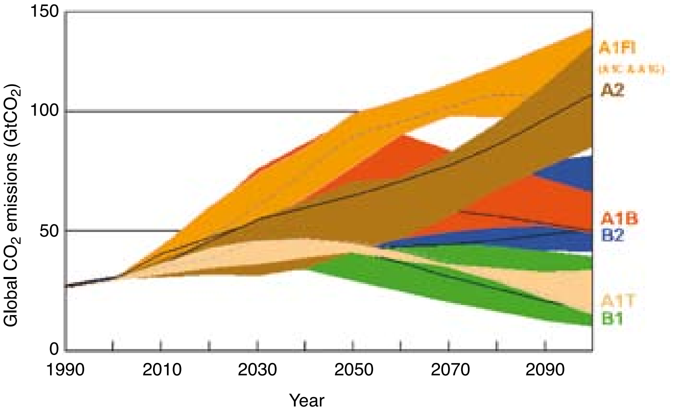

Figure 2.2 Range of annual global CO_2 emission in he SRES scenarios ($GtCO_2$) (Source: IPCC, 2000).

Technology change is one of the key drivers in long-term scenarios and plays a critical role in the SRES scenarios. Future rates of innovation and diffusion are integral parts of, and vary with, the story lines. Scenario-specific technology change may differ in terms of technology clusters (i.e., the type of technologies used) or rate of diffusion. In the fossil-intensive A1FI scenario, innovation concentrates on the fossil source-to-service chains stretching from exploration and resource extraction to fuel upgrading/cleaning, transport, conversion and end-use. Alternatively, innovation in the environmentally-oriented B1 scenario focuses on renewable and hydrogen technologies.

The way in which technology change was included in the SRES scenarios depended on the particular model used. Some models applied autonomous performance improvements to fuel utilization, while others included specific technologies with detailed performance parameters. Even models with a strong emphasis on technology reflected new technologies or innovation in a rather generic manner. For example, advanced coal technology could be either an integrated coal gasification combined cycle (IGCC) plant, a pressurized fluidized bed combustion facility or any other, as-yet-unidentified, technology. The main characteristics of advanced coal technology are attractive investment costs, high thermal efficiency, potential multi-production integration and low pollution emissions – features that are prerequisites for any coal technology carrying the "advanced" label.

In general, technological diversity remained a feature in all scenarios, despite the fact that different clusters may dominate more in different scenarios. The trend towards cleaner and more convenient technologies, especially at the level of end-use (including transport), is common to all scenarios. In addition, transport fuels shift broadly towards supply schemes suitable for pre-combustion decarbonization. Centralized non-fossil technologies penetrate the power sector to various extents, while decentralized and home-based renewable and hydrogen-production infrastructures expand in all scenarios, but mostly in the environmentally-conscious and technology-intensive scenarios.

Despite the trend towards cleaner fuels, CO_2 emissions are projected to rise at different rates, at least until 2050. Emission patterns then diverge. Scenario-specific rates of technology change (performance improvements) and technology diffusion lead to different technology mixes, fuel uses and unit sizes. As regards fossil fuel use for power generation and industrial energy supply, the number of large stationary emission sources generally increases in the absence of restrictions on CO_2 emissions and a fundamental change in the characteristics of these emission

Table 2.4 Sectoral and regional distribution of energy-related CO_2 emissions in 2000 ($MtCO_2$) (Source: IEA, 2003).

	Public electricity and heat production	Unallocated autoproducers	Other energy industries	Manufacturing industries and construction	Transport	Commercial and public services	Residential	Other sectors	CO_2 sectoral approach total
1 Economies in transition	1,118.5	391.4	106.6	521.7	317.1	58.0	312.5	127.7	2,953.6
2 OECD West	1,087.3	132.0	222.8	722.1	1,040.9	175.1	494.6	96.2	3,971.0
3 USA	2,265.1	134.9	272.4	657.9	1,719.9	225.5	371.4	42.7	5,689.7
4 OECD Pacific	509.2	87.0	62.2	301.1	344.4	95.3	75.8	35.7	1,510.5
5 South/East Asia	925.5	104.1	137.9	533.3	451.8	50.9	185.6	39.7	2,428.7
6 Centrally Planned Asia	1,332.2	37.7	138.5	978.4	245.4	72.6	221.4	118.7	3,144.8
7 Middle East	280.6	6.6	118.6	193.0	171.6	16.6	90.8	112.5	990.4
8 Africa	276.3	15.9	40.2	137.7	143.5	5.0	44.5	34.8	697.8
9 Latin America	222.3	37.0	134.5	279.3	396.0	17.9	81.0	41.5	1,209.6
Sector total	**8,016.9**	**946.5**	**1,233.7**	**4,324.7**	**4,830.6**	**716.8**	**1,877.5**	**649.4**	**22,596.1**

sources is unlikely to occur before 2050. In addition, the ratio of low-concentration to high-concentration emission sources remains relatively stable, with low-concentration sources dominating the emission profile.

In some scenarios, low- or zero-carbon fuels such as ethanol, methanol or hydrogen begin to dominate the transport sector and make inroads into the industrial, residential and commercial sectors after 2050. The centralized production of such fuels could lead to a significant change in the number of high-concentration emission sources and a change in the ratio of low- to high-purity emission sources; this is discussed in more detail in Section 2.5.2.

2.3 Geographical distribution of sources

This section discusses the geographical locations of large point sources discussed in the preceding sections. It is necessary to understand how these sources are geographically distributed across the world in order to assess their potential for subsequent storage.

2.3.1 Present

A picture of the geographical distribution of the sources of CO_2 emissions and the potential storage reservoirs helps us to understand the global cost of CO_2 mitigation, particularly those components associated with CO_2 transport. Geographical information about emission sources can be retrieved from a number of data sets. Table 2.4 shows the sectoral and regional distribution of energy-related CO_2 emissions in 2000. As mentioned earlier in this report, over 60% of global CO_2 emissions come from the power and industry sectors. Geographically, these power and industry emissions are dominated by four regions which account for over 90% of the emissions. These regions are: Asia (30%), North America (24%), the transitional economies (13%), and OECD West[1] (12%). All the other regions account individually for less than 6% of the global emissions from the power and industry sectors.

Figure 2.3 shows the known locations of stationary CO_2 sources worldwide, as taken from the database referred to in Section 2.2 (IEA GHG, 2002a). North America is the region with the largest number of stationary sources (37%), followed by Asia (24%) and OECD Europe[2] (14%). Figure 2.3 shows three large clusters of stationary sources located in the central and eastern states of the US, in northwestern and central regions of Europe (Austria, Czech Republic, Germany, Hungary, Netherlands and UK) and in Asia (eastern China and Japan with an additional smaller cluster in the Indian subcontinent).

The distribution of stationary CO_2 emissions as a proportion of the total stationary emissions for 2000 indicates that the regions that are the largest emitters of CO_2 from stationary sources are: Asia at 41% (5.6 $GtCO_2$ yr^{-1}), North America at 20% (2.69 $GtCO_2$ yr^{-1}) and OECD Europe at 13% (1.75 $GtCO_2$ yr^{-1}). All other regions emitted less than 10% of the total CO_2 emission from stationary sources in 2000.

A comparison of the estimates of CO_2 emissions from the IEA and IEA GHG databases showed that the two sets produced

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[1] Note: OECD West refers to the following countries: Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom.

[2] OECD Europe includes the OECD West countries listed above, plus the Czech Republic, Hungary, Iceland, Norway, Poland, Slovak Republic, Switzerland and Turkey.

Figure 2.3 Global distribution of large stationary CO_2 sources (based on a compilation of publicly available information on global emission sources, IEA GHG 2002).

similar estimates for the total of global emissions but that results differed significantly for many countries. Regional differences of this kind have also been noted for other CO_2 emission databases (Marland *et al*., 1999).

2.3.2 Future CO_2 emissions and technical capture potentials

The total CO_2 emissions from fossil fuel combustion in the SRES scenarios provide the upper limit for potential CO_2 capture for this assessment. In fact, the theoretical maximum is even higher because of the possibility of CO_2 capture from biomass. These emissions are also included in the tables of CO_2 emissions and they are therefore potentially available for capture. Obviously, the capture potential that is practical in technical terms is much smaller than the theoretical maximum, and the economic potential[3] is even smaller. Needless to say, it is the economic potential that matters most. This section presents estimates of the technical potential and Chapter 8 will address the economic potential.

Table 2.5 shows the CO_2 emissions by economic sector and major world regions for 2020 and 2050, and for six scenarios[4]. It should be noted that the total CO_2 emissions in Table 2.5 are higher than reported in SRES because emissions from biomass are explicitly included here (as these are potentially available for capture), while they where considered "climate-neutral" in the SRES presentations and therefore not counted as emission releases to the atmosphere. Geographically, the distribution of emission sources is set to change substantially. Between 2000 and 2050, the bulk of emission sources will shift from the OECD countries to the developing regions, especially China, South Asia and Latin America. As to emissions by sector, power generation, transport, and industry will remain the three main sources of CO_2 emissions over the next 50 years. Globally, the projected energy sector emissions will fluctuate around the 40% mark in 2050 (this matches the current figure), emissions from the industry sector will decline and transport sector emissions (i.e., mobile sources) increase. Power generation, which typically represent the bulk of large point sources, will account for about 50% of total emissions by 2050[5].

These emissions form the theoretical maximum potential for CO_2 capture from fossil fuel use. Toth and Rogner (2006) derived a set of capture factors on the basis of the technical or technological feasibility of adding CO_2 capture before, during or after combustion of fossil fuels. Capture factors are defined as the estimated maximum share of emissions for which capture is technically plausible. A detailed assessment of the power plants

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[3] Economic potential is the amount of reductions in greenhouse gas emissions from a specific option that could be achieved cost-effectively given prevailing circumstances (i.e. a price for CO_2 reductions and the costs of other options).

[4] For the four marker scenarios and the technology-intensive A1T and the fossil-intensive A1FI illustrative scenarios, it is important to note that comparisons between the results of different models are not straightforward. First, the modelling methodologies imply different representations of energy technologies and their future evolutions. Secondly, the sectoral disaggregation and the energy/fuel details vary across the models. Thirdly, there are differences in how countries of the world are grouped together into regions. Tables 2.5 and 2.6 are based on the work by Toth and Rogner (2005) that attempts to create the best possible approximation for the purposes of comparing the regional and sectoral model and scenario results.

[5] As regards the share of emissions across sectors in 2020 (Table 2.5), there is an inherent divergence between scenarios with longer and shorter time horizons. Given the quasi perfect foresight of the underlying models, the SRES scenarios account for resource depletion over a period of a century and, due to the anticipated transition to higher-fuel-cost categories in the longer run, they shift to non-fossil energy sources much earlier than, for example, the IEA scenarios, especially for electricity supply. Consequently, the range for the shares of fossil-sourced power generation is between 43 and 58% for 2020, while the IEA projects a share of 71%. The corresponding sectoral shares in CO_2 emissions mirror the electricity generating mix: the IEA projects 43% for power generation (IEA, 2002) compared to a range of 28 to 32% in the six illustrative SRES scenarios.

Table 2.5 Carbon dioxide emissions from sectors in major world regions in six IPCC SRES scenarios in 2020 and 2050 (IPCC, 2000). Continued on next page.

A1B

Sector	Africa	CPA	EEFSU	LAM	Middle East	USA	P-OECD	S&EA	OECD West	Sector total
Power	2,016	3,193	1,482	1,182	721	1,607	698	2,063	1,244	14,207
Industry	1,046	2,512	1,465	1,689	966	1,122	564	1,834	1,123	12,321
Res/Com	642	1,897	439	566	195	637	238	950	933	6,496
Transport	877	1,008	312	1,502	1,052	2,022	659	1,592	2,175	11,199
Region total	4,580	8,610	3,698	4,938	2,934	5,388	2,159	6,439	5,476	44,222

A1T

Sector	Sub-Saharan Africa	CPA	E Europe	FSU	LAM	ME-N Africa	NAM	P-OECD	PAS	SAS	W. Europe	Sector total
Power	333	2,165	356	705	396	368	2,470	448	1,388	195	1,221	10,045
Industry	358	2,840	208	727	885	465	690	292	954	748	530	8,699
Res/Com	730	2,773	105	352	713	149	771	150	795	690	627	7,855
Refineries	107	211	23	196	282	139	370	75	250	42	219	1,913
Synfuels	59	122	9	22	139	36	127	30	211	38	107	900
Hydrogen	57	145	26	80	57	61	231	74	75	47	177	1,030
Transport	435	1,235	96	578	1,159	837	2,394	450	620	432	1,448	9,684
Region total	2,078	9,491	823	2,661	3,631	2,055	7,053	1,519	4,292	2,192	4,330	40,126

A1FI

Sector	Africa	CPA	EEFSU	LAM	Middle East	USA	Canada	P-OECD	South East Asia	W. Europe	Sector total
Power	427	3,732	2,248	680	370	2,618	181	753	2,546	1,640	15,195
Industry	622	3,498	1,121	695	426	1,418	153	416	1,530	1,384	11,262
Res/Com	135	1,363	582	125	25	755	102	115	488	786	4,477
Transport	456	542	588	977	297	2,210	168	357	1,357	1,345	8,297
Synfuels	10	12	126	2	0	52	3	12	2	21	238
Hydrogen	0	0	0	0	0	0	0	0	0	0	0
Fuel flared	21	11	19	135	74	9	1	1	52	4	327
Region total	1,670	9,159	4,682	2,613	1,192	7,062	608	1,654	5,976	5,181	39,796

Source: Total emissions $MtCO_2$ 2020

CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

Table 2.5 Continued.

A2													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	670	1,616	488	923	1,130	857	3,680	224	689	356	1,282	1,663	13,579
Industry	290	1,786	261	417	625	402	808	111	291	218	708	528	6,444
Res/Com	269	746	118	539	209	434	639	92	155	87	251	644	4,181
Transport	358	606	130	314	1,060	569	2,013	200	406	334	332	1,270	7,592
Others	394	439	112	371	644	538	567	68	247	269	142	532	4,324
Region total	1,981	5,193	1,109	2,563	3,668	2,800	7,706	696	1,788	1,264	2,715	4,638	36,120
B1													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	629	1,148	377	670	1,031	699	2,228	128	477	354	972	1,118	9,829
Industry	259	1,377	210	290	531	362	537	79	205	209	611	355	5,024
Res/Com	283	602	108	471	193	350	511	74	132	79	250	557	3,611
Transport	384	578	136	343	987	509	1,708	172	365	314	370	1,204	7,070
Others	392	413	99	291	591	502	481	55	169	266	164	432	3,856
Region total	1,946	4,118	931	2,064	3,333	2,422	5,466	506	1,348	1,222	2,367	3,665	29,389
B2	**Sub-Saharan**												
Sector	**Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**		**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	317	1,451	398	149	338	342	3,317		459	1,017	398	1,234	9,420
Industry	307	2,017	232	956	754	400	993		223	796	634	679	7,990
Res/Com	854	1,936	137	330	462	177	1,213		174	440	929	768	7,420
Refineries	70	241	42	169	223	193	480		98	242	111	271	2,139
Synfuels	30	18	2	32	47	16	126		4	77	12	56	420
Hydrogen	15	274	15	18	24	17	159		31	108	36	119	817
Transport	224	655	105	530	715	506	2,278		384	784	468	1,164	7,812
Region total	1,816	6,591	931	2,184	2,563	1,652	8,566		1,373	3,464	2,589	4,292	36,019

Source: Total emissions $MtCO_2$ 2020

CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

Table 2.5 Continued.

A1B **Sector**	**Africa**	**CPA**	**EEFSU**	**LAM**	**Middle East**	**USA**	**P-OECD**	**S&EA**	**OECD West**	**Sector total**
Power	4,078	2,708	1,276	1,165	840	1,361	588	2,700	1,459	16,174
Industry	2,304	2,555	1,645	2,384	1,635	969	395	3,273	1,038	16,199
Res/Com	2,610	3,297	879	1,074	415	797	236	2,056	1,004	12,369
Transport	4,190	2,082	512	2,841	2,676	2,091	690	4,506	2,278	21,867
Region total	13,182	10,643	4,311	7,465	5,566	5,218	1,909	12,535	5,779	66,609

A1T **Sector**	**Sub-Sharan Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**	**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	925	3,831	119	203	788	958	606	107	1,039	745	147	9,469
Industry	1,871	983	77	299	433	614	420	104	521	1,394	278	6,996
Res/Com	774	2,574	70	448	1,576	598	878	116	1,154	1,285	507	9,979
Refineries	71	477	12	395	314	299	263	32	287	137	42	2,330
Synfuels	811	442	137	118	699	22	715	114	515	339	418	4,329
Hydrogen	290	99	37	364	0	647	0	0	151	256	612	2,456
Transport	1,083	4,319	280	1,121	2,106	1,613	2,094	386	1,839	1,545	1,464	17,851
Region total	5,825	12,725	732	2,949	5,917	4,751	4,977	859	5,506	5,702	3,468	53,411

A1FI **Sector**	**Africa**	**CPA**	**EEFSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**W. Europe**	**Sector total**
Power	4,413	7,598	4,102	2,604	1,409	3,485	240	918	9,530	2,374	36,673
Industry	2,022	4,899	1,066	948	857	1,295	118	337	2,731	1,244	15,517
Res/Com	503	2,093	814	238	70	854	95	112	1,172	854	6,805
Transport	2,680	1,207	1,031	2,173	860	2,753	176	418	4,525	1,516	17,340
Synfuels	259	2,629	2,189	35	0	1,021	50	171	267	418	7,039
Hydrogen	0	0	0	0	0	0	0	0	0	0	0
Fuel flared	50	26	43	102	40	13	3	1	20	6	305
Region total	9,927	18,453	9,246	6,099	3,236	9,421	682	1,958	18,246	6,412	83,679

Source: Total emissions $MtCO_2$ 2050
CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

Table 2.5 Continued.

A2 Sector	Africa	East Asia	E. Europe	FSU	LAM	Middle East	USA	Canada	P-OECD	South East Asia	South Asia	OECD Europe	Sector total
Power	2,144	3,406	913	1,679	2,621	2,518	4,653	310	1,028	967	3,660	1,766	25,666
Industry	881	2,727	345	725	1,118	899	895	115	276	413	1,627	487	10,506
Res/Com	907	1,451	157	735	325	719	644	95	144	179	599	628	6,582
Transport	1,061	901	193	646	1,547	1,370	1,946	191	378	578	703	1,275	10,788
Others	719	643	106	452	754	904	582	67	142	304	359	429	5,461
Region total	5,713	9,127	1,714	4,237	6,365	6,409	8,719	778	1,967	2,441	6,949	4,585	59,003

B1 Sector	Africa	East Asia	E. Europe	FSU	LAM	Middle East	USA	Canada	P-OECD	South East Asia	South Asia	OECD Europe	Sector total
Power	573	251	104	343	496	662	342	30	82	313	1,243	311	4,749
Industry	556	985	121	235	465	574	319	44	103	250	877	171	4,699
Res/Com	517	465	92	358	242	298	338	52	81	105	455	384	3,389
Transport	959	571	127	466	946	834	976	104	204	390	660	732	6,968
Others	414	280	45	209	378	458	230	29	60	198	253	225	2,779
Region total	3,019	2,551	488	1,612	2,527	2,825	2,205	259	529	1,255	3,488	1,824	22,584

B2 Sector	Sub-Saharan Africa	CPA	E. Europe	FSU	LAM	ME-N Africa	NAM	P-OECD	PAS	SAS	W. Europe	Sector total
Power	654	1,703	474	576	274	753	2,280	289	762	1,357	936	10,060
Industry	932	1,751	166	685	688	601	708	66	827	1,499	406	8,328
Res/Com	623	1,850	85	386	477	127	1,084	129	661	1,106	610	7,138
Refineries	43	360	14	409	200	85	382	47	244	262	112	2,157
Synfuels	453	139	56	285	326	448	174	50	223	54	97	2,304
Hydrogen	308	1,312	43	278	277	186	319	29	185	444	364	3,743
Transport	572	1,531	145	840	1,230	799	2,577	340	1,014	1,075	1,336	11,459
Region total	3,584	8,645	984	3,458	3,471	2,999	7,524	951	3,917	5,797	3,861	45,189

Source: Total emissions $MtCO_2$ 2050.

Notes:

The division of the world into large economic regions differs between the various models underlying the SRES scenarios. Tables 2.5 and 2.6 consolidate the original model regions at a level that makes model results comparable (although the exact geographical coverage of the regions may vary).

CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

currently in operation around the world and those planned to be built in the near future was conducted, together with a review of industrial boilers in selected regions. Capture factors were established on the basis of installed capacity, fuel type, unit size, and other technical parameters. Outside the energy and industry sectors, there are only very limited prospects for practical CO_2 capture because sources in the residential sectors are small, dispersed, and often mobile, and contain only low concentrations. These factors result in lower capture factors.

In the assessment of CO_2 capture, perhaps the most important open question is what will happen in the transport sector over the next few decades. If the above average increases in energy use for transport projected by all models in all scenarios involve traditional fossil-fuelled engine technologies, the capture and storage of transport-related CO_2 will – though theoretically possible –remain technically meaningless (excess weight, on-board equipment, compression penalty, etc.). However, depending on the penetration rate of hydrogen-based transport technologies, it should be possible to retrofit CO_2-emitting hydrogen production facilities with CO_2 capture equipment. The transport sector provides a huge potential for indirect CO_2 capture but feasibility depends on future hydrogen production technologies.

CO_2 capture might also be technically feasible from biomass-fuelled power plants, biomass fermentation for alcohol production or units for the production of biomass-derived hydrogen. It is conceivable that these technologies might play a significant role by 2050 and produce negative emissions across the full technology chain.

The results of applying the capture factors developed by Toth and Rogner (2006) to the CO_2 emissions of the SRES scenarios of Table 2.5 are presented in Table 2.6. Depending on the scenario, between 30 and 60% of global power generation emissions could be suitable for capture by 2050 and 30 to 40% of industry emissions could also be captured in that time frame.

The technical potentials for CO_2 capture presented here are only the first step in the full carbon dioxide capture and storage chain. The variations across scenarios reflect the uncertainties inherently associated with scenario and modelling analyses. The ranges of the technical capture potential relative to total CO_2 emissions are 9–12% (or 2.6–4.9 $GtCO_2$) by 2020 and 21–45% (or 4.7–37.5 $GtCO_2$) by 2050.

2.4 Geographical relationship between sources and storage opportunities

The preceding sections in this chapter have described the geographical distributions of CO_2 emission sources. This section gives an overview of the geographic distribution of potential storage sites that are in relative proximity to present-day sites with large point sources.

2.4.1 Global storage opportunities

Global assessments of storage opportunities for CO_2 emissions involving large volumes of CO_2 storage have focused on the options of geological storage or ocean storage, where CO_2 is:

- injected and trapped within geological formations at subsurface depths greater than 800 m where the CO_2 will be supercritical and in a dense liquid-like form in a geological reservoir, or
- injected into deep ocean waters with the aim of dispersing it quickly or depositing it at great depths on the floor of the ocean with the aim of forming CO_2 lakes.

High-level global assessments of both geological and ocean storage scenarios have estimated that there is considerable capacity for CO_2 storage (the estimates range from hundreds to tens of thousands of $GtCO_2$). The estimates in the literature of storage capacity in geological formations and in the oceans are discussed in detail in Chapters 5 and 6 respectively and are not discussed further in this chapter.

2.4.2 Consideration of spatial and temporal relationships

As discussed in Chapter 5, the aim of geological storage is to replicate the natural occurrence of deep subsurface fluids, where they have been trapped for tens or hundreds of millions of years. Due to the slow migration rates of subsurface fluids observed in nature (often centimetres per year), and even including scenarios where CO_2 leakage to the surface might unexpectedly occur, CO_2 injected into the geological subsurface will essentially remain geographically close to the location where it is injected. Chapter 6 shows that CO_2 injected into the ocean water column does not remain in a static location, but will migrate at relatively rapid speed throughout the ocean as dissolved CO_2 within the prevailing circulation of ocean currents. So dissolved CO_2 in the water column will not remain where it is injected in the immediate short term (i.e., a few years to some centuries). Deep-ocean lakes of CO_2 will, in principle, be more static geographically but will dissolve into the water column over the course of a few years or centuries.

These spatial and temporal characteristics of CO_2 migration in geological and ocean storage are important criteria when attempting to make maps of source and storage locations. In both storage scenarios, the possibility of adjoining storage locations in the future and of any possible reciprocal impacts will need to be considered.

2.4.3 Global geographical mapping of source/storage locations

To appreciate the relevance of a map showing the geographic distribution of sources and potential storage locations, it is necessary to know the volumes of CO_2 emissions and the storage capacity that might be available, and to establish a picture of the types and levels of technical uncertainty associated with the

Table 2.6 CO_2 emissions available for capture and storage in 2020 and 2050 from sectors in major world regions under six IPCC SRES scenarios (after Toth and Rogner, 2005). Continued on next page.

Potential CO_2 capture in $MtCO_2$ 2020													
A1B													
Sector	**Africa**	**CPA**	**EEFSU**		**LAM**	**MEA**	**NAM**		**P-OECD**	**S&EA**		**OECD West**	**Sector total**
Power	117	475	319		165	167	479		185	290		351	2,548
Industry	33	182	168		155	127	156		64	130		159	1,173
Res/Com	6	46	21		16	7	30		12	17		51	207
Transport	0	0	0		0	0	0		0	0		0	0
Region total	156	702	508		337	301	665		261	437		561	3,928
A1T	**Sub-Saharan**												
Sector	**Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**		**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	21	334	78	139	39	110	715		128	164	20	366	2,115
Industry	6	195	18	70	56	57	85		21	35	57	65	664
Res/Com	4	59	4	16	14	4	37		7	12	6	36	200
Refineries	22	54	6	50	71	42	113		23	63	11	67	521
Synfuels	30	74	6	16	85	25	91		23	86	16	81	532
Hydrogen	46	125	24	73	50	56	211		68	65	41	162	919
Transport	0	0	0	0	0	0	0		0	0	0	0	0
Region total	129	840	135	364	315	294	1,251		270	426	150	777	4,950
A1FI													
Sector	**Africa**	**CPA**	**EEFSU**		**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**		**W. Europe**	**Sector total**
Power	30	607	525		95	90	791	55	226	401		500	3,319
Industry	15	259	144		49	58	189	22	51	104		198	1,091
Res/Com	1	31	26		4	1	36	4	6	7		48	165
Transport	0	0	0		0	0	0	0	0	0		0	0
Synfuels	5	7	89		1	0	37	2	9	1		16	167
Hydrogen	0	0	0		0	0	0	0	0	0		0	0
Fuel flared	0	0	0		0	0	0	0	0	0		0	0
Region total	50	904	785		149	149	1,053	83	292	513		763	4,741

CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

Table 2.6 Continued.

	Potential CO_2 capture in $MtCO_2$ 2020												
A2													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	41	241	102	217	150	208	1,111	66	201	60	140	477	3,016
Industry	8	127	26	49	42	48	111	15	35	12	49	68	590
Res/Com	3	25	5	26	6	15	30	4	8	2	5	35	163
Transport	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	0	0	0	0	0	0	0	0	0	0	0	0	0
Region total	51	392	134	292	198	271	1,252	86	244	74	194	579	3,769
B1													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	38	156	81	160	147	174	632	35	126	57	129	304	2,040
Industry	6	79	19	32	35	43	68	10	22	10	45	43	411
Res/Com	3	22	5	22	5	11	22	3	6	2	5	28	134
Transport	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	0	0	0	0	0	0	0	0	0	0	0	0	0
Region total	47	256	105	214	187	228	722	49	155	69	179	375	2,584
B2	**Sub-Saharan**												
Sector	**Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**		**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	18	225	82	24	52	100	982		114	153	41	349	2,140
Industry	5	122	19	89	42	50	103		12	19	30	73	565
Res/Com	5	42	5	15	6	4	46		8	6	6	35	178
Refineries	14	60	11	42	56	58	144		29	61	28	81	583
Synfuels	15	11	2	22	28	11	88		3	31	5	42	258
Hydrogen	12	233	14	16	20	16	144		28	92	31	107	712
Transport	0	0	0	0	0	0	0		0	0	0	0	0
Region total	69	693	132	209	204	239	1,507		196	361	140	687	4,437

CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

Table 2.6 Continued.

						Potential CO_2 Capture in $MtCO_2$ 2050							
A1B													
Sector	**Africa**	**CPA**	**EEFSU**		**LAM**	**Middle East**	**NAM**		**P-OECD**	**S&EA**		**OECD West**	**Sector total**
Power	2,167	1,701	831		674	548	1,015		438	1,658		1,092	10,124
Industry	760	931	726		1,015	701	439		165	1,201		481	6,419
Res/Com	222	660	191		128	87	172		68	393		319	2,241
Transport	0	0	0		0	0	0		0	0		0	0
Region total	3,149	3,291	1,747		1,818	1,337	1,627		671	3,253		1,892	18,783
A1T	**Sub-Saharan**												
Sector	**Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**		**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	526	2,530	90	127	469	753	477		84	702	423	115	6,296
Industry	329	307	25	110	165	191	139		33	111	288	102	1,799
Res/Com	66	445	16	94	189	126	190		32	238	140	159	1,694
Refineries	37	367	9	304	242	245	216		26	221	98	35	1,799
Synfuels	665	407	126	109	645	20	660		105	449	296	386	3,867
Hydrogen	283	96	36	354	0	630	0		0	147	249	596	2,392
Transport	0	0	0	0	0	0	0		0	0	0	0	0
Region total	1,905	4,154	301	1,098	1,709	1,965	1,681		280	1,867	1,493	1,393	17,846
A1FI													
Sector	**Africa**	**CPA**	**EEFSU**		**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**		**W. Europe**	**Sector total**
Power	2,369	4,836	2,691		1,486	992	2,677	186	705	5,979		1,862	23,781
Industry	557	1,817	462		332	370	559	53	144	962		569	5,826
Res/Com	37	430	188		27	15	189	23	30	229		279	1,448
Transport	0	0	0		0	0	0	0	0	0		0	0
Synfuels	213	2,425	2,019		32	0	942	46	158	233		385	6,453
Hydrogen	0	0	0		0	0	0	0	0	0		0	0
Fuel flared	0	0	0		0	0	0	0	0	0		0	0
Region total	3,175	9,509	5,360		1,877	1,377	4,367	308	1,038	7,403		3,095	37,508

CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia, OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

Table 2.6 Continued.

	Potential CO_2 Capture in $MtCO_2$ 2050												
A2													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	1,158	2,080	571	1,110	1,407	1,628	3,569	230	779	631	1,912	1,284	16,359
Industry	257	991	128	286	365	319	384	46	112	139	519	194	3,741
Res/Com	78	293	34	155	41	148	143	21	42	30	113	197	1,295
Transport	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	0	0	0	0	0	0	0	0	0	0	0	0	0
Region total	1,493	3,365	733	1,552	1,812	2,095	4,096	298	933	799	2,544	1,675	21,394
B1													
Sector	**Africa**	**East Asia**	**E. Europe**	**FSU**	**LAM**	**Middle East**	**USA**	**Canada**	**P-OECD**	**South East Asia**	**South Asia**	**OECD Europe**	**Sector total**
Power	266	130	63	218	258	418	221	19	52	185	635	203	2,668
Industry	138	268	40	83	137	196	118	16	36	72	271	64	1,437
Res/Com	44	80	19	69	28	57	69	11	21	16	73	111	598
Transport	0	0	0	0	0	0	0	0	0	0	0	0	0
Others	0	0	0	0	0	0	0	0	0	0	0	0	0
Region total	447	478	121	371	423	671	408	46	110	273	980	377	4,703
B2	**Sub-Saharan**												
Sector	**Africa**	**CPA**	**E. Europe**	**FSU**	**LAM**	**ME-N Africa**	**NAM**		**P-OECD**	**PAS**	**SAS**	**W. Europe**	**Sector total**
Power	339	1,067	307	345	164	563	1,710		216	439	673	704	6,526
Industry	166	459	63	248	266	257	225		20	157	238	144	2,243
Res/Com	42	309	18	77	52	16	224		35	102	104	182	1,161
Refineries	22	270	11	306	150	68	305		38	183	183	89	1,625
Synfuels	362	125	51	256	293	403	157		45	189	46	87	2,015
Hydrogen	293	1,246	41	264	263	176	303		27	176	421	345	3,556
Transport	0	0	0	0	0	0	0		0	0	0	0	0
Region total	1,223	3,476	489	1,496	1,187	1,484	2,924		383	1,246	1,665	1,552	17,125

Notes: The division of the world into large economic regions differs in the different models underlying the SRES scenarios. Tables 2.5 and 2.6 consolidate the original model regions at a level that makes model results comparable (although the exact geographical coverage of the regions may vary).
CPA = Centrally Planned Asia. EE = Eastern Europe, FSU = Former Soviet Union, LAM = Latin America, P-OECD = Pacific OECD, S&EA = South and Southeast Asia,
OECD-West = Western Europe + Canada, Africa, ME = Middle East, PAS = Pacific Asia, SAS = South Asia

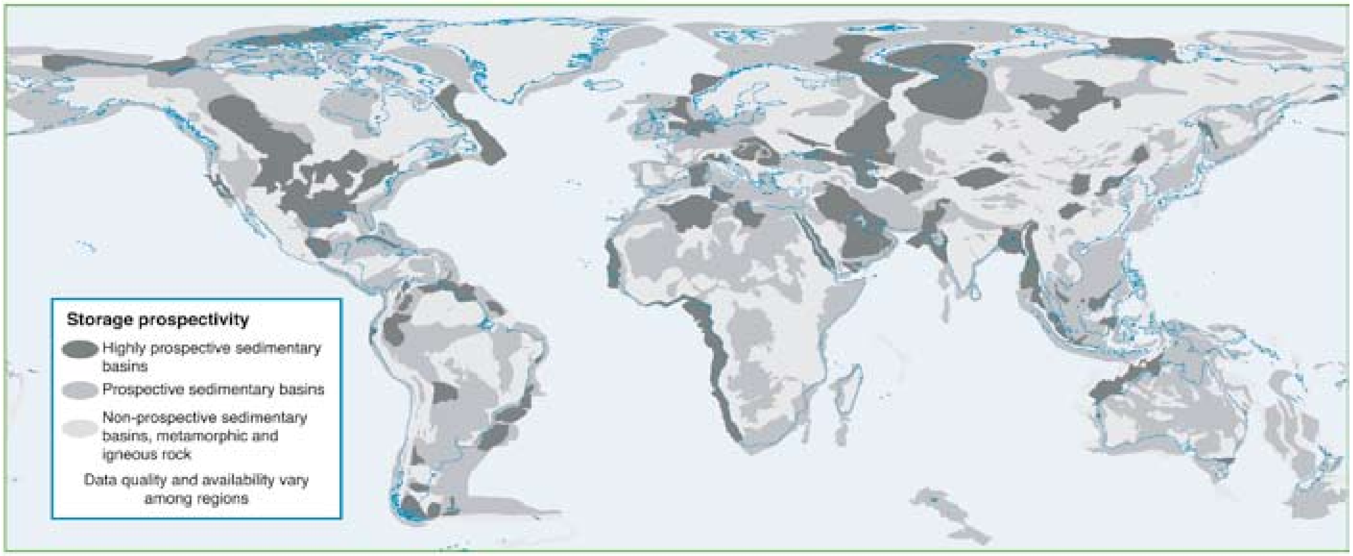

Figure 2.4 Prospective areas in sedimentary basins where suitable saline formations, oil or gas fields, or coal beds may be found. Locations for storage in coal beds are only partly included. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present in a given area based on the available information. This figure should be taken as a guide only, because it is based on partial data, the quality of which may vary from region to region, and which may change over time and with new information (Bradshaw and Dance, 2004).

storage sites that will affect their viability as potential solutions. As indicated above in this chapter, there are some 7,500 large stationary sources with emissions in excess of 0.1 $MtCO_2$ yr^{-1} and that number is projected to rise by 2050. The mapping does not take into account the 'capture factors' presented in Section 2.3.2.

2.4.3.1 Geological storage and source location matching

Chapter 5 includes detailed discussions of the geological characteristics of storage sites. Before discussing the global locations for geological storage opportunities, it is necessary to describe some basic fundamentals of geological storage. The world's geological provinces can be allocated to a variety of rock types, but the main ones relevant to geological storage are sedimentary basins that have undergone only minor tectonic deformation and are at least 1000 m thick with adequate reservoir/seal pairs to allow for the injection and trapping of CO_2. The petroleum provinces of the world are a subset of the sedimentary basins described above, and are considered to be promising locations for the geological storage of CO_2 (Bradshaw *et al*., 2002). These basins have adequate reservoir/seal pairs, and suitable traps for hydrocarbons, whether liquids or gases. The remaining geological provinces of the world can generally be categorized as igneous (rocks formed from crystallization of molten liquid) and metamorphic (pre-existing rocks formed by chemical and physical alteration under the influence of heat, pressure and chemically active fluids) provinces. These rock types are commonly known as hard-rock provinces, and they will not be favourable for CO_2 storage as they are generally not porous and permeable and will therefore not readily transmit fluids. More details on the suitability of sedimentary basins and characterization of specific sites are provided in Chapter 5.

Figure 2.4 shows the 'prospectivity'(see Annex II) of various parts of the world for the geological storage of CO_2. Prospectivity is a term commonly used in explorations for any geological resource, and in this case it applies to CO_2 storage space. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present in a given area based on the available information. By nature, it will change over time and with new information. Estimates of prospectivity are developed by examining data (if possible), examining existing knowledge, applying established conceptual models and, ideally, generating new conceptual models or applying an analogue from a neighbouring basin or some other geologically similar setting. The concept of prospectivity is often used when it is too complex or technically impossible to assign numerical estimates to the extent of a resource.

Figure 2.4 shows the world's geological provinces broken down into provinces that are thought, at a very simplistic level, to have CO_2 storage potential that is either: 1) highly prospective, 2) prospective, or 3) non-prospective (Bradshaw and Dance, 2004). Areas of high prospectivity are considered to include those basins that are world-class petroleum basins, meaning that they are the basins of the world that are producing substantial volumes of hydrocarbons. It also includes areas that are expected to have substantial storage potential. Areas of prospective storage potential are basins that are minor petroleum basins but not world-class, as well as other sedimentary basins that have not been highly deformed. Some of these basins will be highly prospective for CO_2 storage and others will have low prospectivity.

Determining the degree of suitability of any of these basins for CO_2 storage will depend on detailed work in each area. Areas that are non-prospective are highly deformed sedimentary basins and other geological provinces, mainly containing metamorphic and igneous rocks. Some of these

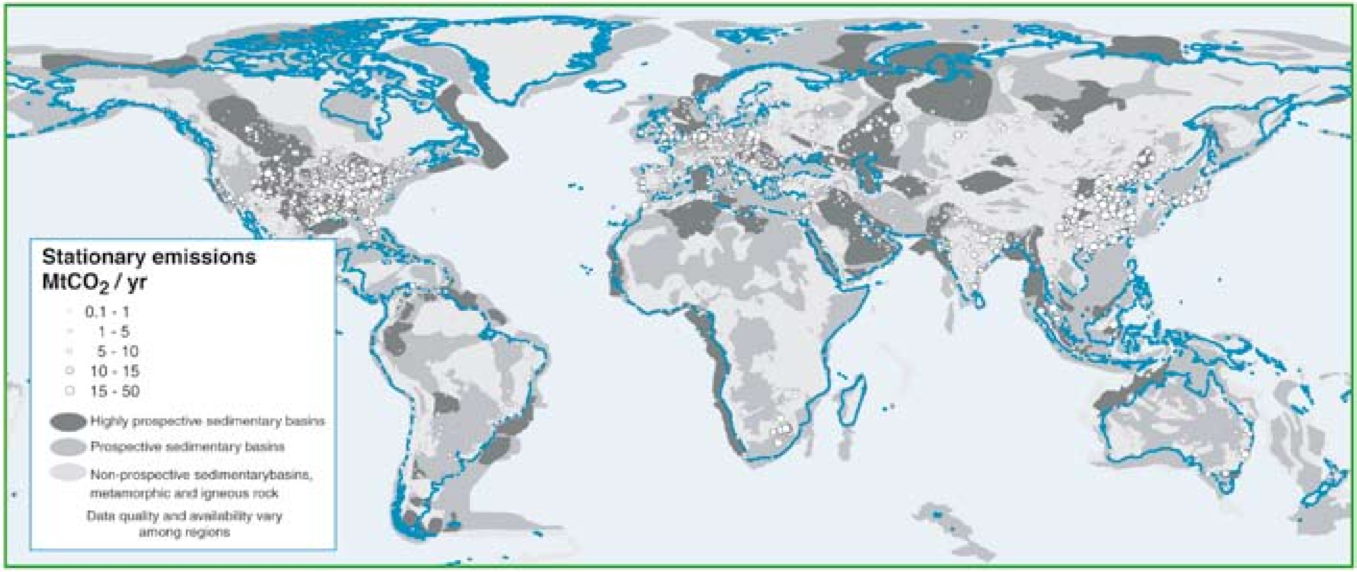

Figure 2.5 Geographical relationship between CO_2 emission sources and prospective geological storage sites. The dots indicate CO_2 emission sources of 0.1–50 $MtCO_2\ yr^{-1}$. Prospectivity is a qualitative assessment of the likelihood that a suitable storage location is present in a given area based on the available information. This figure should be taken as a guide only, because it is based on partial data, the quality of which may vary from region to region, and which may change over time and with new information.

provinces might have some local niche opportunities for CO_2 storage, but at this stage they would not be considered suitable for a conventional form of CO_2 storage. As Bradshaw and Dance (2004) explain, this map is subject to significant caveats and based on significant assumptions because of the data source from which it was generated. However, it can be used as a general (although not specific) guide at the global scale to the location of areas that are likely to provide opportunities for the geological storage of CO_2. Due to the generalized manner in which this map has been created, and the lack of specific or hard data for each of the basins assessed, the 'prospectivity' levels assigned to each category have no meaningful correlative statistical or probabilistic connotation. To achieve a numerical analysis of risk or certainty would require specific information about each and every basin assessed.

Figure 2.5 shows the overlap of the sedimentary basins that are prospective for CO_2 storage potential with the current locations of large sources of stationary emissions (IEA GHG, 2002a). The map can be simplistically interpreted to identify areas where large distances might be required to transport emissions from any given source to a geological storage location. It clearly shows areas with local geological storage potential and low numbers of emission sites (for example, South America) as well as areas with high numbers of emission sites and few geological storage options in the vicinity (the Indian sub-continent, for example). This map, however, does not address the relative capacity of any of the given sites to match either large emission sources or small storage capacities. Neither does it address any of the technical uncertainties that could exist at any of the storage sites, or the cost implications for the emission sources of the nature of the emission plant or the purity of the emission sources. Such issues of detailed source-to-store matching are dealt with in Chapter 5.

Figures 2.6, 2.7 and 2.8 show the regional emission clusters for twelve regions of the world and the available storage opportunities within each region. They also compare the relative ranking of the area of available prospective sedimentary basins in a 300 km radius around emission clusters (Bradshaw and Dance, 2004). The 300 km radius was selected because it was considered useful as an indicator of likely transport distances for potentially viable source-to-storage matches (see Chapter 5). Although this data could suggest trends, such as high emissions for China with a small area of prospective sedimentary basins, or a large area of prospective sedimentary basins with low emissions for the Middle East, it is premature to make too many assumptions until detailed assessments are made in each region as to the quality and viability of each sedimentary basin and specific proposed sites. Each basin will have its own technical peculiarities, and because the science of injection and storage of very large volumes of CO_2 is still developing, it is premature at this stage to make any substantive comments about the viability of individual sedimentary basins unless there are detailed data sets and assessments (see Chapter 5). These maps do, however, indicate where such detailed geological assessments will be required – China and India, for example – before a comprehensive assessment can be made of the likely worldwide impact of the geological storage of CO_2. These maps also show that CO_2 storage space is a resource, just like any other resource; some regions will have many favourable opportunities, and others will not be so well-endowed (Bradshaw and Dance, 2004).

Figure 2.9 shows those emission sources with high concentrations (>95%) of CO_2, with their proximity to prospective geological storage sites. Clusters of high-concentration sources can be observed in China and North America and to lesser extent in Europe.

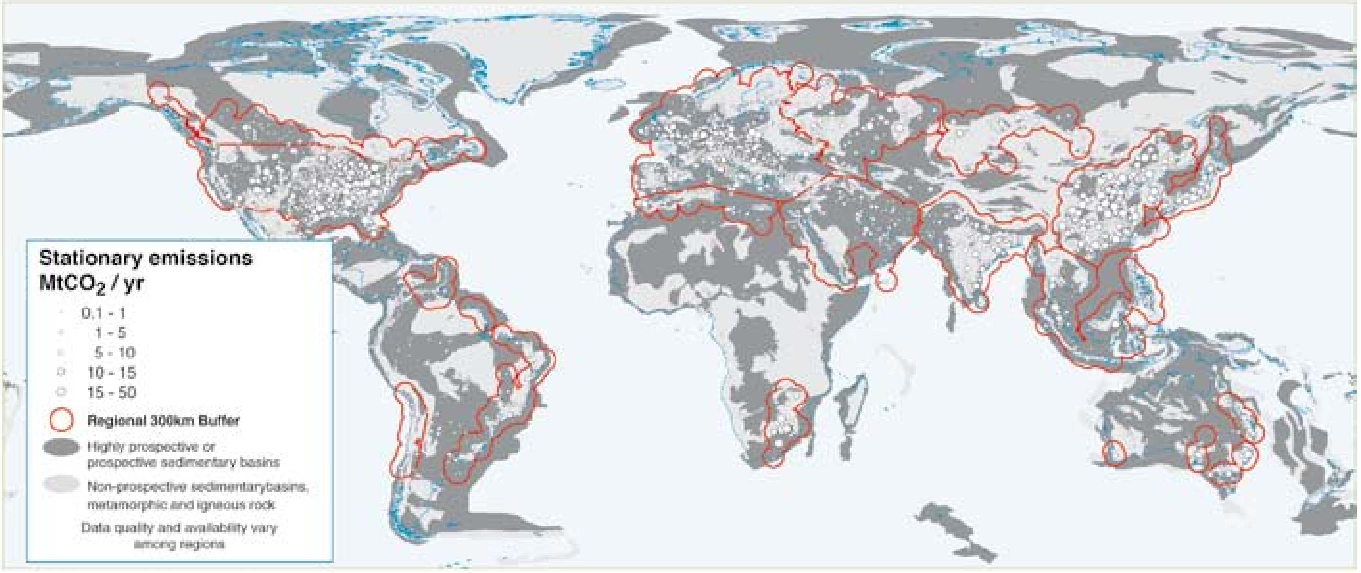

Figure 2.6 Regional emission clusters with a 300 km buffer relative to world geological storage prospectivity (Bradshaw and Dance, 2004).

2.4.3.2 Ocean storage and source-location matching

Due to a lack of publicly available literature, a review of the proximity of large CO_2 point sources and their geographical relationship to ocean storage opportunities on the global scale could not be undertaken. A related study was undertaken that analysed seawater scrubbing of CO_2 from power stations along the coastlines of the world. The study considered the number of large stationary sources (in this case, power generation plants) on the coastlines of the worldwide that are located within 100 km of the 1500 m ocean floor contour (IEA GHG, 2000a). Eighty-nine potential power generation sources were identified that were close to these deep-water locations. This number represents only a small proportion (< 2%) of the total number of large stationary sources in the power generation

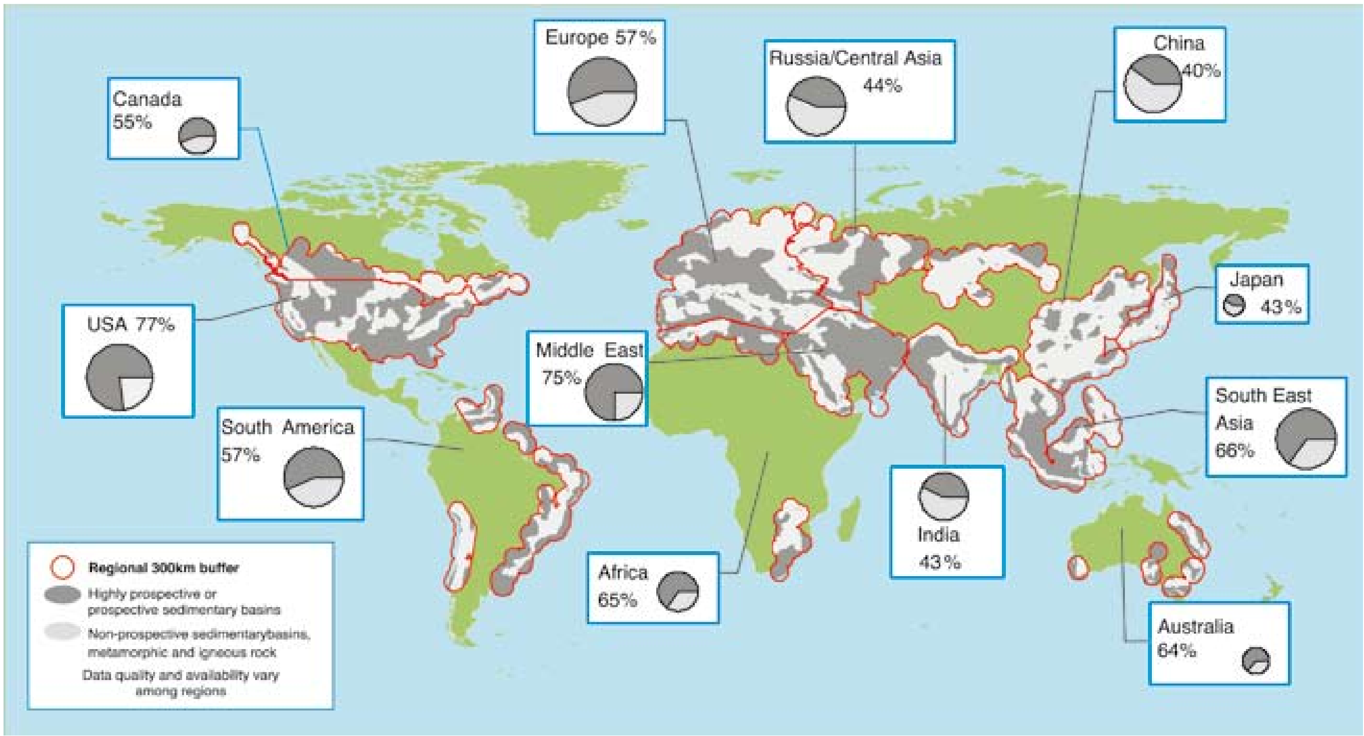

Figure 2.7 Regional storage opportunities determined by using a ratio (percentage) of all prospective areas to non-prospective areas within a 300 km buffer around major stationary emissions. The pie charts show the proportion of the prospective areas (sedimentary basins) in the buffer regions (Bradshaw and Dance, 2004).

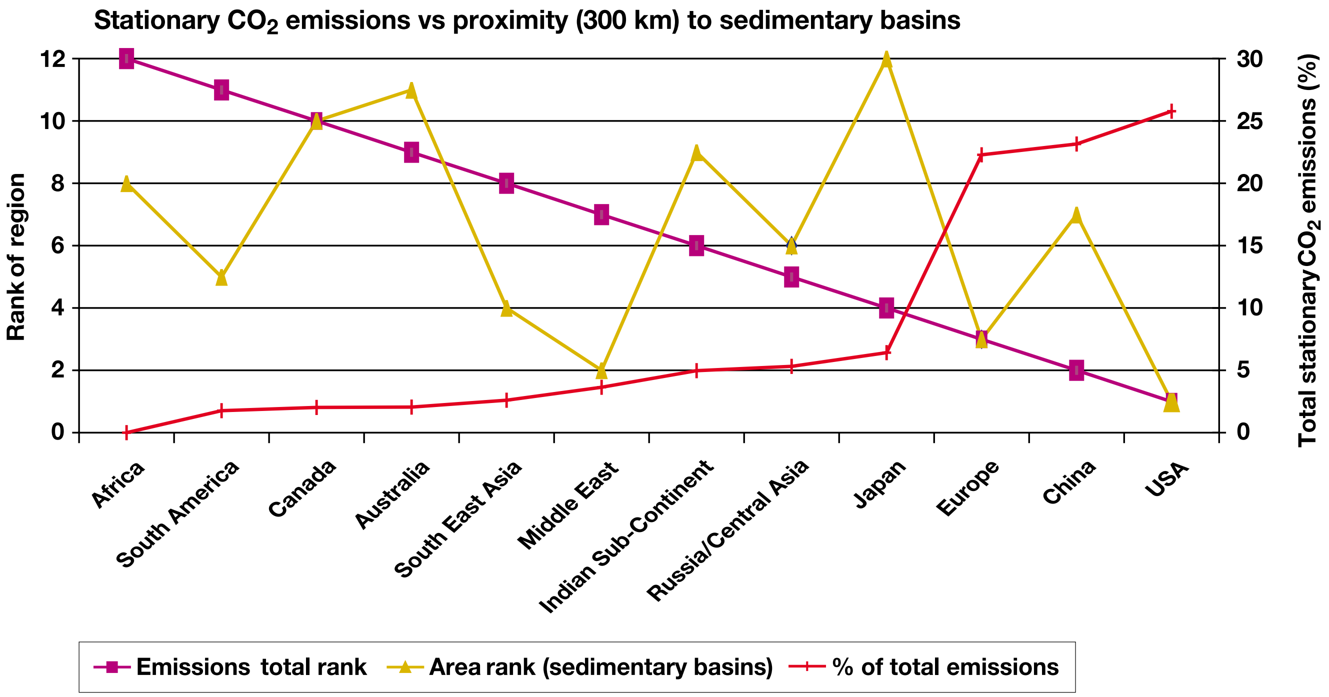

Figure 2.8 Proximity of emissions to sedimentary basins.

sector worldwide (see Section 2.1). A larger proportion of power plants could possibly turn to deep-ocean storage because transport over distances larger than 100 km may prove cost-effective in some cases; nevertheless, this study indicates that a higher fraction of large stationary sources could be more cost-effectively matched to geological storage reservoirs than ocean storage sites. There are many issues that will also need to be addressed when considering deep-ocean storage sites, including jurisdictional boundaries, site suitability, and environmental impact etc., which are discussed in Chapter 6. The spatial and temporal nature of ocean water-column injection may affect the approach to source and storage matching, as the CO_2 will not remain adjacent to the local region where the CO_2 is injected, and conceivably might migrate across jurisdictional boundaries and into sensitive environmental provinces.

2.5 Alternative energy carriers and CO_2 source implications

As discussed earlier in this chapter, a significant fraction of the world's CO_2 emissions comes from transport, residences, and other small, distributed combustion sources. Whilst it is

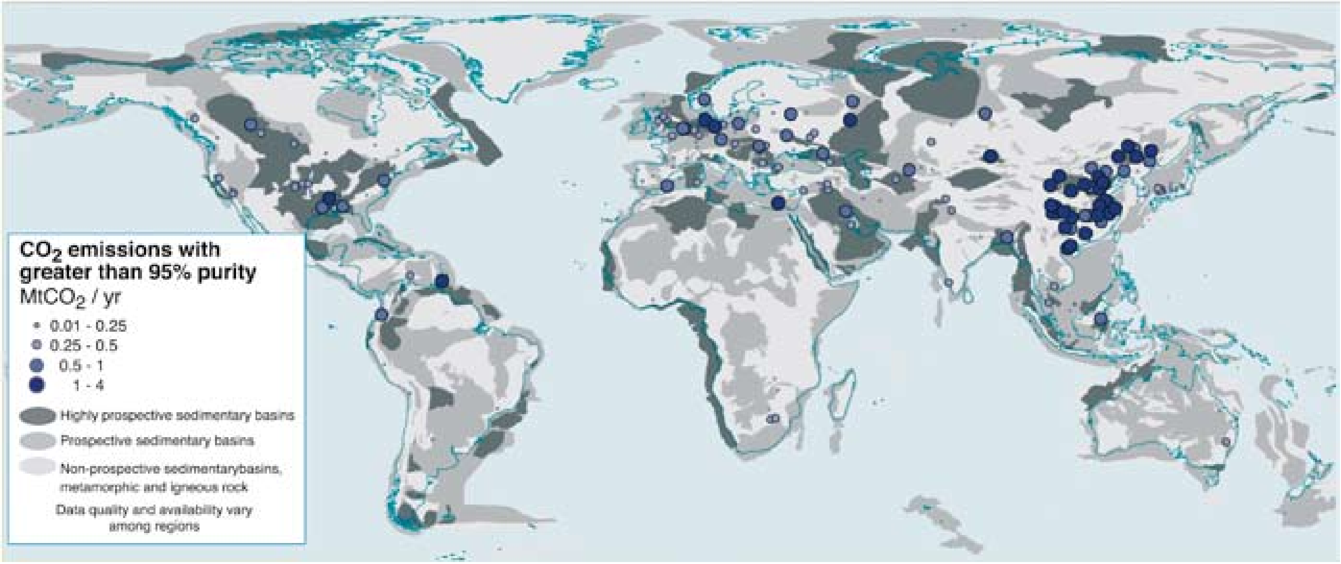

Figure 2.9 Geographical proximity of high-concentration CO_2 emission sources (> 95%) to prospective geological storage sites.

currently not economically feasible to capture and store CO_2 from these small, distributed sources, these emissions could be reduced if the fossil fuels used in these units were replaced with either:

- carbon-free energy carriers (e.g. electricity or hydrogen);
- energy carriers that are less carbon-intensive than conventional hydrocarbon fuels (e.g., methanol, Fischer-Tropsch liquids or dimethyl ether);
- biomass energy that can either be used directly or to produce energy carriers like bioethanol. If the biomass is grown sustainably the energy produced can be considered carbon-neutral.

In the first two cases, the alternative energy carriers can be produced in centralized plants that incorporate CO_2 capture and storage. In the case of biomass, CO_2 capture and storage can also be incorporated into the energy carrier production schemes. The aim of this section is to explore the implications that introducing such alternative energy carriers and energy sources might have for future large point sources of CO_2 emissions.

2.5.1 Carbon-free energy carriers

2.5.1.1 Electricity

The long-term trend has been towards the electrification of the energy economy, and this trend is expected to continue (IPCC, 2000). To the extent that expanded electricity use is a substitute for the direct use of fossil fuels (e.g., in transport, or for cooking or heating applications in households), the result can be less CO_2 emissions if the electricity is from carbon-free primary energy sources (renewable or nuclear) or from distributed generators such as fuel cells powered by hydrogen produced with near-zero fuel-cycle-wide emissions or from large fossil-fuel power plants at which CO_2 is captured and stored.

While, in principle, all energy could be provided by electricity, most energy projections envision that the direct use of fuels will be preferred for many applications (IPCC, 2000). In transport, for example, despite intensive developmental efforts, battery-powered electric vehicles have not evolved beyond niche markets because the challenges of high cost, heavy weight, and long recharging times have not been overcome. Whilst the prospects of current hybrid electric vehicles (which combine fossil fuel and electric batteries) penetrating mass markets seem good, these vehicles do not require charging from centralized electrical grids. The successful development of 'plug-in hybrids' might lead to an expanded role for electricity in transport but such vehicles would still require fuel as well as grid electricity. In summary, it is expected that, although electricity's share of total energy might continue to grow, most growth in large point sources of CO_2 emissions will be the result of increased primary energy demand.

2.5.1.2 Hydrogen

If hydrogen can be successfully established in the market as an energy carrier, a consequence could be the emergence of large new concentrated sources of CO_2 if the hydrogen is manufactured from fossil fuels in large pre-combustion decarbonization plants with CO_2 capture and storage. Such plants produce a high concentration source of CO_2 (see Chapter 3 for details on system design). Where fossil fuel costs are low and CO_2 capture and storage is feasible, hydrogen manufactured in this way is likely to be less costly than hydrogen produced from renewable or nuclear primary energy sources (Williams, 2003; NRC, 2004). It should be noted that this technology can be utilized only if production sites are within a couple of hundred kilometres of where the hydrogen will be used, since cost-effective, long-distance hydrogen transport represents a significant challenge. Producing hydrogen from fossil fuels could be a step in technological development towards a hydrogen economy based on carbon-free primary energy sources through the establishment of a hydrogen utilization infrastructure (Simbeck, 2003).

Energy market applications for hydrogen include its conversion to electricity electrochemically (in fuel cells) and in combustion applications. Substituting hydrogen for fossil fuel burning eliminates CO_2 emissions at the point of energy use. Much of the interest in hydrogen market development has focused on distributed stationary applications in buildings and on transport. Fuel cells are one option for use in stationary distributed energy systems at scales as small as apartment buildings and even single-family residences (Lloyd, 1999). In building applications, hydrogen could also be combusted for heating and cooking (Ogden and Williams, 1989). In the transport sector, the hydrogen fuel cell car is the focus of intense development activity, with commercialization targeted for the middle of the next decade by several major automobile manufacturers (Burns *et al.*, 2002). The main technological obstacles to the widespread use of fuel cell vehicles are the current high costs of the vehicles themselves and the bulkiness of compressed gaseous hydrogen storage (the only fully proven hydrogen storage technology), which restricts the range between refuelling (NRC, 2004). However, the currently achievable ranges might be acceptable to many consumers, even without storage technology breakthroughs (Ogden *et al.*, 2004).

Hydrogen might also be used in internal combustion engine vehicles before fuel cell vehicles become available (Owen and Gordon, 2002), although efficiencies are likely to be less than with fuel cells. In this case, the range between refuelling would also be less than for hydrogen fuel cell vehicles with the same performance (Ogden et al., 2004). For power generation applications, gas turbines originally designed for natural gas operation can be re-engineered to operate on hydrogen (Chiesa *et al.*, 2003).

Currently, there are a number of obstacles on the path to a hydrogen economy. They are: the absence of cost-competitive fuel cells and other hydrogen equipment and the absence of an infrastructure for getting hydrogen to consumers. These challenges are being addressed in many hydrogen R&D programmes and policy studies being carried out around the world (Sperling and Cannon, 2004). There are also safety concerns because, compared to other fuels, hydrogen has a wide flammability and detonation range, low ignition energy, and high flame speed. However, industrial experience shows that hydrogen can be manufactured and used safely in many applications (NRC, 2004).

There is widespread industrial experience with the production and distribution of hydrogen, mainly for the synthesis of ammonia fertilizer and hydro-treatment in oil refineries. Current global hydrogen production is 45 million t yr^{-1}, the equivalent to 1.4% of global primary energy use in 2000 (Simbeck, 2003). Forty-eight per cent is produced from natural gas, 30% from oil, 18% from coal, and 4% via electrolysis of water. Ammonia production, which consumes about 100,000 MW_t of hydrogen, is growing by 2–4% per year. Oil refinery demand for hydrogen is also increasing, largely because of the ongoing shift to heavier crude oils and regulations limiting the sulphur content of transport fuels. Most hydrogen is currently manufactured via steam methane reforming (SMR), steam reforming of naphtha, and the gasification of petroleum residues and coal. The SMR option is generally favoured due to its lower capital cost wherever natural gas is available at reasonable prices. Nevertheless, there are currently about 75 modern commercial gasification plants making about 20,000 MW_t of hydrogen from coal and oil refinery residues (NETL-DOE, 2002); these are mostly ammonia fertilizer plants and hydrogen plants in oil refineries in China, Europe, and North America. There are currently over 16,000 km of hydrogen pipelines around the world. Most are relatively short and located in industrial areas for large customers who make chemicals, reduce metals, and engage in the hydro-treatment of oil at refineries. The longest pipeline currently in operation is 400 km long and is located in a densely populated area of Europe, running from Antwerp to northern France. The pipeline operates at a pressure of about 60 atmospheres (Simbeck, 2004).

Fossil fuel plants producing hydrogen with CO_2 capture and storage would typically be large, producing volumes of the order of 1000 MW_t (720 t day^{-1})[6] in order to keep the hydrogen costs and CO_2 storage costs low. Per kg of hydrogen, the co-production rate would be about 8 $kgCO_2$ with SMR and 15 $kgCO_2$ with coal gasification, so that the CO_2 storage rates (for plants operated at 80% average capacity factor) would be 1.7 and 3.1 million tonnes per year for SMR and coal gasification plants respectively.

Making hydrogen from fossil fuels with CO_2 capture and storage in a relatively small number of large plants for use in large numbers of mobile and stationary distributed applications could lead to major reductions in fuel-cycle-wide emissions compared to petroleum-based energy systems. This takes into account all fossil fuel energy inputs, including energy for petroleum refining and hydrogen compression at refuelling stations (NRC, 2004; Ogden *et al.*, 2004). No estimates have yet been made of the number of large stationary, concentrated CO_2 sources that could be generated via such hydrogen production systems and their geographical distribution.

2.5.2 *Alternative energy carriers and CO_2 source implications*

Interest in synthetic liquid fuels stems from concerns about both the security of oil supplies (TFEST, 2004) and the expectation that it could possibly be decades before hydrogen can make a major contribution to the energy economy (NRC, 2004).

There is considerable activity worldwide relating to the manufacture of Fischer-Tropsch liquids from stranded natural gas supplies. The first major gas to liquids plant, producing 12,500 barrels per day, was built in Malaysia in 1993. Several projects are underway to make Fischer-Tropsch liquid fuels from natural gas in Qatar at plant capacities ranging from 30,000 to 140,000 barrels per day. Although gas to liquids projects do not typically produce concentrated by-product streams of CO_2, synthetic fuel projects using synthesis gas derived from coal (or other solid feedstocks such as biomass or petroleum residuals) via gasification could produce large streams of concentrated CO_2 that are good candidates for capture and storage. At Sasol in South Africa, coal containing some 20 million tonnes of carbon is consumed annually in the manufacture of synthetic fuels and chemicals. About 32% of the carbon ends up in the products, 40% is vented as CO_2 in dilute streams, and 28% is released as nearly pure CO_2 at a rate of about 20 million tonnes of CO_2 per year. In addition, since 2000, 1.5 million tonnes per year of CO_2 by-product from synthetic methane production at a coal gasification plant in North Dakota (United States) have been captured and transported 300 km by pipeline to the Weyburn oil field in Saskatchewan (Canada), where it is used for enhanced oil recovery (see Chapter 5 for more details). Coal-based synthetic fuel plants being planned or considered in China include six 600,000 t yr^{-1} methanol plants, two 800,000 t yr^{-1} dimethyl ether plants, and two or more large Fischer-Tropsch liquids plants[7]. In the United States, the Department of Energy is supporting a demonstration project in Pennsylvania to make 5,000 barrels/day of Fischer-Tropsch liquids plus 41 MW_e of electricity from low-quality coal.

If synthesis-gas-based energy systems become established in the market, economic considerations are likely to lead, as in the case of hydrogen production, to the construction of large facilities that would generate huge, relatively pure, CO_2 co-product streams. Polygeneration plants, for example plants that could produce synthetic liquid fuels plus electricity, would benefit as a result of economies of scale, economies of scope, and opportunities afforded by greater system operating flexibility (Williams *et al.*, 2000; Bechtel *et al.*, 2003; Larson and Ren, 2003; Celik *et al.*, 2005). In such plants, CO_2 could be captured from shifted synthesis gas streams both upstream and downstream of the synthesis reactor where the synthetic fuel is produced.

With CO_2 capture and storage, the fuel-cycle-wide greenhouse gas emissions per GJ for coal derived synthetic

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[6] A plant of this kind operating at 80% capacity could support 2 million hydrogen fuel cell cars with a gasoline-equivalent fuel economy of 2.9 L per 100 km driving 14,000 km per year.

[7] Most of the methanol would be used for making chemicals and for subsequent conversion to dimethyl ether, although some methanol will be used for transport fuel. The dimethyl ether would be used mainly as a cooking fuel.

fuels can sometimes be less than for crude oil-derived fuels. For example, a study of dimethyl ether manufacture from coal with CO_2 capture and storage found that fuel-cycle-wide greenhouse gas emissions per GJ ranged from 75 to 97% of the emission rate for diesel derived from crude oil, depending on the extent of CO_2 capture (Celik *et al*., 2005).

The CO_2 source implications of making synthetic low-carbon liquid energy carriers with CO_2 capture and storage are similar to those for making hydrogen from fossil fuels: large quantities of concentrated CO_2 would be available for capture at point sources. Again, no estimates have yet been made of the number of large stationary sources that could be generated or of their geographical distribution.

2.5.3 CO_2 source implications of biomass energy production

There is considerable interest in some regions of the world in the use of biomass to produce energy, either in dedicated plants or in combination with fossil fuels. One set of options with potentially significant but currently uncertain implications for future CO_2 sources is bioenergy with CO_2 capture and storage. Such systems could potentially achieve negative CO_2 emissions. The perceived CO_2 emission benefits and costs of such systems are discussed elsewhere in this report (see Chapters 3 and 8) and are not discussed further here. The aim of this section is to assess the current scale of emissions from biomass energy production, to consider how they might vary in the future, and therefore to consider their impact on the future number, and scale, of CO_2 emission sources.

2.5.3.1 Bioethanol production

Bioethanol is the main biofuel being produced today. Currently, the two largest producers of bioethanol are the USA and Brazil. The USA produced 11 billion litres in 2003, nearly double the capacity in 1995. Production is expected to continue to rise because of government incentives. Brazilian production was over 14 billion litres per year in 2003/2004, similar to the level in 1997/1998 (Möllersten *et al*., 2003). Bioethanol is used directly in internal combustion engines, without modification, as a partial replacement for petroleum-based fuels (the level of replacement in Europe and the USA is 5 to 10%).

Bioethanol plants are a high-concentration source of CO_2 at atmospheric pressure that can be captured and subsequently stored. As can be seen in Table 2.3, the numbers of these plants are significant in the context of high-purity sources, although their global distribution is restricted. These sources are comparable in size to those from ethylene oxide plants but smaller than those from ammonia plants.

Although the trend in manufacture is towards larger production facilities, the scale of future production will be determined by issues such as improvements in biomass production and conversion technologies, competition with other land use, water demand, markets for by-product streams and competition with other transport fuels.

On the basis of the literature currently available, it is not possible to estimate the number of bioethanol plants that will be built in the future or the likely size of their CO_2 emissions.

2.5.3.2 Biomass as a primary energy source

A key issue posed by biomass energy production, both with and without CO_2 capture and storage, is that of size. Current biomass energy production plants are much smaller than fossil fuel power plants; typical plant capacities are about 30 MW_e, with CO_2 emissions of less than 0.2 $MtCO_2$ per year. The size of these biomass energy production plants reflects the availability and dispersed nature of current biomass supplies, which are mainly crop and forestry residues.

The prospects for biomass energy production with CO_2 capture and storage might be improved in the future if economies of scale in energy production and/or CO_2 capture and storage can be realized. If, for instance, a CO_2 pipeline network is established in a country or region, then small CO_2 emission sources (including those from biomass energy plants) could be added to any nearby CO_2 pipelines if it is economically viable to do so. A second possibility is that existing large fossil fuel plants with CO_2 capture and storage represent an opportunity for the co-processing of biomass. Co-processing biomass at coal power plants already takes place in a number of countries. However, it must be noted that if biomass is co-processed with a fossil fuel, these plants do not represent new large-scale emissions sources. A third possibility is to build larger biomass energy production plants than the plants typically in place at present. Larger biomass energy production plants have been built or are being planned in a number of countries, typically those with extensive biomass resources. For example, Sweden already has seven combined heat and power plants using biomass at pulp mills, with each plant producing around 130 MW_e equivalent. The size of biomass energy production plants depends on local circumstances, in particular the availability of concentrated biomass sources; pulp mills and sugar processing plants offer concentrated sources of this kind.

Larger plants could also be favoured if there were a shift from the utilization of biomass residues to dedicated energy crops. Several studies have assessed the likely size of future biomass energy production plants, but these studies conflict when it comes to the scale issue. One study, cited in Audus and Freund (2004), surveyed 28 favoured sites using woody biomass crops in Spain and concluded that the average appropriate scale would be in the range 30 to 70 MW_e. This figure is based on the fact that transport distances longer than the assumed maximum of 40 km would render larger plants uneconomic. In contrast, another study based on dedicated energy crops in Brazil and the United States estimated that economies of scale outweigh the extra costs of transporting biomass over long distances. This study found that plant capacities of hundreds of MW_e were feasible (Marrison and Larson, 1995). Other studies have come up with similar findings (Dornburg and Faaij, 2001; Hamelinck and Faaij, 2002). A recent study analyzed a variety of options including both electricity and synthetic fuel production and indicated that large plants processing about 1000 MW_{th} of biomass would tend to be preferred for dedicated energy crops in the United States (Greene *et al.*, 2004).

The size of future emission sources from bioenergy options depends to a large degree on local circumstances and the extent to which economic forces and/or public policies will encourage the development of dedicated energy crops. The projections of annual global biomass energy use rise from 12–60 EJ by 2020, to 70–190 EJ per year by 2050, and to 120–380 EJ by 2100 in the SRES Marker Scenarios (IPCC, 2000), showing that many global energy modellers expect that dedicated energy crops may well become more and more important during the course of this century. So if bioenergy systems prove to be viable at scales suitable for CO_2 capture and storage, then the negative emissions potential of biomass (see Chapter 8) might, during the course of this century, become globally important. However, it is currently unclear to what extent it will be feasible to exploit this potential, both because of the uncertainties about the scale of bioenergy conversion and the extent to which dedicated biomass energy crops will play a role in the energy economy of the future.

In summary, based on the available literature, it is not possible at this stage to make reliable quantitative statements on number of biomass energy production plants that will be built in the future or the likely size of their CO_2 emissions.

2.6 Gaps in knowledge

Whilst it is possible to determine emission source data for the year 2000 (CO_2 concentration and point source geographical location) with a reasonable degree of accuracy for most industrial sectors, it is more difficult to predict the future location of emission point sources. Whilst all projections indicate there will be an increase in CO_2 emissions, determining the actual locations for new plants currently remains a subjective business.

A detailed description of the storage capacity for the world's sedimentary basins is required. Although capacity estimates have been made, they do not yet constitute a full resource assessment. Such information is essential to establish a better picture of the existing opportunities for storing the CO_2 generated at large point sources. At present, only a simplistic assessment is possible based on the limited data about the storage capacity currently available in sedimentary basins.

An analysis of the storage potential in the ocean for emissions from large point sources was not possible because detailed mapping indicating the relationship between storage locations in the oceans and point source emissions has not yet been carefully assessed.

This chapter highlights the fact that fossil fuel-based hydrogen production from large centralized plants will potentially result in the generation of more high-concentration emission sources. However, it is not currently possible to predict with any accuracy the number of these point sources in the future, or when they will be established, because of market development uncertainties surrounding hydrogen as an energy carrier. For example, before high-concentration CO_2 sources associated with hydrogen production for energy can be exploited, cost-effective end-use technologies for hydrogen (e.g., low-temperature fuel cells) must be readily available on the market. In addition, it is expected that it will take decades to build a hydrogen infrastructure that will bring the hydrogen from large centralized sources (where CCS is practical) to consumers.

Synthetic liquid fuels production or the co-production of liquid fuels and electricity via the gasification of coal or other solid feedstocks or petroleum residuals can also lead to the generation of concentrated streams of CO_2. It is unclear at the present time to what extent such synthetic fuels will be produced as alternatives to crude-oil-derived hydrocarbon fuels. The co-production options, which seem especially promising, require market reforms that make it possible to co-produce electricity at a competitive market price.

During the course of this century, biomass energy systems might become significant new large CO_2 sources, but this depends on the extent to which bioenergy conversion will take place in large plants, and the global significance of this option may well depend critically on the extent to which dedicated energy crops are pursued.

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