# 8. Costs and economic potential

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## Executive summary

The major components of a carbon dioxide capture and storage (CCS) system include capture (separation plus compression), transport, and storage (including measurement, monitoring and verification). In one form or another, these components are commercially available. However, there is relatively little commercial experience with configuring all of these components into fully integrated CCS systems at the kinds of scales which would likely characterize their future deployment. The literature reports a fairly wide range of costs for employing CCS systems with fossil-fired power production and various industrial processes. The range spanned by these cost estimates is driven primarily by site-specific considerations such as the technology characteristics of the power plant or industrial facility, the specific characteristics of the storage site, and the required transportation distance of carbon dioxide ($CO_2$). In addition, estimates of the future performance of components of the capture, transport, storage, measurement and monitoring systems are uncertain. The literature reflects a widely held belief that the cost of building and operating $CO_2$ capture systems will fall over time as a result of technological advances.

The cost of employing a full CCS system for electricity generation from a fossil-fired power plant is dominated by the cost of capture. The application of capture technology would add about 1.8 to 3.4 US\$ct $kWh^{-1}$ to the cost of electricity from a pulverized coal power plant, 0.9 to 2.2 US\$ct $kWh^{-1}$ to the cost for electricity from an integrated gasification combined cycle coal power plant, and 1.2 to 2.4 US\$ct $kWh^{-1}$ from a natural-gas combined-cycle power plant. Transport and storage costs would add between –1 and 1 US\$ct $kWh^{-1}$ to this range for coal plants, and about half as much for gas plants. The negative costs are associated with assumed offsetting revenues from $CO_2$ storage in enhanced oil recovery (EOR) or enhanced coal bed methane (ECBM) projects. Typical costs for transportation and geological storage from coal plants would range from 0.05–0.6 US\$ct $kWh^{-1}$. CCS technologies can also be applied to other industrial processes, such as hydrogen ($H_2$) production. In some of these non-power applications, the cost of capture is lower than for capture from fossil-fired power plants, but the concentrations and partial pressures of $CO_2$ in the flue gases from these sources vary widely, as do the costs. In addition to fossil-based energy conversion processes, CCS may be applied to biomass-fed energy systems to create useful energy (electricity or transportation fuels). The product cost of these systems is very sensitive to the potential price of the carbon permit and the associated credits obtained with systems resulting in negative emissions. These systems can be fuelled solely by biomass, or biomass can be co-fired in conventional coal-burning plants, in which case the quantity is normally limited to about 10–15% of the energy input.

Energy and economic models are used to study future scenarios for CCS deployment and costs. These models indicate that CCS systems are unlikely to be deployed on a large scale in the absence of an explicit policy that substantially limits greenhouse gas emissions to the atmosphere. The literature and current industrial experience indicate that, in the absence of measures to limit $CO_2$ emissions, there are only small, niche opportunities for the deployment of CCS technologies. These early opportunities for CCS deployment – that are likely to involve $CO_2$ captured from high-purity, low-cost sources and used for a value-added application such as EOR or ECBM production – could provide valuable early experience with CCS deployment, and create parts of the infrastructure and knowledge base needed for the future large-scale deployment of CCS systems.

With greenhouse gas emission limits imposed, many integrated assessment analyses indicate that CCS systems will be competitive with other large-scale mitigation options, such as nuclear power and renewable energy technologies. Most energy and economic modelling done to date suggests that the deployment of CCS systems starts to be significant when carbon prices begin to reach approximately 25–30 US\$/$tCO_2$ (90–110 US\$/tC). They foresee the large-scale deployment of CCS systems within a few decades from the start of any significant regime for mitigating global warming. The literature indicates that deployment of CCS systems will increase in line with the stringency of the modelled emission reduction regime. Least-cost $CO_2$ concentration stabilization scenarios, that also take into account the economic efficiency of the system, indicate that emissions mitigation becomes progressively more stringent over time. Most analyses indicate that, notwithstanding significant penetration of CCS systems by 2050, the majority of CCS deployment will occur in the second half of this century. They also indicate that early CCS deployment will be in the industrialized nations, with deployment eventually spreading worldwide. While different scenarios vary the quantitative mix of technologies needed to meet the modelled emissions constraint, the literature consensus is that CCS could be an important component of a broad portfolio of energy technologies and emission reduction approaches. In addition, CCS technologies are compatible with the deployment of other potentially important long-term greenhouse gas mitigation technologies such as $H_2$ production from biomass and fossil fuels.

Published estimates (for $CO_2$ stabilization scenarios between 450–750 ppmv) of the global cumulative amount of $CO_2$ that might be stored over the course of this century in the ocean and various geological formations span a wide range: from very small contributions to thousands of gigatonnes of $CO_2$. This wide range can largely be explained by the uncertainty of long-term, socio-economic, demographic and technological change, the main drivers of future $CO_2$ emissions. However, it is important to note that the majority of stabilization scenarios from 450–750 ppmv tend to cluster in the range of 220–2200 $GtCO_2$ (60–600 GtC). This demand for $CO_2$ storage appears to be within global estimates of total $CO_2$ storage capacity. The actual use of CCS is likely to be lower than the estimates for economic potential indicated by these energy and economic models, as there are other barriers to technology development not adequately accounted for in these modelling frameworks. Examples include concerns about environmental impact, the lack of a clear legal framework and uncertainty about how quickly learning-by-doing will lower costs. This chapter concludes with a review of knowledge gaps that affect the reliability of these model results.

Given the potential for hundreds to thousands of gigatonnes of $CO_2$ to be stored in various geological formations and the ocean, questions have been raised about the implications of gradual leakage from these reservoirs. From an economic perspective, such leakage – if it were to occur – can be thought of as another potential source of future $CO_2$ emissions, with the cost of offsetting this leaked $CO_2$ being equal to the cost of emission offsets when the stored $CO_2$ leaks to the atmosphere. Within this purely economic framework, the few studies that have looked at this topic indicate that some $CO_2$ leakage can be accommodated while progressing towards the goal of stabilizing atmospheric concentrations of $CO_2$.

## 8.1 Introduction

In this chapter, we address two of the key questions about any $CO_2$ mitigation technology: ‘How much will it cost?’ and ‘How do CCS technologies fit into a portfolio of greenhouse gas mitigation options?’ There are no simple answers to these questions. Costs for CCS technologies depend on many factors: fuel prices, the cost of capital, and costs for meeting potential regulatory requirements like monitoring, to just name a few. Add to this the uncertainties associated with technology development, the resource base for storage potential, the regulatory environment, etc., and it becomes obvious why there are many answers to what appear to be simple questions.

This chapter starts (in Section 8.2) by looking at the costs of the system components, namely capture and compression, transport, and storage (including monitoring costs and by-product credits from operations such as EOR). The commercial operations associated with each of these components provide a basis for the assessment of current costs. Although it involves greater uncertainty, an assessment is also included of how these costs will change in the future. The chapter then reviews the findings from economic modelling (Section 8.3). These models take component costs at various levels of aggregation and then model how the costs change with time and how CCS technologies compete with other $CO_2$ mitigation options given a variety of economic and policy assumptions. The chapter concludes with an examination of the economic implications of different storage times (Section 8.4) and a summary of the known knowledge gaps (Section 8.5).

## 8.2 Component Costs

This section presents cost summaries for the three key components of a CCS system, namely capture (including compression), transport, and storage. Sections 8.2.1–8.2.3 summarize the results from Chapters 3–7. Readers are referred to those chapters for more details of component costs. Results are presented here in the form most convenient for each section. Transport costs are given in US$/t$CO_2$ per kilometre, while storage costs are stated in US$/t$CO_2$ stored. Capture costs for different types of power plants are represented as an increase in the electricity generation cost (US\$ $MWh^{-1}$). A discussion of how one integrates the costs of capture, transport and storage for a particular system into a single value is presented in Section 8.2.4.

### *8.2.1 Capture and Compression*[1]

For most large sources of $CO_2$ (e.g., power plants), the cost of capturing $CO_2$ is the largest component of overall CCS costs. In this report, capture costs include the cost of compressing the $CO_2$ to a pressure suitable for pipeline transport (typically about 14 MPa). However, the cost of any additional booster compressors that may be needed is included in the cost of transport and/or storage.

The total cost of $CO_2$ capture includes the additional capital requirements, plus added operating and maintenance costs incurred for any particular application. For current technologies, a substantial portion of the overall cost is due to the energy requirements for capture and compression. As elaborated in Chapter 3, a large number of technical and economic factors related to the design and operation of both the $CO_2$ capture system, and the power plant or industrial process to which it is applied, influence the overall cost of capture. For this reason, the reported costs of $CO_2$ capture vary widely, even for similar applications.

**Table 8.1.** Summary of new plant performance and $CO_2$ capture cost based on current technology

Table 8.1 summarizes the $CO_2$ capture costs reported in Chapter 3 for baseload operations of new fossil fuel power plants (in the size range of 300–800 MW) employing current commercial technology. The most widely studied systems are new power plants based on coal combustion or gasification. For costs associated with retrofitting existing power plants, see Table 3.8. For a modern (high-efficiency) coal-burning power plant, $CO_2$ capture using an amine-based scrubber increases the cost of electricity generation (COE) by approximately 40 to 70 per cent while reducing $CO_2$ emissions per kilowatt-hour (kWh) by about 85%. The same $CO_2$ capture technology applied to a new natural gas combined cycle (NGCC) plant increases the COE by approximately 40 to 70 per cent. For a new coal-based plant employing an integrated gasification combined cycle (IGCC) system, a similar reduction in $CO_2$ using current technology (in this case, a water gas shift reactor followed by a physical absorption system) increases the COE by 20 to 55 per cent. The

[1] This section is based on material presented in Section 3.7. The reader is referred to that section for a more detailed analysis and literature references.

lower incremental cost for IGCC systems is due in large part to the lower gas volumes and lower energy requirements for $CO_2$ capture relative to combustion-based systems. It should be noted that the absence of industrial experience with large-scale capture of $CO_2$ in the electricity sector means that these numbers are subject to uncertainties, as is explained in Section 3.7.

Studies indicate that, in most cases, IGCC plants are slightly higher in cost without capture and slightly lower in cost with capture than similarly sized PC plants fitted with a CCS system. On average, NGCC systems have a lower COE than both types of new coal-based plants with or without capture for baseload operation. However, the COE for each of these systems can vary markedly due to regional variations in fuel cost, plant utilization, and a host of other parameters. NGCC costs are especially sensitive to the price of natural gas, which has risen significantly in recent years. So comparisons of alternative power system costs require a particular context to be meaningful.

For existing, combustion-based, power plants, $CO_2$ capture can be accomplished by retrofitting an amine scrubber to the existing plant. However, a limited number of studies indicate that the post-combustion retrofit option is more cost-effective when accompanied by a major rebuild of the boiler and turbine to increase the efficiency and output of the existing plant by converting it to a supercritical unit. For some plants, similar benefits can be achieved by repowering with an IGCC system that includes $CO_2$ capture technology. The feasibility and cost of any of these options is highly dependent on site-specific circumstances, including the size, age and type of unit, and the availability of space for accommodating a $CO_2$ capture system. There has not yet been any systematic comparison of the feasibility and cost of alternative retrofit and repowering options for existing plants, as well as the potential for more cost-effective options employing advanced technology such as oxyfuel combustion.

Table 8.1 also illustrates the cost of $CO_2$ capture in the production of $H_2$, a commodity used extensively today for fuels and chemical production, but also widely viewed as a potential energy carrier for future energy systems. Here, the cost of $CO_2$ capture is mainly due to the cost of $CO_2$ compression, since separation of $CO_2$ is already carried out as part of the $H_2$ production process. Recent studies indicate that the cost of $CO_2$ capture for current processes adds approximately 5 to 30 per cent to the cost of the $H_2$ product.

In addition to fossil-based energy conversion processes, $CO_2$ could also be captured in power plants fuelled with biomass. At present, biomass plants are small in scale (<100 $MW_e$). Hence, the resulting costs of capturing $CO_2$ are relatively high compared to fossil alternatives. For example, the capturing of 0.19 $MtCO_2$ a year in a 24 $MW_e$ biomass IGCC plant is estimated to be about 82 US$/$tCO_2$ (300 US$/tC), corresponding to an increase of the electricity costs due to capture of about 80 US$ $MWh^{-1}$ (Audus and Freund, 2004). Similarly, $CO_2$ could be captured in biomass-fuelled $H_2$ plants. The cost is reported to be between 22 and 25 US$/$tCO_2$ avoided (80–92 US$/tC) in a plant producing 1 million $Nm^3\ d^{-1}$ of $H_2$ (Makihira *et al.*, 2003). This corresponds to an increase in the $H_2$ product costs of about 2.7 US$ $GJ^{-1}$ (i.e., 20% of the $H_2$ costs without CCS). The competitiveness of biomass CCS systems is very sensitive to the value of $CO_2$ emission reductions, and the associated credits obtained with systems resulting in negative emissions. Moreover, significantly larger biomass plants could benefit from economies of scale, bringing down costs of the CCS systems to broadly similar levels as those in coal plants. However, there is too little experience with large-scale biomass plants as yet, so that their feasibility has still not been proven and their costs are difficult to estimate.

CCS technologies can also be applied to other industrial processes. Since these other industrial processes produce off-gases that are very diverse in terms of pressure and $CO_2$ concentration, the costs range very widely. In some of these non-power applications where a relatively pure $CO_2$ stream is produced as a by-product of the process (e.g., natural gas processing, ammonia production), the cost of capture is significantly lower than capture from fossil-fuel-fired power plants. In other processes like cement or steel production, capture costs are similar to, or even higher than, capture from fossil-fuel-fired power plants.

New or improved technologies for $CO_2$ capture, combined with advanced power systems and industrial process designs, can significantly reduce the cost of $CO_2$ capture in the future. While there is considerable uncertainty about the magnitude and timing of future cost reductions, studies suggest that improvements to current commercial technologies could lower $CO_2$ capture costs by at least 20–30%, while new technologies currently under development may allow for more substantial cost reductions in the future. Previous experience indicates that the realization of cost reductions in the future requires sustained R&D in conjunction with the deployment and adoption of commercial technologies.

### *8.2.2 Transport*[2]

The most common and usually the most economical method to transport large amounts of $CO_2$ is through pipelines. A cost-competitive transport option for longer distances at sea might be the use of large tankers.

The three major cost elements for pipelines are construction costs (e.g., material, labour, possible booster station), operation and maintenance costs (e.g., monitoring, maintenance, possible energy costs) and other costs (e.g., design, insurance, fees, right-of-way). Special land conditions, like heavily populated areas, protected areas such as national parks, or crossing major waterways, may have significant cost impacts. Offshore pipelines are about 40% to 70% more costly than onshore pipes of the same size. Pipeline construction is considered to be a mature technology and the literature does not foresee many cost reductions.

**Figure 8.1.** $CO_2$ transport costs range for onshore and offshore pipelines per 250 km, 'normal' terrain conditions. The figure shows high (solid lines) and low ranges (dotted lines). Data based on various sources (for details see Chapter 4).

Figure 8.1 shows the transport costs for 'normal' terrain conditions. Note that economies of scale dramatically reduce the cost, but that transportation in mountainous or densely populated areas could increase cost.

Tankers could also be used for transport. Here, the main cost elements are the tankers themselves (or charter costs), loading and unloading facilities, intermediate storage facilities, harbour fees, and bunker fuel. The construction costs for large special-purpose $CO_2$ tankers are not accurately known since none have been built to date. On the basis of preliminary designs, the costs of $CO_2$ tankers are estimated at US$ 34 million for ships of 10,000 tonnes, US$ 58 million for 30,000-tonne vessels, and US$ 82 million for ships with a capacity of 50,000 tonnes.

To transport 6 $MtCO_2$ per year a distance of 500 km by ship would cost about 10 US$/$tCO_2$ (37 US$/tC) or 5 US$/$tCO_2$/250km (18 US$/tC/250km). However, since the cost is relatively

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[2] This section is based on material presented in Section 4.6. The reader is referred to that section for a more detailed analysis and literature references.

insensitive to distance, transporting the same 6 $MtCO_2$ a distance of 1250 km would cost about 15 US$/$tCO_2$ (55 US$/tC) or 3 US$/$tCO_2$/250km (11 US$/tC/250km). This is close to the cost of pipeline transport, illustrating the point that ship transport becomes cost-competitive with pipeline transport if $CO_2$ needs to be transported over larger distances. However, the break-even point beyond which ship transportation becomes cheaper than pipeline transportation is not simply a matter of distance; it involves many other aspects.

### *8.2.3 Storage*

#### *8.2.3.1 Geological storage*[3]

Because the technologies and equipment used for geological storage are widely used in the oil and gas industries, the cost estimates can be made with confidence. However, there will be a significant range and variability of costs due to site-specific factors: onshore versus offshore, the reservoir depth and the geological characteristics of the storage formation (e.g., permeability, thickness, etc.). Representative estimates of the cost for storage in saline formations and disused oil and gas fields (see Table 8.2) are typically between 0.5–8.0 US$/$tCO_2$ stored (2–29 US$/tC), as explained in Section 5.9.3. The lowest storage costs will be associated with onshore, shallow, high permeability reservoirs and/or the reuse of wells and infrastructure in disused oil and gas fields.

The full range of cost estimates for individual options is very large. Cost information for storage monitoring is currently limited, but monitoring is estimated to add 0.1–0.3 US$ per tonne of $CO_2$ stored (0.4–1.1 US$/tC). These estimates do not include any well remediation or long-term liabilities. The costs of storage monitoring will depend on which technologies are used for how long, regulatory requirements and how long-term monitoring strategies evolve.

When storage is combined with EOR, enhanced gas recovery (EGR) or ECBM, the benefits of enhanced production can offset some of the capture and storage costs. Onshore EOR operations have paid in the range of 10–16 US$ per tonne of $CO_2$ (37–59 US$/tC). The economic benefit of enhanced production depends very much on oil and gas prices. It should be noted that most of the literature used as the basis for this report did not take into account the rise in oil and gas prices that started in 2003. For example, oil at 50 US$/barrel could justify a credit of 30 US$/$tCO_2$ (110 US$/tC). The economic benefits from enhanced production make EOR and ECBM potential early cost-effective options for geological storage.

**Table 8.2.** Estimates of $CO_2$ storage costs

#### *8.2.3.2 Ocean storage*[4]

The cost of ocean storage is a function of the distance offshore and injection depth. Cost components include offshore transportation and injection of the $CO_2$. Various schemes for ocean storage have been considered. They include:

- tankers to transport low temperature (–55 to –50$^{o}$C), high pressure (0.6–0.7 MPa) liquid $CO_2$ to a platform, from where it could be released through a vertical pipe to a depth of 3000 m;
- carrier ships to transport liquid $CO_2$, with injection through a towed pipe from a moving dispenser ship;

[3] This section is based on material presented in Section 5.9. The reader is referred to that section for a more detailed analysis and literature references.

[4] This section is based on material presented in Section 6.9. The reader is referred to that section for a more detailed analysis and literature references.

- undersea pipelines to transport $CO_2$ to an injection site.

Table 8.2 provides a summary of costs for transport distances of 100–500 km offshore and an injection depth of 3000 m.

Chapter 6 also discusses the option of carbonate neutralization, where flue-gas $CO_2$ is reacted with seawater and crushed limestone. The resulting mixture is then released into the upper ocean. The cost of this process has not been adequately addressed in the literature and therefore the possible cost of employing this process is not addressed here.

#### *8.2.3.3 Storage via mineral carbonation*[5]

Mineral carbonation is still in its R&D phase, so costs are uncertain. They include conventional mining and chemical processing. Mining costs include ore extraction, crushing and grinding, mine reclamation and the disposal of tailings and carbonates. These are conventional mining operations and several studies have produced cost estimates of 10 US$/t$CO_2$ (36 US$/tC) or less. Since these estimates are based on similar mature and efficient operations, this implies that there is a strong lower limit on the cost of mineral storage. Carbonation costs include chemical activation and carbonation. Translating today's laboratory implementations into industrial practice yields rough cost estimates of about 50–100 US$/t$CO_2$ stored (180–370 US$/tC). Costs and energy penalties (30–50% of the power plant output) are dominated by the activation of the ore necessary to accelerate the carbonation reaction. For mineral storage to become practical, additional research must reduce the cost of the carbonation step by a factor of three to four and eliminate a significant portion of the energy penalty by, for example, harnessing as much as possible the heat of carbonation.

### *8.2.4 Integrated systems*

The component costs given in this section provide a basis for the calculation of integrated system costs. However, the cost of mitigating $CO_2$ emissions cannot be calculated simply by summing up the component costs for capture, transport and storage in units of 'US$/t$CO_2$'. This is because the amount of $CO_2$ captured will be different from the amount of atmospheric $CO_2$ emissions 'avoided' during the production of a given amount of a useful product (e.g., a kilowatt-hour of electricity or a kilogram of $H_2$). So any cost expressed per tonne of $CO_2$ should be clearly defined in terms of its basis, e.g., either a *captured* basis or an *avoided* basis (see Box 8.1). Mitigation cost is best represented as avoided cost. Table 8.3 presents ranges for total avoided costs for $CO_2$ capture, transport, and storage from four types of sources.

[5] This section is based on material presented in Section 7.2. The reader is referred to that section for a more detailed analysis and literature references.

**Box 8.1.** Defining avoided costs for a fossil fuel power plant

In general, the capture, transport, and storage of $CO_2$ require energy inputs. For a power plant, this means that amount of fuel input (and therefore $CO_2$ emissions) increases per unit of net power output. As a result, the amount of $CO_2$ produced per unit of product (e.g., a kWh of electricity) is greater for the power plant with CCS than the reference plant, as shown in the diagram below. To determine the $CO_2$ reductions one can attribute to CCS, one needs to compare $CO_2$ emissions of the plant with capture to those of the reference plant without capture. These are the avoided emissions. Unless the energy requirements for capture and storage are zero, the amount of $CO_2$ avoided is always less than the amount of $CO_2$ captured. The cost in US$/tonne avoided is therefore greater than the cost in US$/tonne captured.

**Figure 8.2.** $CO_2$ capture and storage from power plants. The increased $CO_2$ production resulting from loss in overall efficiency of power plants due to the additional energy required for capture, transport and storage, and any leakage from transport result in a larger amount of "$CO_2$ produced per unit of product"(lower bar) relative to the reference plant (upper bar) without capture

**Table 8.3a.** Range of total costs for $CO_2$ capture, transport, and geological storage based on current technology for new power plants

**Table 8.3b.** Range of total costs for $CO_2$ capture, transport, and geological storage based on current technology for a new $H_2$ production plant

The mitigation costs (US$/t$CO_2$ avoided) reported in Table 8.3 are context-specific and depend very much on what is chosen as a reference plant. In Table 8.3, the reference plant is a power plant of the same type as the power plant with CCS. The mitigation costs here therefore represent the incremental cost of capturing and storing $CO_2$ from a particular type of plant.

In some situations, it can be useful to calculate a cost of $CO_2$ avoided based on a reference plant that is different from the CCS plant (e.g., a PC or IGCC plant with CCS using an NGCC reference plant). In Table 8.4, the reference plant represents the least-cost plant that would 'normally' be built at a particular location in the absence of a carbon constraint. In many regions today, this would be either a PC plant or an NGCC plant.

**Table 8.4.** Mitigation cost for different combinations of reference and CCS plants based on current technology and new power plants

A $CO_2$ mitigation cost also can be defined for a collection of plants, such as a national energy system, subject to a given level of $CO_2$ abatement. In this case the plant-level product costs presented in this section would be used as the basic inputs to energy-economic models that are widely used for policy analysis and for the quantification of overall mitigation strategies and costs for $CO_2$ abatement. Section 8.3 discusses the nature of these models and presents illustrative model results, including the cost of CCS, its economic potential, and its relationship to other mitigation options.

## 8.3 CCS deployment scenarios

Energy-economic models seek the mathematical representation of key features of the energy system in order to represent the evolution of the system under alternative assumptions, such as population growth, economic development, technological change, and environmental sensitivity. These models have been employed increasingly to examine how CCS technologies would deploy in a greenhouse gas constrained environment. In this section we first provide a brief introduction to the types of energy and economic models and the main assumptions driving future greenhouse gas emissions and the corresponding measures to reduce them. We then turn to the principal focus of this section: an examination of the literature based on studies using these energy and economic models, with an emphasis on what they say about the potential use of CCS technologies.

### *8.3.1 Model approaches and baseline assumptions*

The modelling of climate change abatement or mitigation scenarios is complex and a number of modelling techniques have been applied, including input-output models, macroeconomic (top-down) models, computable general equilibrium (CGE) models and energy-sector-based engineering models (bottom-up).

#### *8.3.1.1 Description of bottom-up and top-down models*

The component and systems level costs provided in Section 8.2 are based on technology-based bottom-up models. These models can range from technology-specific, engineering-economic calculations embodied in a spreadsheet to broader, multi-technology, integrated, partial-equilibrium models. This may lead to two contrasting approaches: an engineering-economic approach and a least-cost equilibrium one. In the first approach, each technology is assessed independently, taking into account all its parameters; partial-equilibrium least-cost models consider all technologies simultaneously and at a higher level of aggregation before selecting the optimal mix of technologies in all sectors and for all time periods.

Top-down models evaluate the system using aggregate economic variables. Econometric relationships between aggregated variables are generally more reliable than those between disaggregated variables, and the behaviour of the models tends to be more stable. It is therefore common to adopt high levels of aggregation for top-down models; especially when they are applied to longer-term analyses. Technology diffusion is often described in these top-down models in a more stylized way, for example using aggregate production functions with price-demand or substitution elasticities.

Both types of models have their strengths and weaknesses. Top-down models are useful for, among other things, calculating gross economic cost estimates for emissions mitigation. Most of these top-down macro-economic models tend to overstate costs of meeting climate change targets because, among other reasons, they do not take adequate account of the potential for no-regret measures and they are not particularly adept at estimating the benefits of climate change mitigation. On the other hand, many of these models – and this also applies to bottom-up models – are not adept at representing economic and institutional inefficiencies, which would lead to an underestimation of emissions mitigation costs.

Technologically disaggregated bottom-up models can take some of these benefits into account but may understate the costs of overcoming economic barriers associated with their deployment in the market. Recent modelling efforts have focused on the coupling of top-down and bottom-up models in order to develop scenarios that are consistent from both the macroeconomic and systems engineering perspectives. Readers interested in a more detailed discussion of these modelling frameworks and their application to understanding future energy, economic and emission scenarios are encouraged to consult the IPCC's Working Group III's assessment of the international work on both bottom-up and top-down analytical approaches (Third Assessment Report; IPCC, 2001).

*8.3.1.2 Assumptions embodied in emissions baselines*

Integrated Assessment Models (IAMs) constitute a particular category of energy and economic models and will be used here to describe the importance of emissions baselines before examining model projections of potential future CCS use. IAMs integrate the simulation of climate change dynamics with the modelling of the energy and economic systems. A common and illuminating type of analysis conducted with IAMs, and with other energy and economic models, involves the calculation of the cost differential or the examination of changes in the portfolio of energy technologies used when moving from a baseline (i.e., no climate policy) scenario to a control scenario (i.e., a case where a specific set of measures designed to constrain GHG emissions is modelled). It is therefore important to understand what influences the nature of these baseline scenarios. A number of parameters spanning economic, technological, natural and demographic resources shape the energy use and resulting emissions trajectories of these baseline cases. How these parameters change over time is another important aspect driving the baseline scenarios. A partial list of some of the major parameters that influence baseline scenarios include, for example, modelling assumptions centring on:

- global and regional economic and demographic developments;
- costs and availability of
  1) global and regional fossil fuel resources
  2) fossil-based energy conversion technologies (power generation, $H_2$ production, etc.), including technology-specific parameters such as efficiencies, capacity factors, operation and maintenance costs as well as fuel costs.
  3) zero-carbon energy systems (renewables and nuclear), which might still be non-competitive in the baseline but may play a major role competing for market shares with CCS if climate policies are introduced;
- rates of technological change in the baseline and the specific way in which technological change is represented in the model;
- the relative contribution of $CO_2$ emissions from different economic sectors.

Modelling all of these parameters as well as alternative assumptions for them yields a large number of ‘possible futures’. In other words, they yield a number of possible baseline scenarios. This is best exemplified by the Special Report on Emission Scenarios (SRES, 2000): it included four different narrative storylines and associated scenario families, and identified six ‘illustrative’ scenario groups – labelled A1FI, A1B, A1T, A2, B1, B2 – each representing different plausible combinations of socio-economic and technological developments in the absence of any climate policy (for a detailed discussion of these cases, see SRES, 2000). The six scenario groups depict alternative developments of the energy system based on different assumptions about economic and demographic change, hydrocarbon resource availability, energy demand and prices, and technology costs and their performance. They lead to a wide range of possible future worlds and $CO_2$ emissions consistent with the full uncertainty range of the underlying literature (Morita and Lee, 1998). The cumulative emissions from 1990 to 2100 in the scenarios range from less than 2930 to 9170 $GtCO_2$ (800 to 2500 GtC). This range is divided into four intervals, distinguishing between scenarios with high, medium-high, medium-low, and low emissions:

- high (≥6600 $GtCO_2$ or ≥1800 GtC);
- medium-high (5320–6600 $GtCO_2$ or 1450–1800 GtC);
- medium-low (4030–5320 $GtCO_2$ or 1100–1450 GtC);
- low (≤4030 $GtCO_2$ or ≤1100 GtC).

As illustrated in Figure 8.3, each of the intervals contains multiple scenarios from more than one of the six SRES scenario groups (see the vertical bars on the right side of Figure 8.3, which show the ranges for cumulative emissions of the respective SRES scenario group). Other scenario studies, such as the earlier set of IPCC scenarios developed in 1992 (Pepper *et al*., 1992) project similar levels of cumulative emissions over the period 1990 to 2100, ranging from 2930 to 7850 $GtCO_2$ (800 to 2140 GtC). For the same time horizon, the IIASA-WEC scenarios (Nakicenovic *et al*., 1998) report 2270–5870 $GtCO_2$ (620–1600 GtC), and the Morita and Lee (1998) database – which includes more than 400 emissions scenarios – report cumulative emissions up to 12280 $GtCO_2$ (3350 GtC).

**Figure 8.3.** Annual and cumulative global emissions from energy and industrial sources in the SRES scenarios ($GtCO_2$). Each interval contains alternative scenarios from the six SRES scenario groups that lead to comparable cumulative emissions. The vertical bars on the right-hand side indicate the ranges of cumulative emissions (1990–2100) of the six SRES scenario groups.

The SRES scenarios illustrate that similar future emissions can result from very different socio-economic developments, and that similar developments in driving forces can nonetheless result in wide variations in future emissions. The scenarios also indicate that the future development of energy systems will play a central role in determining future emissions and suggests that technological developments are at least as important a driving force as demographic change and economic development. These findings have major implications for CCS, indicating that the pace at which these technologies will be deployed in the future – and therefore their long-term potential – is affected not so much by economic or demographic change but rather by the choice of the technology path of the energy system, the major driver of future emissions. For a detailed estimation of the technical potential of CCS by sector for some selected SRES baseline scenarios, see Section 2.3.2. In the next section we shall discuss the economic potential of CCS in climate control scenarios.

### *8.3.2 CCS economic potential and implications*

As shown by the SRES scenarios, uncertainties associated with alternative combinations of socio-economic and technological developments may lead to a wide range of possible future emissions. Each of the different baseline emissions scenarios has different implications for the potential use of CCS technologies in emissions control cases.[6] Generally, the size of the future market for CCS depends mostly on the carbon intensity of the baseline scenario and the stringency of the assumed climate stabilization target. The higher the $CO_2$ emissions in the baseline, the more emissions reductions are required to achieve a given level of allowable emissions, and the larger the markets for CCS. Likewise, the tighter the modelled constraint on $CO_2$ emissions, the more CCS deployment there is likely to be. This section will examine what the literature says about possible CCS deployment rates, the timing of CCS deployment, the total deployment of these systems under various scenarios, the economic impact of CCS systems and how CCS systems interact with other emissions mitigation technologies.

#### *8.3.2.1 Key drivers for the deployment of CCS*

Energy and economic models are increasingly being employed to examine how CCS technologies would deploy in environments where $CO_2$ emissions are constrained (i.e., in control cases). A

[6] As no climate policy is assumed in SRES, there is also no economic value associated with carbon. The potential for CCS in SRES is therefore limited to applications where the supplementary benefit of injecting $CO_2$ into the ground exceeds its costs (e.g., EOR or ECBM). The potential for these options is relatively small as compared to the long-term potential of CCS in stabilization scenarios. Virtually none of the global modelling exercises in the literature that incorporate SRES include these options and so there is also no CCS system deployment assumed in the baseline scenarios.

number of factors have been identified that drive the rate of CCS deployment and the scale of its ultimate deployment in modelled control cases:[7]

1. *The policy regime*; the interaction between CCS deployment and the policy regime in which energy is produced and consumed cannot be overemphasized; the magnitude and timing of early deployment depends very much on the policy environment; in particular, the cumulative extent of deployment over the long term depends strongly on the stringency of the emissions mitigation regime being modelled; comparatively low stabilization targets (e.g., 450 ppmv) foster the relatively faster penetration of CCS and the more intensive use of CCS (where 'intensity of use' is measured both in terms of the percentage of the emissions reduction burden shouldered by CCS as well as in terms of how many cumulative gigatonnes of $CO_2$ is to be stored) (Dooley *et al*., 2004b; Gielen and Podanski, 2004; Riahi and Roehrl, 2000);
2. *The reference case (baseline)*; storage requirements for stabilizing $CO_2$ concentrations at a given level are very sensitive to the choice of the baseline scenario. In other words, the assumed socio-economic and demographic trends, and particularly the assumed rate of technological change, have a significant impact on CCS use (see Section 8.4.1, Riahi and Roehrl, 2000; Riahi *et al*., 2003);
3. *The nature, abundance and carbon intensity of the energy resources / fuels* assumed to exist in the future (e.g., a future world where coal is abundant and easily recoverable would use CCS technologies more intensively than a world in which natural gas or other less carbon-intensive technologies are inexpensive and widely available). See Edmonds and Wise (1998) and Riahi and Roehrl (2000) for a comparison of two alternative regimes of fossil fuel availability and their interaction with CCS;
4. *The introduction of flexibility mechanisms such as emissions trading* can significantly influence the extent of CCS deployment. For example, an emissions regime with few, or significantly constrained, emissions trading between nations entails the use of CCS technologies sooner and more extensively than a world in which there is efficient global emissions trading and therefore lower carbon permit prices (e.g., Dooley *et al*., 2000 and Scott *et al*., 2004). Certain regulatory regimes that explicitly emphasize CCS usage can also accelerate its deployment (e.g., Edmonds and Wise, 1998).
5. *The rate of technological change (induced through learning or other mechanisms)* assumed to take place with CCS and other salient mitigation technologies (e.g., Edmonds *et al*., 2003, or Riahi *et al*., 2003). For example, Riahi *et al.* (2003) indicate that the long-term economic potential of CCS systems would increase by a factor of 1.5 if it assumed that technological learning for CCS systems would take place at rates similar to those observed historically for sulphur removal technologies when compared to the situation where no technological change is specified.[8]

The marginal value of $CO_2$ emission reduction permits is one of the most important mechanisms through which these factors impact CCS deployment. CCS systems tend to deploy quicker and more extensively in cases with higher marginal carbon values. Most energy and economic modelling done to date suggests that CCS systems begin to deploy at a significant level when carbon dioxide prices begin to reach approximately 25–30 US\$/t$CO_2$ (90–110 US\$/tC) (IEA, 2004;

[7] Integrated assessment models represent the world in an idealized way, employing different methodologies for the mathematical representation of socio-economic and technological developments in the real world. The representation of some real world factors, such as institutional barriers, inefficient legal frameworks, transaction costs of carbon permit trading, potential free-rider behaviour of geopolitical agents and the implications of public acceptance has traditionally been a challenge in modelling. These factors are represented to various degrees (often generically) in these models.

[8] The factor increase of 1.5 corresponds to about 250 to 360 Gt$CO_2$ of additional capture and storage over the course of the century.

Johnson and Keith, 2004; Wise and Dooley, 2004; McFarland *et al*., 2004). The only caveat to this carbon price as a lower limit for the deployment of these systems is the 'early opportunities' literature discussed below.

Before turning to a specific focus on the possible contribution of CCS in various emissions mitigation scenarios, it is worth reinforcing the point that there is a broad consensus in the technical literature that no single mitigation measure will be adequate to achieve a stable concentration of $CO_2$. This means that the $CO_2$ emissions will most likely be reduced from baseline scenarios by a portfolio of technologies in addition to other social, behavioural and structural changes (Edmonds *et al*., 2003; Riahi and Roehrl, 2000). In addition, the choice of a particular stabilization level from any given baseline significantly affects the technologies needed for achieving the necessary emissions reduction (Edmonds *et al*., 2000; Roehrl and Riahi, 2000). For example, a wider range of technological measures and their widespread diffusion, as well as more intensive use, are required for stabilizing at 450 ppmv compared with stabilization at higher levels (Nakicenovic and Riahi, 2001). These and other studies (e.g., IPCC, 2001) have identified several classes of robust mitigation measures: reductions in demand and/or efficiency improvements; substitution among fossil fuels; deployment of non-carbon energy sources (i.e., renewables and nuclear); $CO_2$ capture and storage; and afforestation and reforestation.

### *8.3.3 The share of CCS in total emissions mitigation*

When used to model energy and carbon markets, the aim of integrated assessment models is to capture the heterogeneity that characterizes energy demand, energy use and the varying states of development of energy technologies that are in use at any given point in time, as well as over time. These integrated assessment tools are also used to model changes in market conditions that would alter the relative cost-competitiveness of various energy technologies. For example, the choice of energy technologies would vary as carbon prices rise, as the population grows or as a stable population increases its standard of living. The graphs in Figure 8.4 show how two different integrated assessment models (MiniCAM and MESSAGE) project the development of global primary energy (upper panels), the contribution of major mitigation measures (middle panels), and the marginal carbon permit price in response to a modelled policy that seeks to stabilize atmospheric concentrations of $CO_2$ at 550 ppmv in accordance with the main greenhouse gas emissions drivers of the IPCC-SRES B2 scenario (see Box 8.2). As can be seen from Figure 8.4, CCS coupled with coal and natural-gas-fired electricity generation are key technologies in the mitigation portfolio in both scenarios and particularly in the later half of the century under this particular stabilization scenario. However, solar/wind, biomass, nuclear power, etc. still meet a sizeable portion of the global demand for electricity. This demonstrates that the world will continue to use a multiplicity of energy technologies to meet its energy demands and that, over space and time, a large portfolio of these technologies will be used at any one time.

**Figure 8.4.** The set of graphs shows how two different integrated assessment models (MiniCAM and MESSAGE) project the development of global primary energy (upper panels) and the corresponding contribution of major mitigation measures (middle panels). The lower panel depicts the marginal carbon permit price in response to a modelled mitigation regime that seeks to stabilize atmospheric concentrations of $CO_2$ at 550 ppmv. Both scenarios adopt harmonized assumptions with respect to the main greenhouse gas emissions drivers in accordance with the IPCC-SRES B2 scenario. (Source: Dooley *et al*., 2004b; Riahi and Roehrl, 2000)

**Box 8.2.** Two illustrative 550 ppmv stabilization scenarios based on IPCC SRES B2

The MESSAGE and MiniCAM scenarios illustrated in Figure 8.4 represent two alternative quantifications of the B2 scenario family of the IPCC SRES. They are used for subsequent $CO_2$ mitigation analysis and explore the main measures that would lead to the stabilization of atmospheric concentrations at 550 ppmv.

The scenarios are based on the B2 storyline, a narrative description of how the world will evolve during the twenty-first century, and share harmonized assumptions concerning salient drivers of $CO_2$ emissions, such as economic development, demographic change, and final energy demand. In accordance with the B2 storyline, gross world product is assumed to grow from US$ 20 trillion in 1990 to about US$ 235 trillion in 2100 in both scenarios, corresponding to a long-term average growth rate of 2.2%. Most of this growth takes place in today's developing countries. The scenarios adopt the UN median 1998 population projection (UN, 1998), which assumes a continuation of historical trends, including recent faster-than-expected fertility declines, towards a completion of the demographic transition within the next century. Global population increases to about 10 billion by 2100. Final energy intensity of the economy declines at about the long-run historical rate of about one per cent per year through 2100. On aggregate, these trends constitute 'dynamics-as-usual' developments, corresponding to middle-of-the-road assumptions compared to the scenario uncertainty range from the literature (Morita and Lee, 1999).

In addition to the similarities mentioned above, the MiniCAM and MESSAGE scenarios are based on alternative interpretations of the B2 storyline with respect to a number of other important assumptions that affect the potential future deployment of CCS. These assumptions relate to fossil resource availability, long-term potentials for renewable energy, the development of fuel prices, the structure of the energy system and the sectoral breakdown of energy demand, technology costs, and in particular technological change (future prospects for costs and performance improvements for specific technologies and technology clusters).

The two scenarios therefore portray alternative but internally consistent developments of the energy technology portfolio, associated $CO_2$ emissions, and the deployment of CCS and other mitigation technologies in response to the stabilization target of 550 ppmv $CO_2$, adopting the same assumptions for economic, population, and aggregated demand growth. Comparing the scenarios' portfolio of mitigation options (Figure 8.4) illustrates the importance of CCS as part of the mitigation portfolio. For more details, see Dooley *et al.* (2004b) and Riahi and Roehrl (2000).

When assessing how various technologies will contribute to the goal of addressing climate change, these technologies are modelled in such a way that they all compete for market share to provide the energy services and emissions reduction required by society, as this is what would happen in reality. There are major uncertainties associated with the potential and costs of these options, and so the absolute deployment of CCS depends on various scenario-specific assumptions consistent with the underlying storyline and the way they are interpreted in the different models. In the light of this competition and the wide variety of possible emissions futures, the contribution of CCS to total emissions reduction can only be assessed within relatively wide margins.

The uncertainty with respect to the future deployment of CCS and its contribution to total emissions reductions for achieving stabilization of $CO_2$ concentrations between 450 and 750 ppmv is illustrated by the IPCC TAR mitigation scenarios (Morita *et al*., 2000; 2001). The TAR mitigation scenarios are based upon SRES baseline scenarios and were developed by nine different modelling teams. In total, 76 mitigation scenarios were developed for TAR, and about half of them (36 scenarios from three alternative models: DNE21, MARIA, and MESSAGE) consider $CO_2$ capture and storage explicitly as a mitigation option. An overview of the TAR scenarios is presented in

Morita *et al.* (2000). It includes eleven publications from individual modelling teams about their scenario assumptions and results.

As illustrated in Figure 8.5, which is based upon the TAR mitigation scenarios, the average share of CCS in total emissions reductions may range from 15% for scenarios aiming at the stabilization of $CO_2$ concentrations at 750 ppmv to 54% for 450 ppmv scenarios.[9] However, the full uncertainty range of the set of TAR mitigation scenarios includes extremes on both the high and low sides, ranging from scenarios with zero CCS contributions to scenarios with CCS shares of more than 90 per cent in total emissions abatement.

**Figure 8.5.** Relationship between (1) the imputed share of CCS in total cumulative emissions reductions in per cent and (2) total cumulative CCS deployment in $GtCO_2$ (2000–2100). The scatter plots depict values for individual TAR mitigation scenarios for the six SRES scenario groups. The vertical dashed lines show the average share of CCS in total emissions mitigation across the 450 to 750 ppmv stabilization scenarios, and the dashed horizontal lines illustrate the scenarios' average cumulative storage requirements across 450 to 750 ppmv stabilization.

### *8.3.3.1 Cumulative CCS deployment*

Top-down and bottom-up energy-economic models have been used to examine the likely total deployment of CCS technologies (expressed in GtC). These analyses reflect the fact that the future usage of CCS technologies is associated with large uncertainties. As illustrated by the IPCC-TAR mitigation scenarios, global cumulative CCS during the 21st century could range – depending on the future characteristics of the reference world (i.e., baselines) and the employed stabilization target (450 to 750 ppmv) – from zero to more than 5500 $GtCO_2$ (1500 GtC) (see Figure 8.6). The average cumulative $CO_2$ storage (2000–2100) across the six scenario groups shown in Figure 8.6 ranges from 380 $GtCO_2$ (103 GtC) in the 750 ppmv stabilization scenarios to 2160 $GtCO_2$ (590 GtC) in the 450 ppmv scenarios (Table 8.5).[10] However, it is important to note that the majority of the six individual TAR scenarios (from the 20th to the 80th percentile) tend to cluster in the range of 220–2200 $GtCO_2$ (60–600 GtC) for the four stabilization targets (450–750 ppmv).

**Figure 8.6.** Global cumulative $CO_2$ storage (2000–2100) in the IPCC TAR mitigation scenarios for the six SRES scenario groups and $CO_2$ stabilization levels between 450 and 750 ppmv. Values refer to averages across scenario results from different modelling teams. The contribution of CCS increases with the stringency of the stabilization target and differs considerably across the SRES scenario groups.

The deployment of CCS in the TAR mitigation scenarios is comparable to results from similar scenario studies projecting storage of 576–1370 $GtCO_2$ (157–374 GtC) for stabilization scenarios that span 450 to 750 ppmv (Edmonds *et al*., 2000) and storage of 370 to 1250 $GtCO_2$ (100 to 340 GtC) for stabilization scenarios that span 450 to 650 ppmv (Dooley and Wise, 2003). Riahi *et al.* (2003) project 330–890 $GtCO_2$ (90–243 GtC) of stored $CO_2$ over the course of the current century for various 550 ppmv stabilization cases. Fujii and Yamaji (1998) have also included ocean storage as an option. They calculate that, for a stabilization level of 550 ppmv, 920 $GtCO_2$ (250 GtC) of the

[9] The range for CCS mitigation in the TAR mitigation scenarios is calculated on the basis of the cumulative emissions reductions from 1990 to 2100, and represents the average contribution for 450 and 750 ppmv scenarios across alternative modelling frameworks and SRES baseline scenarios. The full range across all scenarios for 450 ppmv is 20 to 95% and 0 to 68% for 750 ppmv scenarios respectively.

[10] Note that Table 8.5 and Figure 8.6 show average values of CCS across alternative modelling frameworks used for the development of the TAR mitigation scenarios. The deployment of CCS over time, as well as cumulative $CO_2$ storage in individual TAR mitigation scenarios, are illustrated in Figures 8.5 and 8.7.

emissions reductions could be provided by the use of CCS technologies and that approximately one-third of this could be stored in the ocean. This demand for $CO_2$ storage appears to be within global estimates of total $CO_2$ storage capacity presented in Chapters 5 and 6.

### *8.3.3.2 Timing and deployment rate*

Recently, two detailed studies of the cost of $CO_2$ transport and storage costs have been completed for North America (Dooley *et al*., 2004a) and Western Europe (Wildenborg *et al*., 2004). These studies concur about the large potential of $CO_2$ storage capacity in both regions. Well over 80% of the emissions from current $CO_2$ point sources could be transported and stored in candidate geologic formations for less than 12–15 US$/t$CO_2$ in North America and 25 US$/t $CO_2$ in Western Europe. These studies are the first to define at a continental scale a '$CO_2$ storage supply curve', conducting a spatially detailed analysis in order to explore the relationship between the price of $CO_2$ transport and storage and the cumulative amount of $CO_2$ stored. Both studies conclude that, at least for these two regions, the $CO_2$ storage supply curves are dominated by a very large single plateau (hundreds to thousands of gigatonnes of $CO_2$), implying roughly constant costs for a wide range of storage capacity[11]. In other words, at a practical level, the cost of $CO_2$ transport and storage in these regions will have a cap. These studies and a handful of others (see, for example, IEA GHG, 2002) have also shown that early (i.e., low cost) opportunities for $CO_2$ capture and storage hinge upon a number of factors: an inexpensive (e.g., high-purity) source of $CO_2$; a (potentially) active area of advanced hydrocarbon recovery (either EOR or ECBM); and the relatively close proximity of the $CO_2$ point source to the candidate storage reservoir in order to minimize transportation costs. These bottom-up studies provide some of the most detailed insights into the graded CCS resources presently available, showing that the set of CCS opportunities likely to be encountered in the real world will be very heterogeneous. These studies, as well as those based upon more top-down modelling approaches, also indicate that, once the full cost of the complete CCS system has been accounted for, CCS systems are unlikely to deploy on a large scale in the absence of an explicit policy or regulatory regime that substantially limits greenhouse gas emissions to the atmosphere. The literature and current industrial experience indicate that, in the absence of measures to limit $CO_2$ emissions, there are only small, niche opportunities for the deployment of CCS technologies. These early opportunities could provide experience with CCS deployment, including the creation of parts of the infrastructure and the knowledge base needed for the future large-scale deployment of CCS systems.

Most analyses of least-cost $CO_2$ stabilization scenarios indicate that, while there is significant penetration of CCS systems over the decades to come, the majority of CCS deployment will occur in the second half of this century (Edmonds *et al*., 2000, 2003; Edmonds and Wise, 1998; Riahi *et al*., 2003). One of the main reasons for this trend is that the stabilization of $CO_2$ concentrations at relatively low levels (<650 ppmv) generally leads to progressively more constraining mitigation regimes over time, resulting in carbon permit prices that start out quite low and steadily rise over the course of this century. The TAR mitigation scenarios (Morita *et al*., 2000) based upon the SRES baselines report cumulative $CO_2$ storage due to CCS ranging from zero to 1100 Gt$CO_2$ (300 GtC) for the first half of the century, with the majority of the scenarios clustering below 185 Gt$CO_2$ (50 GtC). By comparison, the cumulative contributions of CCS range from zero to 4770 Gt$CO_2$ (1300 GtC) in the second half of the century, with the majority of the scenarios stating figures below 1470 Gt$CO_2$ (400 GtC). The deployment of CCS over time in the TAR mitigation scenarios is illustrated in Figure 8.7. As can be seen, the use of CCS is highly dependent upon the underlying base case. For example, in the high economic growth and carbon-intensive baseline scenarios (A1FI), the development path of CCS is characterized by steadily increasing contributions, driven by the

[11] See Chapter 5 for a full assessment of the estimates of geological storage capacity.

rapidly growing use of hydrocarbon resources. By contrast, other scenarios (e.g., A1B and B2) depict CCS deployment to peak during the second half of the century. In a number of these scenarios, the contribution of CCS declines to less than 11 $GtCO_2$ a year (3 GtC a year) until the end of the century. These scenarios reflect the fact that CCS could be viewed as a transitional mitigation option (bridging the transition from today's fossil-intensive energy system to a post-fossil system with sizable contributions from renewables).

**Figure 8.7.** Deployment of CCS systems as a function of time from 1990 to 2100 in the IPCC TAR mitigation scenarios where atmospheric $CO_2$ concentrations stabilize at between 450 to 750 ppmv. Coloured thick lines show the minimum and maximum contribution of CCS for each SRES scenario group, and thin lines depict the contributions in individual scenarios. Vertical axes on the right-hand side illustrate the range of CCS deployment across the stabilization levels for each SRES scenario group in the year 2100.

Given these models' relatively coarse top-down view of the world, there is less agreement about when the first commercial CCS units will become operational. This is – at least in part – attributable to the importance of policy in creating the context in which initial units will deploy. For example, McFarland *et al*. (2003) foresee CCS deployment beginning around 2035. Other modelling exercises have shown CCS systems beginning to deploy – at a lower level of less than 370 $MtCO_2$ a year (100 MtC a year) – in the period 2005–2020 (see, for example, Dooley *et al*., 2000). Moreover, in an examination of CCS deployment in Japan, Akimoto *et al*. (2003) show CCS deployment beginning in 2010–2020. In a large body of literature (Edmonds *et al*. 2003; Dooley and Wise, 2003; Riahi *et al*. 2003; IEA, 2004), there is agreement that, in a $CO_2$-constrained world, CCS systems might begin to deploy in the next few decades and that this deployment will expand significantly after the middle of the century. The variation in the estimates of the timing of CCS-system deployment is attributable to the different ways energy and economic models parameterize CCS systems and to the extent to which the potential for early opportunities – such as EOR or ECBM – is taken into account. Other factors that influence the timing of CCS diffusion are the rate of increase and absolute level of the carbon price.

#### *8.3.3.3 Geographic distribution*

McFarland *et al*. (2003) foresee the eventual deployment of CCS technologies throughout the world but note that the timing of the entry of CCS technologies into a particular region is influenced by local conditions such as the relative price of coal and natural gas in a region. Dooley *et al*. (2002) show that the policy regime, and in particular the extent of emissions trading, can influence where CCS technologies are deployed. In the specific case examined by this paper, it was demonstrated that, where emissions trading was severely constrained (and where the cost of abatement was therefore higher), CCS technologies tended to deploy more quickly and more extensively in the US and the EU. On the other hand, in the absence of an efficient emissions-trading system spanning all of the Annex B nations, CCS was used less intensively and CCS utilization was spread more evenly across these nations as the EU and US found it cheaper to buy CCS-derived emission allowances from regions like the former Soviet Union.

Table 8.5 gives the corresponding deployment of CCS in the IPCC TAR mitigation scenarios for four world regions.[12] All values are given as averages across scenario results from different

[12] The OECD90 region includes the countries belonging to the OECD in 1990. The REF ('reforming economies') region aggregates the countries of the Former Soviet Union and Eastern Europe. The ASIA region represents the developing countries on the Asian continent. The ROW region covers the rest of the world, aggregating countries in sub-Saharan Africa, Latin America and the Middle East. For more details see SRES, 2000.

modelling teams. The data in this table (in particular the far left-hand column which summarizes average $CO_2$ storage across all scenarios) help to demonstrate a common and consistent finding of the literature: over the course of this century, CCS will deploy throughout the world, most extensively in the developing nations of today (tomorrow's largest emitters of $CO_2$). These nations will therefore be likely candidates for adopting CCS to control their growing emissions.[13]

**Table 8.5** Cumulative $CO_2$ storage (2000 to 2100) in the IPCC TAR mitigation scenarios in $GtCO_2$. CCS contributions for the world and for the four SRES regions are shown for four alternative stabilization targets (450, 550, 650, and 750 ppmv) and six SRES scenario groups. Values refer to averages across scenario results from different modelling teams.

Fujii *et al.* (2002) note that the actual deployment of CCS technologies in any given region will depend upon a host of geological and geographical conditions that are, at present, poorly represented in top-down energy and economic models. In an attempt to address the shortcomings noted by Fujii *et al.* (2002) and others, especially in the way in which the cost of $CO_2$ transport and storage are parameterized in top-down models, Dooley *et al.* (2004b) employed graded $CO_2$ storage supply curves for all regions of the world based upon a preliminary assessment of the literature's estimate of regional $CO_2$ storage capacity. In this framework, where the cost of $CO_2$ storage varies across the globe depending upon the quantity, quality (including proximity) and type of $CO_2$ storage reservoirs present in the region, as well as upon the demand for $CO_2$ storage (driven by factors such as the size of the regional economy, the stringency of the modelled emissions reduction regime), the authors show that the use of CCS across the globe can be grouped into three broad categories: (1) countries in which the use of CCS does not appear to face either an economic or physical constraint on CCS deployment given the large potential $CO_2$ storage resource compared to projected demand (e.g., Australia, Canada, and the United States) and where CCS should therefore deploy to the extent that it makes economic sense to do so; (2) countries in which the supply of potential geological storage reservoirs (the authors did not consider ocean storage) is small in comparison to potential demand (e.g., Japan and South Korea) and where other abatement options must therefore be pressed into service to meet the modelled emissions reduction levels; and (3) the rest of the world in which the degree to which CCS deployment is constrained is contingent upon the stringency of the emission constraint and the useable $CO_2$ storage resource. The authors note that discovering the true $CO_2$ storage potential in regions of the world is a pressing issue; knowing whether a country or a region has 'sufficient' $CO_2$ storage capacity is a critical variable in these modelling analyses because it can fundamentally alter the way in which a country's energy infrastructure evolves in response to various modelled emissions constraints.

#### *8.3.3.4 Long-term economic impact*

An increasing body of literature has been analyzing short- and long-term financial requirements for CCS. The World Energy Investment Outlook 2003 (IEA, 2003) estimates an upper limit for investment in CCS technologies for the OECD of about US$ 350 to US$ 440 billion over the next 30 years, assuming that all new power plant installations will be equipped with CCS. Similarly, Riahi *et al.* (2004) estimate that up-front investments for initial niche market applications and demonstration plants could amount to about US$ 70 billion or 0.2 per cent of the total global energy systems costs over the next 20 years. This would correspond to a market share of CCS of about 3.5% of total installed fossil-power generation capacities in the OECD countries by 2020, where most of the initial CCS capacities are expected to be installed.

[13] This trend can be seen particularly clearly in the far left-hand column of Table 8.5, which gives the average CCS deployment across all scenarios from the various models. Note, nevertheless, a few scenarios belonging to the B1 and B2 scenario family, which suggest larger levels of deployment for CCS in the developed world.

Long-term investment requirements for the full integration of CCS in the electricity sector as a whole are subject to major uncertainties. Analyses with integrated assessment models indicate that the costs of decarbonizing the electricity sector via CCS might be about three to four per cent of total energy-related systems costs over the course of the century (Riahi *et al*., 2004). Most importantly, these models also point out that the opportunity costs of CCS not being part of the $CO_2$ mitigation portfolio would be significant. Edmonds *et al*. (2000) indicate that savings over the course of this century associated with the wide-scale deployment of CCS technologies when compared to a scenario in which these technologies do not exist could be in the range of tens of billions of 1990 U.S. dollars for high $CO_2$ concentrations limits such as 750 ppm, to trillions of dollars for more stringent $CO_2$ concentrations such as 450 ppm.[14] Dooley *et al*. (2002) estimate cost savings in excess of 36% and McFarland *et al*. (2004) a reduction in the carbon permit price by 110 US$/t$CO_2$ in scenarios where CCS technologies are allowed to deploy when compared to scenarios in which they are not.

*8.3.3.5 Interaction with other technologies*

As noted above, the future deployment of CCS will depend on a number of factors, many of which interact with each other. The deployment of CCS will be impacted by factors such as the development and deployment of renewable energy and nuclear power (Mori, 2000). Edmonds *et al*. (2003) report that CCS technologies can synergistically interact with other technologies and in doing so help to lower the cost and therefore increase the overall economic potential of less carbon-intensive technologies. The same authors note that these synergies are perhaps particularly important for the combination of CCS, $H_2$ production technologies and $H_2$ end-use systems (e.g., fuel cells). On the other hand, the widespread availability of CCS technologies implies an ability to meet a given emissions reduction at a lower marginal cost, reducing demand for substitute technologies at the margin. In other words, CCS is competing with some technologies, such as energy-intensity improvements, nuclear, fusion, solar power options, and wind. The nature of that interaction depends strongly on the climate policy environment and the costs and potential of alternative mitigation options, which are subject to large variations depending on site-specific, local conditions (IPCC, 2001). At the global level, which is spatially more aggregated, this variation translates into the parallel deployment of alternative options, taking into account the importance of a diversified technology portfolio for addressing emissions mitigation in a cost-effective way.

An increasing body of literature (Willams, 1998; Obersteiner *et al*., 2001; Rhodes and Keith, 2003; Makihira *et al*., 2003; Edmonds *et al*., 2003, Möllersten *et al*., 2003) has begun to examine the use of CCS systems with biomass-fed energy systems to create useful energy (electricity or transportation fuels) as well as excess emissions credits generated by the system's resulting 'negative emissions'. These systems can be fuelled solely by biomass, or biomass can be co-fired in conventional coal-burning plants, in which case the quantity is normally limited to about 10–15% of the energy input. Obersteiner *et al*. (2001) performed an analysis based on the SRES scenarios, estimating that 880 to 1650 Gt$CO_2$ (240 to 450 GtC) of the scenario's cumulative emissions that are vented during biomass-based energy-conversion processes could potentially be available for capture and storage over the course of the century. Rhodes and Keith (2003) note that, while this coupled bio-energy CCS system would generate expensive electricity in a world of low carbon prices, this system could produce competitively priced electricity in a world with carbon prices in excess of 54.5 US$/t$CO_2$ (200 US$/tC). Similarly, Makihira *et al*. (2003) estimate that $CO_2$ capture during

[14] Savings are measured as imputed gains of GDP due to CCS deployment, in contrast to a world where CCS is not considered to be part of the mitigation portfolio.

hydrogen production from biomass could become competitive at carbon prices above 54.5 to 109 US$/t$CO_2$ (200 to 400 US$/tC).

## 8.4 Economic impacts of different storage times

As discussed in the relevant chapters, geological and ocean storage might not provide permanent storage for all of the $CO_2$ injected. The question arises of how the possibility of leakage from reservoirs can be taken into account in the evaluation of different storage options and in the comparison of $CO_2$ storage with mitigation options in which $CO_2$ emissions are avoided.

Chapters 5 and 6 discuss the expected fractions of $CO_2$ retained in storage for geological and ocean reservoirs respectively. For example, Box 6.7 suggests four types of measures for ocean storage: storage efficiency, airborne fraction, net present value, and global warming potential. Chapter 9 discusses accounting issues relating to the possible impermanence of stored $CO_2$. Chapter 9 also contains a review of the broader literature on the value of delayed emissions, primarily focusing on sequestration in the terrestrial biosphere. In this section, we focus specifically on the economic impacts of differing storage times in geological and ocean reservoirs.

Herzog *et al*. (2003) suggest that $CO_2$ storage and leakage can be looked upon as two separate, discrete events. They represent the value of temporary storage as a familiar economic problem, with explicitly stated assumptions about the discount rate and carbon prices. If someone stores a tonne of $CO_2$ today, they will be credited with today's carbon price. Any future leakage will have to be compensated by paying the carbon price in effect at that time. Whether non-permanent storage options will be economically attractive depends on assumptions about the leakage rate, discount rate and relative carbon permit prices. In practice, this may turn out to be a difficult issue since the commercial entity that undertakes the storage may no longer exist when leakage rates have been clarified (as Baer (2003) points out), and hence governments or society at large might need to cover the leakage risk of many storage sites rather than the entity that undertakes the storage.

Ha-Duong and Keith (2003) explore the trade-offs between discounting, leakage, the cost of $CO_2$ storage and the energy penalty. They use both an analytical approach and an integrated assessment numerical model in their assessment. In the latter case, with CCS modelled as a backstop technology, they find that, for an optimal mix of $CO_2$ abatement and CCS technologies, 'an (annual) leakage rate of 0.1% is nearly the same as perfect storage while a leakage rate of 0.5% renders storage unattractive'.

Some fundamental points about the limitations of the economic valuation approaches presented in the literature have been raised by Baer (2003). He argues that financial efficiency, which is at the heart of the economic approaches to the valuation of, and decisions about, non-permanent storage is only one of a number of important criteria to be considered. Baer points out that at least three risk categories should to be taken into account as well:

- ecological risk: the possibility that 'optimal' leakage may preclude future climate stabilization;
- financial risk: the possibility that future conditions will cause carbon prices to greatly exceed current expectations, with consequences for the maintenance of liability and distribution of costs; and
- political risk: the possibility that institutions with an interest in $CO_2$ storage may manipulate the regulatory environment in their favour.

As these points have not been extensively discussed in the literature so far, the further development of the scientific debate on these issues must be followed closely.

In summary, within this purely economic framework, the few studies that have looked at this topic indicate that some $CO_2$ leakage can be accommodated while still making progress towards the goal of stabilizing atmospheric concentrations of $CO_2$. However, due to the uncertainties of the assumptions, the impact of different leakage rates and therefore the impact of different storage times are hard to quantify.

## 8.5 Gaps in knowledge

Cost developments for CCS technologies are now estimated based on literature, expert views and a few recent CCS deployments. Costs of large-scale integrated CCS applications are still uncertain and their variability depends among other things on many site-specific conditions. Especially in the case of large-scale CCS biomass based applications, there is a lack of experience and therefore little information in the literature about the costs of these systems.

There is little empirical evidence about possible cost decreases related to 'learning by doing' for integrated CCS systems since the demonstration and commercial deployment of these systems has only recently begun. Furthermore, the impact of targeted research, development and deployment (RD&D) of CCS investments on the level and rate of CCS deployment is poorly understood at this time. This lack of knowledge about how technologies will deploy in the future and the impact of RD&D on the technology's deployment is a generic issue and is not specific to CCS deployment.

In addition to current and future CCS technological costs, there are other possible issues that are not well known at this point and that would affect the future deployment of CCS systems: for example, costs related to the monitoring and regulatory framework, possible environmental damage costs, costs associated with liability and possible public-acceptance issues.

There are at present no known, full assessments of life-cycle costs for deployed CCS systems, and in particular the economic impact of the capture, transport and storage of non-pure $CO_2$ streams.

The development of bottom-up CCS deployment cost curves that take into account the interplay between large $CO_2$ point sources and available storage capacity in various regions of the world should continue; these cost curves would help to show how CCS technologies will deploy in practice and would also help improve the economic modelling of CCS deployment in response to various modelled scenarios.

Recent changes in energy prices and changes in policy regimes related to climate change are not fully reflected in the literature available as this chapter was being written. This suggests a need for a continuous effort to update analyses and perhaps draft a range of scenarios with a wider range of assumptions (e.g., fuel prices, climate policies) in order to understand better the robustness and sensitivity of the current outcomes.

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# Tables

**Table 8.1.** Summary of new plant performance and $CO_2$ capture cost based on current technology

| Performance and Cost Measures | New NGCC Plant | | | New PC Plant | | | New IGCC Plant | | | New Hydrogen Plant | | | (Units for $H_2$ Plant) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Range | | *Rep.* | Range | | *Rep.* | Range | | *Rep.* | Range | | *Rep.* | |
| | **low** | **high** | *Value* | **low** | **high** | *Value* | **low** | **high** | *Value* | **low** | **high** | *Value* | |
| Emission rate w/o capture (kg $CO_2$ $MWh^{-1}$) | 344 | 379 | *367* | 736 | 811 | *762* | 682 | 846 | *773* | 78 | 174 | *137* | kg $CO_2$ $GJ^{-1}$ (w/o capture) |
| Emission rate with capture (kg $CO_2$ $MWh^{-1}$) | 40 | 66 | *52* | 92 | 145 | *112* | 65 | 152 | *108* | 7 | 28 | *17* | kg $CO_2$ $GJ^{-1}$ (with capture) |
| Percent $CO_2$ reduction per kWh (%) | 83 | 88 | *86* | 81 | 88 | *85* | 81 | 91 | *86* | 72 | 96 | *86* | % reduction/unit of product |
| Plant efficiency with capture, LHV basis (% ) | 47 | 50 | *48* | 30 | 35 | *33* | 31 | 40 | *35* | 52 | 68 | *60* | Capture plant efficiency (% LHV) |
| Capture energy requirement (% more input $MWh^{-1}$) | 11 | 22 | *16* | 24 | 40 | *31* | 14 | 25 | *19* | 4 | 22 | *8* | % more energy input/GJ product |
| Total capital requirement w/o capture (US$ $kW^{-1}$) | 515 | 724 | *568* | 1161 | 1486 | *1286* | 1169 | 1565 | *1326* | *[No unique normalization for multi-product plants]* | | | Capital requirement w/o capture |
| Total capital requirement with capture (US$ $kW^{-1}$) | 909 | 1261 | *998* | 1894 | 2578 | *2096* | 1414 | 2270 | *1825* | | | | Capital requirement with capture |
| Percent increase in capital cost with capture (%) | 64 | 100 | *76* | 44 | 74 | *63* | 19 | 66 | *37* | –2 | 54 | *18* | % increase in capital cost |
| COE w/o capture (US$ $MWh^{-1}$) | 31 | 50 | *37* | 43 | 52 | *46* | 41 | 61 | *47* | 6.5 | 10.0 | *7.8* | $H_2$ cost w/o capture (US$ $GJ^{-1}$) |
| COE with capture only (US$ $MWh^{-1}$) | 43 | 72 | *54* | 62 | 86 | *73* | 54 | 79 | *62* | 7.5 | 13.3 | *9.1* | $H_2$ cost with capture (US$ $GJ^{-1}$) |
| Increase in COE with capture (US$ $MWh^{-1}$) | 12 | 24 | *17* | 18 | 34 | *27* | 9 | 22 | *16* | 0.3 | 3.3 | *1.3* | Increase in $H_2$ cost (US$ $GJ^{-1}$) |
| Percent increase in COE with capture (%) | 37 | 69 | *46* | 42 | 66 | *57* | 20 | 55 | *33* | 5 | 33 | *15* | % increase in $H_2$ cost |
| Cost of $CO_2$ captured (US$/t$CO_2$) | 33 | 57 | *44* | 23 | 35 | *29* | 11 | 32 | *20* | 2 | 39 | *12* | US$/t$CO_2$ captured |
| Cost of $CO_2$ avoided (US$/t$CO_2$) | 37 | 74 | *53* | 29 | 51 | *41* | 13 | 37 | *23* | 2 | 56 | *15* | US$/t$CO_2$ avoided |
| Capture Cost Confidence Level (see Table 3.7) | moderate | | | moderate | | | moderate | | | moderate to high | | | Confidence Level (see Table 3.7) |

<u>Notes:</u> [a] Ranges and representative values are based on data from Tables 3.7, 3.9, 3.10 and 3.11. All costs in this table are for capture only and do not include the costs of $CO_2$ transport and storage; see Chapter 8 for total CCS costs. [b] All PC and IGCC data are for bituminous coals only at costs of 1.0–1.5 US$ $GJ^{-1}$ (LHV); all PC plants are supercritical units.
[c] NGCC data based on natural gas prices of 2.8–4.4 US$ $GJ^{-1}$ (LHV basis). [d] Costs are in constant US$ (approx. year 2002 basis). [e] Power plant sizes range from approximately 400–800 MW without capture and 300–700 MW with capture. [f] Capacity factors vary from 65–85% for coal plants and 50–95% for gas plants (average for each=80%). [g] Hydrogen plant feedstocks are natural gas (4.7–5.3 US$ $GJ^{-1}$) or coal (0.9–1.3 US$ $GJ^{-1}$); some plants in dataset produce electricity in addition to hydrogen. [h] Fixed charge factors vary from 11–16% for power plants and 13–20% for hydrogen plants. [i] All costs include $CO_2$ compression but not additional $CO_2$ transport and storage costs.

**Table 8.2.** Estimates of $CO_2$ storage costs

| Option | Representative Cost Range (US$/tonne $CO_2$ stored) | Representative Cost Range (US$/tonne C stored) |
|---|---|---|
| Geological - Storage[1] | 0.5–8.0 | 2–29 |
| Geological - Monitoring | 0.1–0.3 | 0.4–1.1 |
| Ocean[2] | | |
| Pipeline | 6–31 | 22–114 |
| Ship (Platform or Moving Ship Injection) | 12–16 | 44–59 |
| Mineral Carbonation[3] | 50–100 | 180–370 |

[1] Does not include monitoring costs.
[2] Includes offshore transportation costs; range represents 100–500 km distance offshore and 3000 m depth.
[3] Unlike geological and ocean storage, mineral carbonation requires significant energy inputs equivalent to approximately 40% of the power plant output.

**Table 8.3a.** Range of total costs for $CO_2$ capture, transport, and geological storage based on current technology for new power plants

| | Pulverized Coal Power Plant | Natural Gas Combined Cycle Power Plant | Integrated Coal Gasification Combined Cycle Power Plant |
|---|---|---|---|
| Cost of Electricity without CCS (US$ $MWh^{-1}$) | 43–52 | 31–50 | 41–61 |
| **Power Plant with Capture** | | | |
| Increased Fuel Requirement (%) | 24–40 | 11–22 | 14–25 |
| $CO_2$ Captured (kg $MWh^{-1}$) | 820–970 | 360–410 | 670–940 |
| $CO_2$ Avoided (kg $MWh^{-1}$) | 620–700 | 300–320 | 590–730 |
| % $CO_2$ Avoided | 81–88 | 83–88 | 81–91 |
| **Power Plant with Capture and Geological Storage**[15] | | | |
| Cost of Electricity (US$ $MWh^{-1}$) | 63–99 | 43–77 | 55–91 |
| Electricity Cost increase (US$ $MWh^{-1}$) | 19–47 | 12–29 | 10–32 |
| % increase | 43–91 | 37–85 | 21–78 |
| Mitigation Cost (US$/t$CO_2$ avoided) | 30–71 | 38–91 | 14–53 |
| Mitigation Cost (US$/tC avoided) | 110–260 | 140–330 | 51–200 |
| **Power Plant with Capture and Enhanced Oil Recovery**[16] | | | |
| Cost of Electricity (US$ $MWh^{-1}$) | 49–81 | 37–70 | 40–75 |
| Electricity Cost increase (US$ $MWh^{-1}$) | 5–29 | 6–22 | (–5)–19 |
| % increase | 12–57 | 19–63 | (–10)–46 |
| Mitigation Cost (US$/t$CO_2$ avoided) | 9–44 | 19–68 | (–7)–31 |
| Mitigation Cost (US$/tC avoided) | 31–160 | 71–250 | (–25)–120 |

[15] Capture costs represent range from Tables 3.7, 3.9 and 3.10. Transport costs range from US$0–5/t$CO_2$. Geological storage cost (including monitoring) range from 0.6–8.3 US$/t$CO_2$.
[16] Capture costs represent range from Tables 3.7, 3.9 and 3.10. Transport costs range from 0–5 US$/t$CO_2$ stored. Costs for geological storage including EOR range from –10 to –16 US$/t$CO_2$ stored.

**Table 8.3b.** Range of total costs for $CO_2$ capture, transport, and geological storage based on current technology for a new $H_2$ production plant

| | Hydrogen Production Plant |
|---|---|
| Cost of $H_2$ without CCS (US\$ $GJ^{-1}$) | 6.5–10.0 |
| **Hydrogen Plant with Capture** | |
| Increased Fuel Requirement (%) | 4–22 |
| $CO_2$ Captured (kg $GJ^{-1}$) | 75–160 |
| $CO_2$ Avoided (kg $GJ^{-1}$) | 60–150 |
| % $CO_2$ Avoided | 73–96 |
| **Hydrogen Plant with Capture and Geological Storage**[17] | |
| Cost of $H_2$ (US\$ $GJ^{-1}$) | 7.6–14.4 |
| $H_2$ cost increase (US\$ $GJ^{-1}$) | 0.4–4.4 |
| % increase | 6–54 |
| Mitigation Cost (US\$/t$CO_2$ avoided) | 3–75 |
| Mitigation Cost (US\$/tC avoided) | 10–280 |
| **Hydrogen Plant with Capture and Enhanced Oil Recovery**[18] | |
| Cost of $H_2$ (US\$ $GJ^{-1}$) | 5.2–12.9 |
| $H_2$ cost increase (US\$ $GJ^{-1}$) | (–2.0)–2.8 |
| % increase | (–28)–28 |
| Mitigation Cost (US\$/t$CO_2$ avoided) | (–14)–49 |
| Mitigation Cost (US\$/tC avoided) | (–53)–180 |

**Table 8.4.** Mitigation cost for different combinations of reference and CCS plants based on current technology and new power plants

| | NGCC Reference Plant | | PC Reference Plant | |
|---|---|---|---|---|
| | US\$/t$CO_2$ avoided | US\$/tC avoided | US\$/t$CO_2$ avoided | US\$/tC avoided |
| **Power Plant with Capture and Geological Storage** | | | | |
| NGCC | 40 – 90 | 140 – 330 | 20 – 60 | 80 – 220 |
| PC | 70 – 270 | 260 – 980 | 30 – 70 | 110 – 260 |
| IGCC | 40 – 220 | 150 – 790 | 20 – 70 | 80 – 260 |
| **Power Plant with Capture and EOR** | | | | |
| NGCC | 20 – 70 | 70 – 250 | 1 – 30 | 4 – 130 |
| PC | 50 – 240 | 180 – 890 | 10 – 40 | 30 – 160 |
| IGCC | 20 – 190 | 80 – 710 | 1 – 40 | 4 – 160 |

17 Capture costs represent range from Table 3.11. Transport costs range from \$0–5/t$CO_2$. Geological storage costs (including monitoring) range from 0.6–8.3 US\$/t$CO_2$.

18 Capture costs represent range from Table 3.11. Transport costs range from 0–5 US\$/t$CO_2$. EOR credits range from 10–16 US\$/t$CO_2$.

**Table 8.5** Cumulative $CO_2$ storage (2000 to 2100) in the IPCC TAR mitigation scenarios in $GtCO_2$. CCS contributions for the world and for the four SRES regions are shown for four alternative stabilization targets (450, 550, 650, and 750 ppmv) and six SRES scenario groups. Values refer to averages across scenario results from different modelling teams.

| | All scenarios (average) | A1 A1FI | A1 A1B | A1 A1T | A2 | B2 | B1 |
|---|---|---|---|---|---|---|---|
| WORLD | | | | | | | |
| 450 ppmv | 2162 | 5628 | 2614 | 1003 | 1298 | 1512 | 918 |
| 550 ppmv | 898 | 3462 | 740 | 225 | 505 | 324 | 133 |
| 650 ppmv | 614 | 2709 | 430 | 99 | 299 | 149 | 0 |
| 750 ppmv | 377 | 1986 | 0 | 0 | 277 | 0 | 0 |
| OECD90* | | | | | | | |
| 450 ppmv | 551 | 1060 | 637 | 270 | 256 | 603 | 483 |
| 550 ppmv | 242 | 800 | 202 | 82 | 174 | 115 | 80 |
| 650 ppmv | 172 | 654 | 166 | 54 | 103 | 55 | 0 |
| 750 ppmv | 100 | 497 | 0 | 0 | 104 | 0 | 0 |
| REF* | | | | | | | |
| 450 ppmv | 319 | 536 | 257 | 152 | 512 | 345 | 110 |
| 550 ppmv | 87 | 233 | 99 | 42 | 55 | 79 | 16 |
| 650 ppmv | 55 | 208 | 56 | 0 | 31 | 37 | 0 |
| 750 ppmv | 36 | 187 | 0 | 0 | 28 | 0 | 0 |
| ASIA* | | | | | | | |
| 450 ppmv | 638 | 2207 | 765 | 292 | 156 | 264 | 146 |
| 550 ppmv | 296 | 1262 | 226 | 47 | 153 | 67 | 20 |
| 650 ppmv | 223 | 1056 | 162 | 20 | 67 | 33 | 0 |
| 750 ppmv | 111 | 609 | 0 | 0 | 57 | 0 | 0 |
| ROW* | | | | | | | |
| 450 ppmv | 652 | 1825 | 955 | 289 | 366 | 300 | 179 |
| 550 ppmv | 273 | 1167 | 214 | 54 | 124 | 63 | 17 |
| 650 ppmv | 164 | 791 | 45 | 24 | 99 | 25 | 0 |
| 750 ppmv | 130 | 693 | 0 | 0 | 89 | 0 | 0 |

* The OECD90 region includes the countries belonging to the OECD in 1990. The REF ('reforming economies') region aggregates the countries of the Former Soviet Union and Eastern Europe. The ASIA region represents the developing countries on the Asian continent. The ROW region covers the rest of the world, aggregating countries in sub-Saharan Africa, Latin America and the Middle East. For more details, see SRES (2000).

## Figures

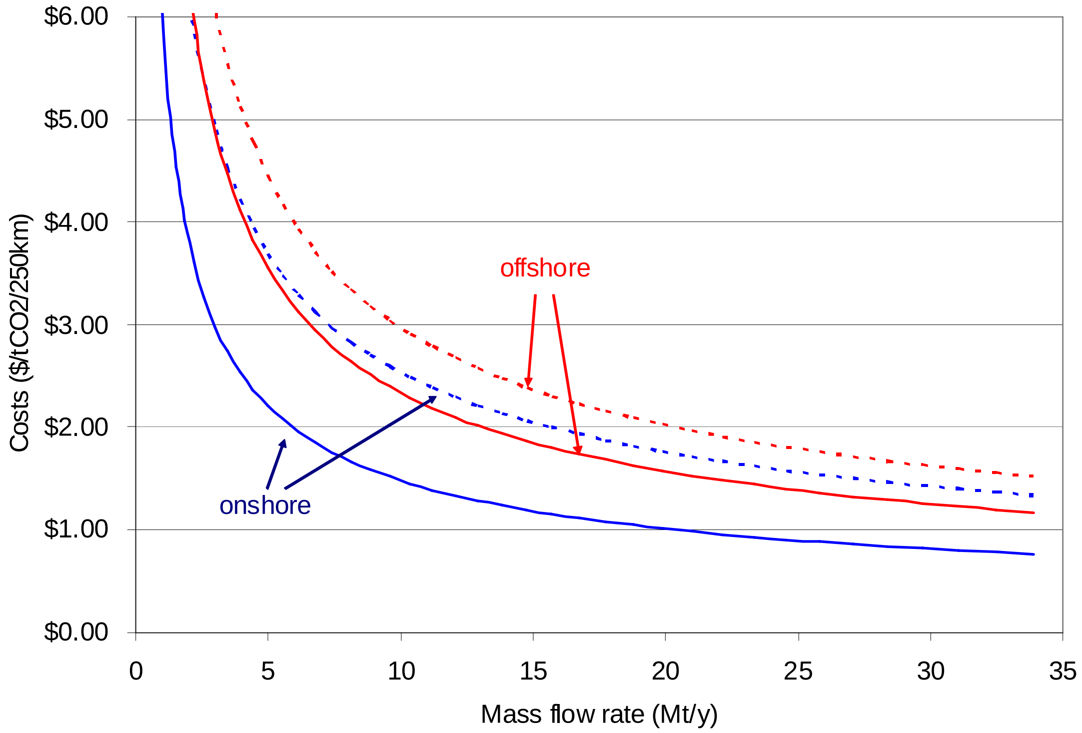


**Figure 8.2.** $CO_2$ transport costs range for onshore and offshore pipelines per 250 km, 'normal' terrain conditions. The figure shows high (solid lines) and low ranges (dotted lines). Data based on various sources (for details see Chapter 4).

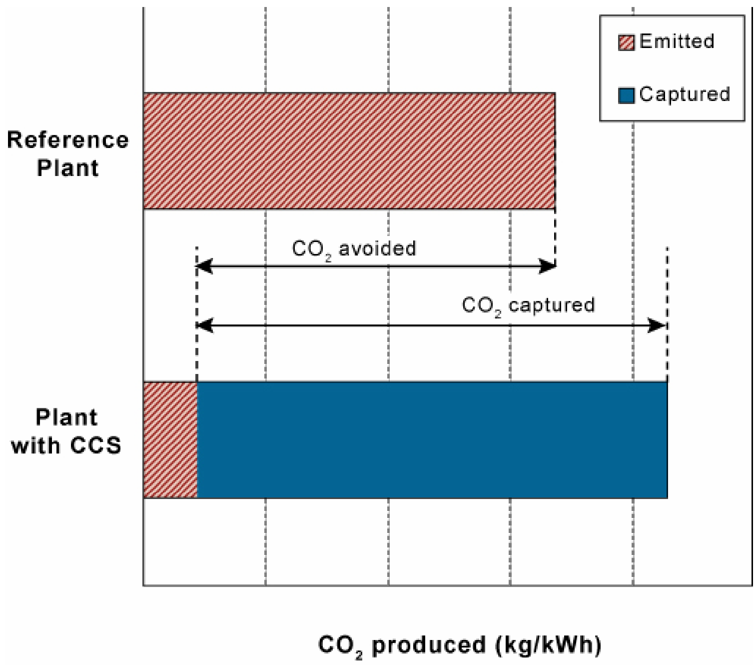


**Figure 8.2.** $CO_2$ capture and storage from power plants. The increased $CO_2$ production resulting from loss in overall efficiency of power plants due to the additional energy required for capture, transport and storage, and any leakage from transport result in a larger amount of "$CO_2$ produced per unit of product"(lower bar) relative to the reference plant (upper bar) without capture

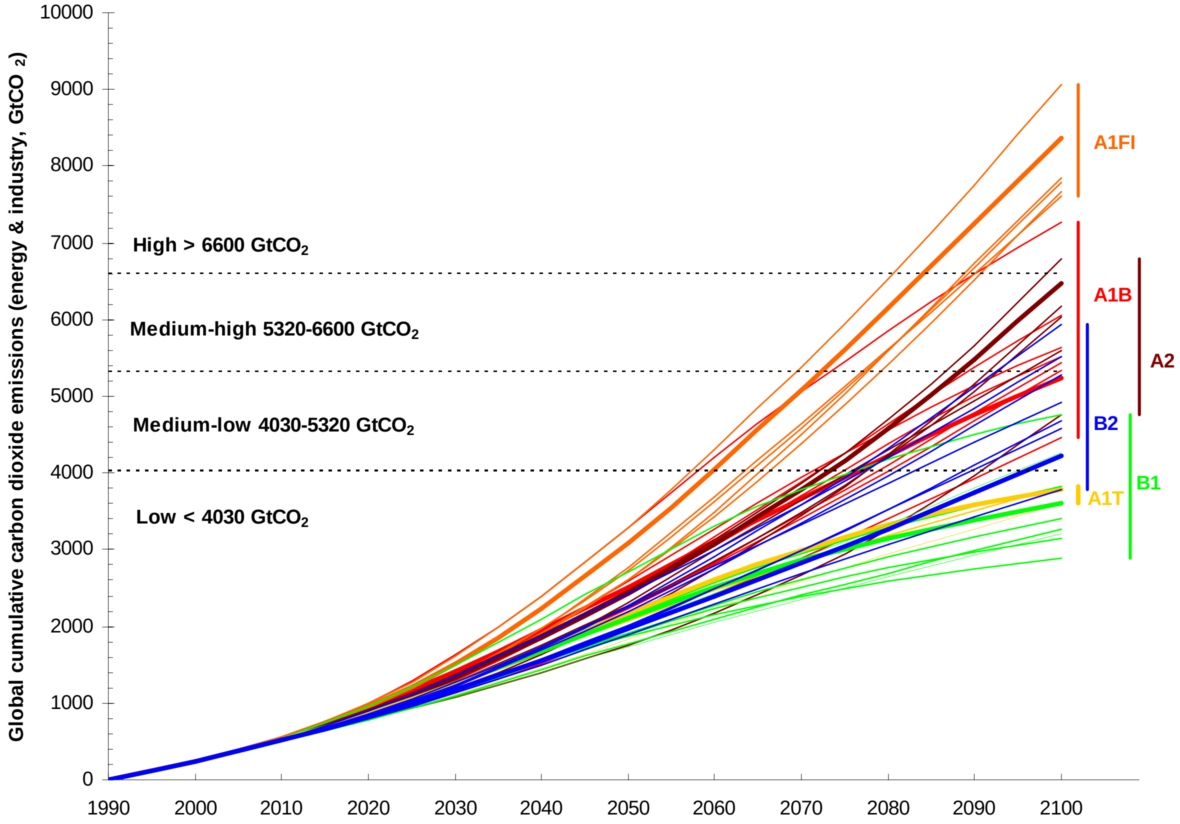


**Figure 8.3.** Annual and cumulative global emissions from energy and industrial sources in the SRES scenarios ($GtCO_2$). Each interval contains alternative scenarios from the six SRES scenario groups that lead to comparable cumulative emissions. The vertical bars on the right-hand side indicate the ranges of cumulative emissions (1990–2100) of the six SRES scenario groups.

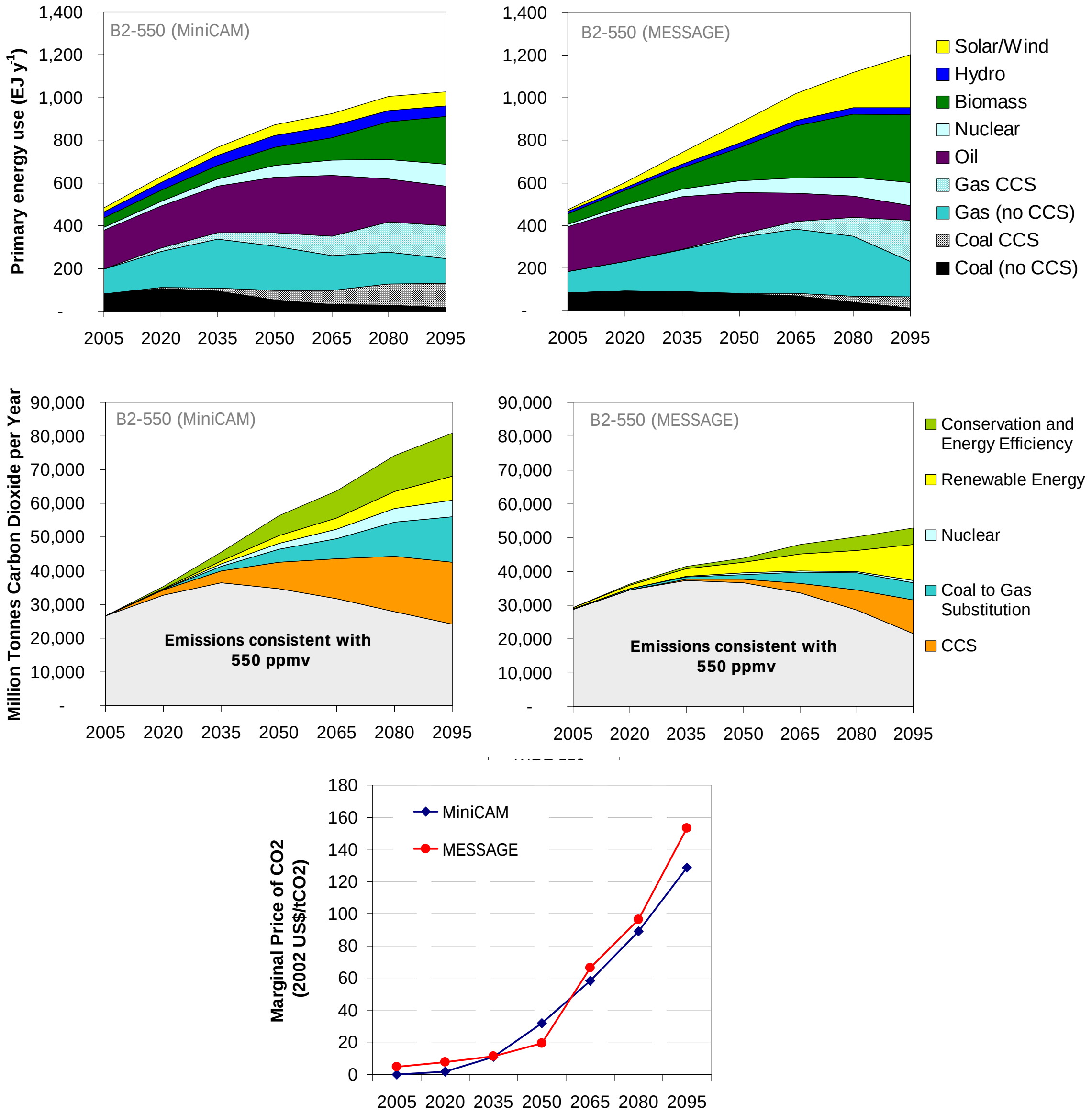


**Figure 8.4.** The set of graphs shows how two different integrated assessment models (MiniCAM and MESSAGE) project the development of global primary energy (upper panels) and the corresponding contribution of major mitigation measures (middle panels). The lower panel depicts the marginal carbon permit price in response to a modelled mitigation regime that seeks to stabilize atmospheric concentrations of $CO_2$ at 550 ppmv. Both scenarios adopt harmonized assumptions with respect to the main greenhouse gas emissions drivers in accordance with the IPCC-SRES B2 scenario. (Source: Dooley *et al*., 2004b; Riahi and Roehrl, 2000)

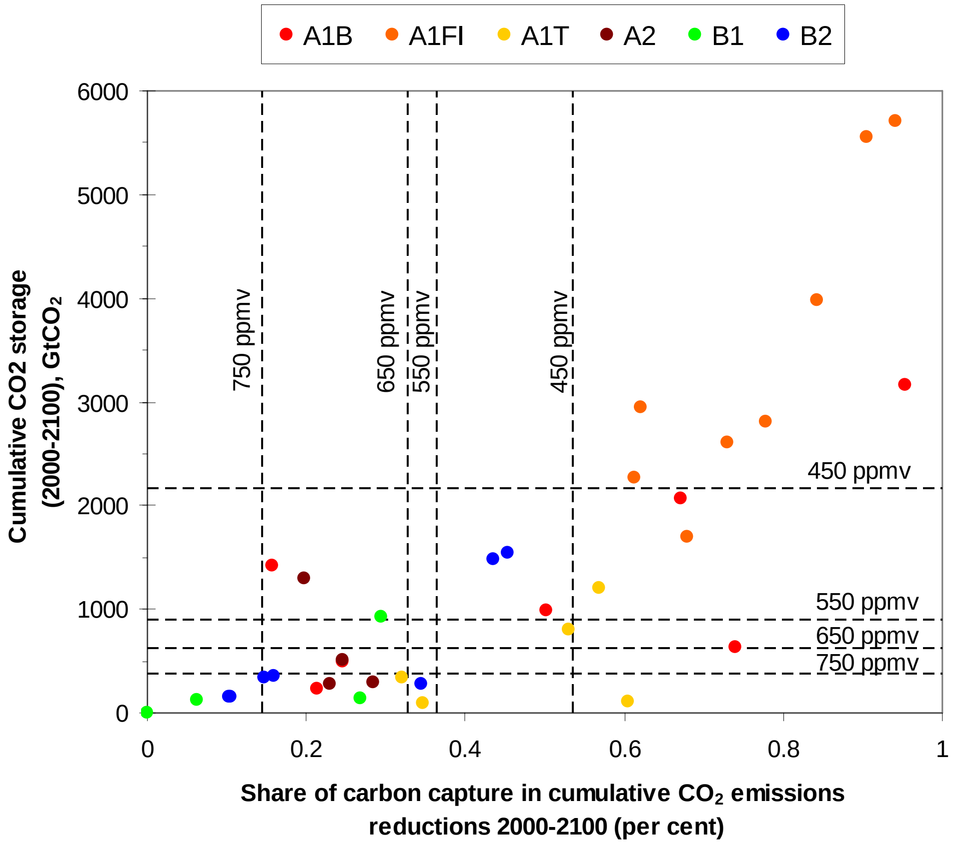


**Figure 8.5.** Relationship between (1) the imputed share of CCS in total cumulative emissions reductions in per cent and (2) total cumulative CCS deployment in $GtCO_2$ (2000–2100). The scatter plots depict values for individual TAR mitigation scenarios for the six SRES scenario groups. The vertical dashed lines show the average share of CCS in total emissions mitigation across the 450 to 750 ppmv stabilization scenarios, and the dashed horizontal lines illustrate the scenarios' average cumulative storage requirements across 450 to 750 ppmv stabilization.

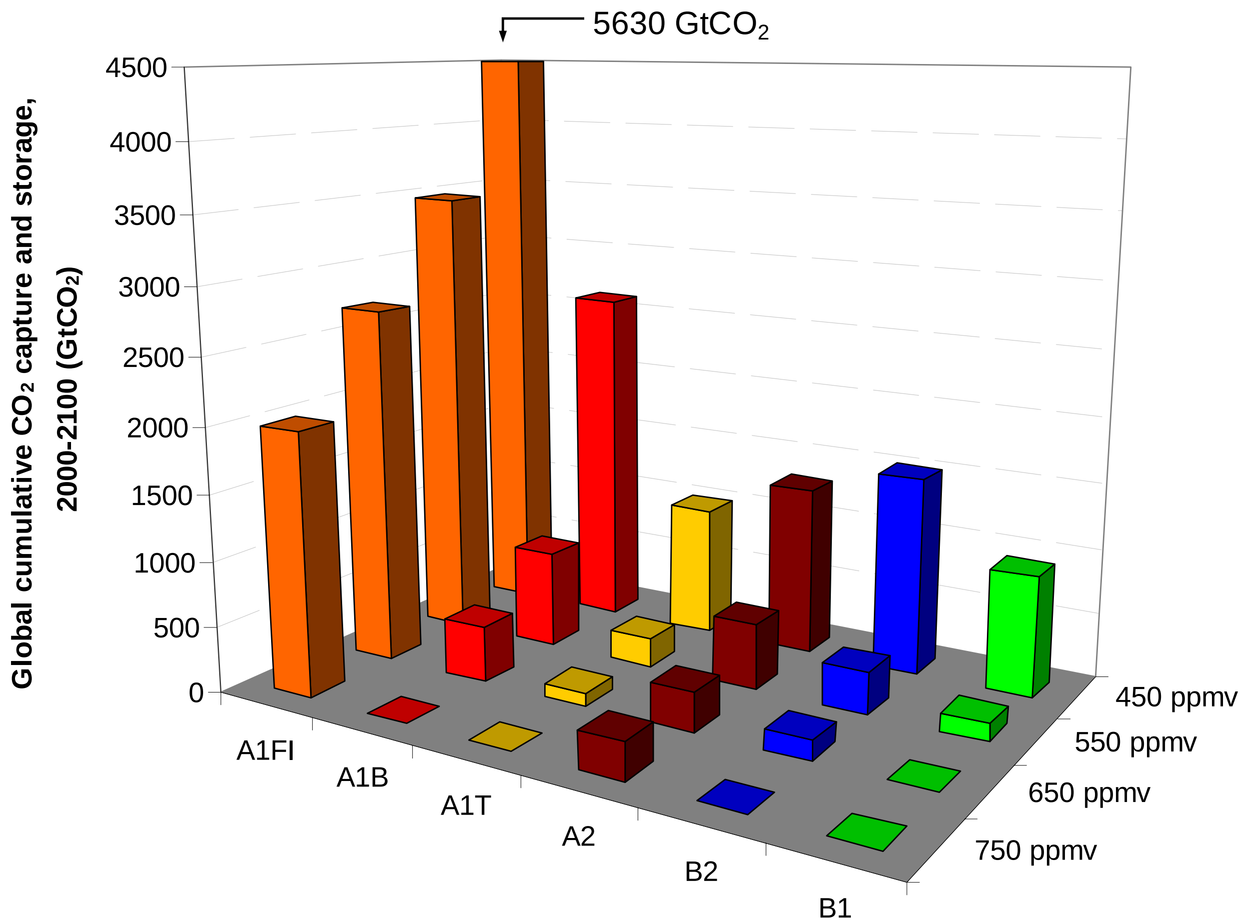


**Figure 8.6.** Global cumulative $CO_2$ storage (2000–2100) in the IPCC TAR mitigation scenarios for the six SRES scenario groups and $CO_2$ stabilization levels between 450 and 750 ppmv. Values refer to averages across scenario results from different modelling teams. The contribution of CCS increases with the stringency of the stabilization target and differs considerably across the SRES scenario groups.

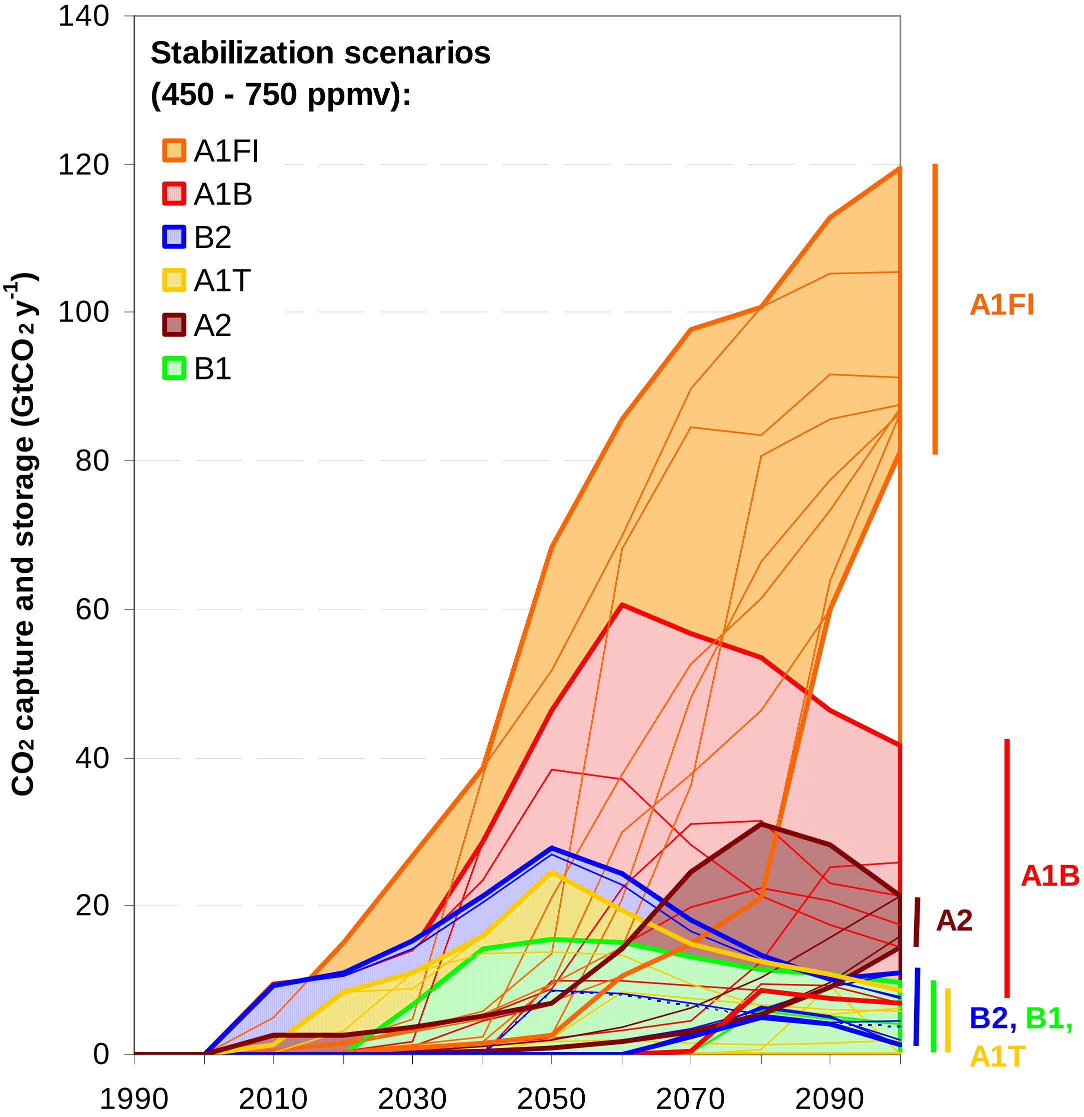


**Figure 8.7.** Deployment of CCS systems as a function of time from 1990 to 2100 in the IPCC TAR mitigation scenarios where atmospheric $CO_2$ concentrations stabilize at between 450 to 750 ppmv. Coloured thick lines show the minimum and maximum contribution of CCS for each SRES scenario group, and thin lines depict the contributions in individual scenarios. Vertical axes on the right-hand side illustrate the range of CCS deployment across the stabilization levels for each SRES scenario group in the year 2100.