



Issue Brief

CARBON CAPTURE AND STORAGE (CCS)

OVERVIEW

Context

40% of current global CO₂ emissions from fuel combustion are from burning fossil fuels in power plants. With the advent of the Kyoto Protocol and other measures, the power generation sector is operating in an increasingly carbon constrained world. Nevertheless, the demand for cheap, reliable electricity supply means the share of fossil fuels in the generating mix is projected by the International Energy Agency (IEA) to increase to over 70% by 2030.¹

Technically speaking, there are four methods to reduce CO₂ emissions from the power sector: 1) to operate plants more efficiently, 2) to switch from consuming fossil fuels to other resources (i.e., renewables, nuclear) and/or 3) to reduce demand for electricity by efficiency or conservation measures. Carbon capture and storage (CCS) offers a potential fourth method: "capturing" CO₂ which would have been emitted and "storing" it would allow fossil fuels to continue to be used without resulting in atmospheric CO₂ emissions.

What is CCS?

CCS is defined as "a process consisting of separation of CO₂ from industrial and energy-related sources, transport to a storage location, and long-term isolation from the atmosphere."²

CCS consists of three major stages:

1. Capture (*separation of CO₂*)
2. Transport
3. Storage (*long-term isolation*).

Transportation of CO₂ by pipeline and shipping is considered to be technically mature and is not considered further in this *Issue Brief*. Further details can be seen in the recently

published *IPCC Special Report on Carbon Dioxide Capture and Storage*.³

CCS could be applied to both electricity and hydrogen production plants. Its future application to hydrogen could allow emissions from transport and distributed energy supply systems to be controlled, although this option would not be significant in the short- to medium-term.

CO₂ CAPTURE TECHNOLOGIES

Technical options

Technical options for CO₂ capture fall under three major categories (see also Figure 1):

1. Post-combustion capture

CO₂ is removed from the flue gas leaving the combustion chamber of the power station. The principal technologies for separation under development are: solvent scrubbing (chemical and physical absorption); cryogenic fractionation; gas membrane separation and adsorption. Optimal technology is selected according to the flue gas condition such as temperature, pressure, concentration and volume of flow. The best established system is solvent scrubbing based on chemical absorption that uses heat induced CO₂ recovery or physical absorption with pressure induced CO₂ recovery. The absorption process has reached the commercial stage for CO₂ capture, albeit not on the scale required for the flue gases from a large (in the order of 600 MW) power plant. Most of those installed have been for food/beverage applications and chemical production; only a few schemes have also incorporated subsequent storage.

2. Pre-combustion capture

In this process, CO₂ is removed prior to the combustion process of the power station via gasification plants such



as integrated gasification combined cycle (IGCC). Gasified coal or natural gas are reformed and shifted to H₂, CO and subsequently CO₂. The H₂ is then used as fuel in a turbine, while the CO₂ is removed and sent for storage. Although the technology employs the same techniques as post-combustion capture for removing the CO₂, the lower volume and higher partial pressures than flue gas improve the overall economics of the process substantially.

3. Oxyfuel firing

In oxyfuel processes, fairly pure CO₂ is captured directly from the flue gas through the firing of the fossil fuel in pure oxygen. This process bypasses the need for a separate CO₂ removal process. Oxyfuel combustion suppresses NOx formation and may also allow some of the flue gas cleaning equipment to be omitted. However, oxygen separation from air remains expensive both in terms of capital and energy consumption; so, the large quantity of oxygen required by the process appears a lasting hindrance if there is no improvement in the separation technology.

captured increases. Capturing and storing 100% of CO₂ emissions would be prohibitively expensive – 85-95% capture is considered to be the optimum level.

The combination of capture efficiencies below 100% and the energy needs of capture mean that plants and processes with fitted CCS systems will still emit CO₂. CCS could eliminate the majority of CO₂ emissions from fossil fuel-fired power generation, but a significant share of CO₂ (in the order of 10-20%) would still be emitted. Further CO₂ could subsequently be emitted if there were any leakage of stored CO₂.

The impacts of scale

For all capture technologies, the cost per unit of captured CO₂ decreases with size. The key targets for all sectors, including power, are thus large plants. The IPCC *Summary for Policymakers*⁵ identifies all sources of CO₂ with annual emissions of at least 0.1 MtCO₂/year. Power plants dominate both sources and emissions:

- Power plants represent 4,942 of the total of 7,887 identified sources (i.e., 63%);
- Power plants were responsible for 10,539 of the total emissions of 13,466 Mt CO₂/year (i.e., 78%).

Power plants are thus the largest potential application of CCS.

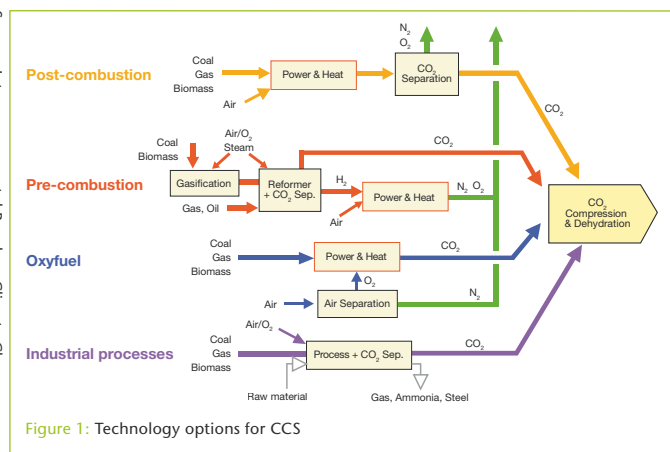
CO₂ STORAGE: OPTIONS AND POTENTIAL

The following estimates of potential storage capacity are derived from the recent IPCC study.⁶

Atmospheric isolation (storage) of CO₂ does not yet have the experience to demonstrate that it can store CO₂ over the very long term. Technical experts are confident that storage in carefully chosen and managed sites would be secure. In part, this confidence is due to an understanding of physical processes: “depths of 800-1,000m would prevent CO₂ from migrating to the surface due to various physical and geo-chemical trapping mechanisms, because CO₂ becomes supercritical and has a liquid-like density (about 500-800 kg/m³) that provides the potential for efficient utilisation of underground storage space and improves storage security.”⁷ Issues regarding storage permanence vary by option.

Long-term storage remains the subject of significant technological, economic and political attention.

Source: Intergovernmental Panel on Climate Change, Special Report on Carbon Dioxide Capture and Storage, 2005.



Capture efficiency and energy use

Capture requires energy to drive it, which in all practical cases would consume fossil fuel resources and lead to CO₂ emissions.

Depending on plant type, the extra energy required ranges from 10-40%⁴, of which the majority is needed for capture.

Whatever the physical and chemical process used, CO₂ capture becomes less energy efficient as the fraction

Depleted oil & gas reservoirs

CO₂ can be stored in oil and gas reservoirs after they have been economically depleted and abandoned. Advantages to storing CO₂ in depleted oil and gas fields include: low exploration costs; well-known geology; and potentially secure traps, which have trapped liquids and gases for millions of years. However, their resource exploitation has led to the digging of numerous wells and geo-mechanical pressures, which could be a source of fracturing and leaks. The potential capacity for CO₂ storage in depleted oil & gas reservoirs is estimated to be around 900-1,200 Gt CO₂ globally, with the majority in depleted oil fields. Important locations include the North Sea, Permian Basin (Texas), South China Sea, Arabia, Australia.

Enhanced oil recovery

CO₂ is an effective solvent for oil in geological traps, and as such can be used for enhanced oil recovery (EOR) in mature oil fields. The increased revenue accrued from EOR can actually offset some of the costs of CO₂ storage. EOR projects are currently under way in a number of countries. There are more than 70 EOR operations employing CO₂ (both natural and anthropogenic) worldwide, most of which are in North America. A large-scale commercial EOR project is currently in progress at the Weyburn oil field in Canada.

Deep (unmineable) coal seams

Another potential CO₂ storage site is abandoned or uneconomic coal seams. The pore structure of coal allows it to physically adsorb CO₂ and consequently displace adsorbed methane. Provided the coal is never mined, this storage option permanently immobilizes the CO₂. There is estimated to be some 15-200 Gt (Gigatons) CO₂ storage capacity worldwide in coal seams.

Coal bed methane

Injecting CO₂ into unmineable coal beds also has the value-added benefit of enhanced coal bed methane recovery (ECBMR). The coal matrix can adsorb two CO₂ molecules for each CH₄ (methane) molecule displaced. This additional CH₄ removal, as it can be used for electricity generation, can offset the cost of coal seam CO₂ storage or even make it cost free.

There are currently 59 opportunities in North America, Europe and Asia where ECBMR technology is being investigated. Although CO₂ storage in deep unmineable coal

seams will likely not have a substantial impact on a global scale, its potential could be significant in some regional niches.

Saline aquifers

Deep saline aquifers are widely distributed below major land masses and oceans; however, for an aquifer to be considered appropriate for CO₂ storage, it must be comprised of porous sedimentary rock and have a low permeability overlying layer ("cap rock") to minimize the potential for vertical migration of CO₂ out of the reservoir. CO₂ storage capacities in deep saline aquifers are estimated to be at least 1,000 Gt CO₂ worldwide, with an upper bound of over 10,000 Gt CO₂. CO₂ storage in aquifers has been implemented in the North Sea since 1996, where 1 Mt CO₂ per year from the gas in the Sleipner field is separated and stored in the Utsira sandstone formation under the seabed.

Oceanic

Compared to all other storage reservoirs, the ocean has by far the largest estimated potential capacity (2,300-10,700 Gt CO₂) for anthropogenic CO₂ emissions. Although it has never been attempted in practice, injecting CO₂ directly into the ocean has been proposed, supplementing the relatively slow natural absorption process. Deep ocean storage approaches under consideration include direct injection of CO₂. At intermediate depths (1,500-3,000 meters) the CO₂ would undergo dissolution and dispersion, at depths below 3,000 meters it would form a "CO₂ lake". The process is of particular interest in areas with low geological resources like Japan. Public and NGO reaction to oceanic storage has been strong: scientific knowledge remains weak and the risks of major impacts could be significant.

Mineral carbonation

It is possible to react CO₂ with metal oxides to produce stable carbonates, hence sequestering the CO₂. Metal oxides are abundant in silicate materials and, in small quantities, in waste streams. This option is in the research stage and is not considered further.

Total storage capacity available

Evidence suggests that worldwide, it is likely that there is a technical potential of at least 2,000 Gt CO₂ of storage in geological formations. This is likely to be sufficient to cover the demand for geological storage over the next century,

but the useful storage potential would need to be checked. Major concerns include validation of feasibility, safety and public acceptance.

STATUS

Each part of the required technical process is in use today (e.g., capture and reservoir engineering in the oil and gas sector). CCS is the application of known techniques to a new challenge - putting together all parts of the process in an integrated and economic whole will be complex. Different CCS solutions are needed for each emissions source (e.g., the power sector).

The IPCC *Special Report*⁸ summarizes the state of development of each element in the CCS cycle. Table 1 below, taken from the report, shows that at least one option within the capture, transportation and storage categories is already at *mature market* status.

CCS component	CCS technology	Research phase	Demonstration phase	Economically feasible under specific conditions	Mature market
Capture	Post-combustion			X	
	Pre-combustion			X	
	Oxyfuel combustion		X		
	Industrial separation (natural gas processing, ammonia production)				X
Transportation	Pipeline				X
	Shipping			X	
Geological storage	Enhanced oil recovery (EOR)				X
	Gas or oil fields			X	
	Saline formations			X	
	Enhanced coal bed methane recovery (ECBM)		X		
Ocean storage	Direct injection (dissolution type)	X			
	Direct injection (lake type)	X			
Mineral carbonation	Natural silicate minerals	X			
	Waste materials		X		
Industrial uses of CO ₂					X

Table 1: Current State of technological development of CCS system components.

Note: The X's indicate the highest level of maturity for each component.

Status and prospects for implementation in the power sector

CCS for power plants has not yet been implemented on a commercial basis. Different parts of the CCS cycle are at different stages of development. CCS as an integrated whole is a major challenge and currently in the demonstration phase.



CO₂ post-combustion capture at a plant in Malaysia.
Courtesy of Petronas Fertilizer Kedah and Mitsubishi Heavy Industries.

Large-scale implementation in the power sector is not expected for another 20 years, and will depend on how the costs of CCS compare to other methods of avoiding CO₂ emissions.

A range of options exists for applying CCS in the power sector. The key need is to apply CCS to coal-fired plants – without CCS, coal generation in a carbon-constrained world would be significantly limited. This would represent a major challenge in the parts of the world where coal is the only large-scale, economic resource available for electricity generation. Coal gasification for power generation (IGCC) is regarded as particularly compatible with carbon capture because the concentration of the CO₂ in the exhaust stream is higher, making it easier to capture.

IMPACTS

Environmental – Global and local

CO₂ can be dissolved in aquifers and can potentially cause environmental contamination. Stored CO₂ also presents a potential risk of oxygen deprivation should a sudden large-scale release of CO₂ occur. Proper CO₂ monitoring systems and remediation measures can prevent such problems.

The environmental impacts associated with CO₂ storage are likely to play a key role in determining the acceptability of

CCS technologies. The key problem is whether CO₂ will leak from storage sites back into the atmosphere and how the leakage will affect surrounding ecosystems and human health (where large releases could lead to oxygen deprivation). CO₂ leakage may occur and it is difficult to prove the permanence of secure storage over a long period of time. Progress in modelling allows increasingly accurate forecasts of the long-term fate of the CO₂, which cannot be tested in practice. The recent IPCC *Special Report*⁹ summarizes available estimates of risk and probabilities of events.

Social/Community

In order to gain acceptance as a large scale option, CCS must convince the public that:

- It is safe;
- Storage would be long-term;
- The energy it uses is a reasonable use of limited fossil fuel resources;
- Inter-generational equity concerns of a CCS legacy can be met.

This will require transparent communication of complex scientific, technical and economic issues. Effective stakeholder engagement will be an important part of any CCS strategy.

In-depth research & development is still required for improving knowledge about securing transportation and storage as well as the energy balance of the whole process. Local and regional specificities should be taken into account: fossil fuel resources, storage options, transport range, advantages and drawbacks, comparison of technologies, etc. Life cycle analysis should provide sound criteria to make decisions. Generating the well-founded information for all stakeholders to decide on possible large-scale implementation in 20-25 years is a motivating challenge.

REGULATORY DEVELOPMENTS

Overview

The potential of CCS to significantly reduce CO₂ emissions from the power sector will require stored (sequestered) carbon to be recognized as avoided emissions by international and national regulations and policy. This will include both energy policy and the recognition of avoided CO₂ emissions within the Kyoto Protocol and its Clean Development Mechanism (CDM). Whatever the approach used, and whether it is a market-based approach or not,

it is vital that CCS be treated fairly in comparison to other options for avoiding CO₂ emissions. Flexible but long-term policy is required, with mechanisms covering all options and fuel types.

Inventories and accounting practices need to be modified to allow the accounting of CCS. One of the key challenges in policy development will be to decide the liabilities for long-term leakage of CO₂.

It will be much more straightforward to implement CCS in countries which recognize that they must limit CO₂ emissions (most of the developed world) than those that do not. This presents a major challenge for the parts of the developing world that rely heavily on coal for their electricity generation.

UNFCCC and the Kyoto Protocol

There are no specific clauses in either the United Nations Framework Convention on Climate Change (UNFCCC) or the Kyoto Protocol that would suggest that CCS may not be eligible under these agreements. Indeed, Article 2 (1) (a) (ii) of the Kyoto Protocol refers to the enhancement sinks and reservoirs of CO₂, which could be interpreted as including CCS operations. Therefore, the Kyoto Protocol, or subsequent protocols, could provide an additional incentive for CCS.

There are no qualified CCS projects under the Kyoto Protocol emissions trading mechanisms at present. Neither have rules been established for CCS in other international CO₂ trading mechanisms such as the EU's Emissions Trading Scheme.

However, the CDM Executive Board has now recognized CCS as a potential CDM activity, and further investigations are ongoing at the level of different convention bodies of the UNFCCC, taking into account issues related to project boundaries, leakage and permanence.

In order for further implementation to be realized, monitoring, reporting and verification protocols will need to be agreed by the Executive Board, and host countries need to approve projects. For projects in developed countries, the recognition of storage activities in national GHG inventories will be of critical importance.

Marine dumping of wastes – London Convention, OSPAR etc.

All relevant international marine treaties (e.g., the London and OSPAR Conventions) have been drafted without specific consideration of CO₂ storage. In terms of marine protection, although CO₂ is not defined explicitly as a waste or

exception in existing legal texts, prohibition against marine dumping of waste could present a significant constraint to CCS under the related international framework. In order to be compatible within the respective objectives of climate change and marine protection, clarity is needed before the widespread deployment of CCS can be taken forward in the marine environment.

The technical summary draft of the IPCC Special Report¹⁰ reviews the current status:

Currently, there are several treaties (notably the UN Convention on the Law of the Sea, and the London and OSPAR Conventions) that potentially apply to the offshore injection of CO₂ into marine environments (i.e., both into the sea and the sub-seabed). All these treaties have been drafted without specific consideration of CO₂ storage. An assessment undertaken by the Jurists and Linguists Group to the OSPAR Convention (relating to the North East Atlantic region), for example, found that depending on the method and purpose of injection, CO₂ injection into the geological sub-seabed and the ocean could be compatible with the treaty in some cases, such as when the CO₂ is transported via a pipeline from land. A similar assessment is now underway by Parties to the London Convention. Furthermore, papers by legal commentators have concluded that CO₂ captured from an oil or natural gas extraction operation and stored offshore in a geological formation (like the Sleipner operation) would not be considered "dumping" under, and thus prohibited by, the London Convention.

A proposed amendment to the London Convention aims to allow gas which is "overwhelmingly CO₂" to be stored under the sea-bed, providing that there is no trans-boundary movement of the CO₂. The OSPAR Convention has not yet decided to make any such change, and the next action point will not be before the next annual OSPAR meeting scheduled for June 2007.

Regulatory needs going forward

National legal and regulatory situations for CCS vary from one country to another depending on the fossil fuel resources available, each country's CO₂ storage technology stage, and specific public acceptance concerns. At the Federal and State levels in the US, there is a reasonably clear regulatory framework governing CCS operations through the Underground Injection Control (UIC) regulations. Other countries such as the UK, Canada, Australia and the EU are currently applying existing legal frameworks to CCS projects. These frameworks were not specifically designed to address

CCS and will need to be updated to take into account the scientific progress that has been achieved and in light of new GHG mitigation objectives.

COSTS AND POTENTIAL

Definition of costs

CCS costs can be defined in different ways. Consider a plant that emits 1 metric ton of CO₂. Adding CCS will increase the amount of energy used and hence the emissions (assuming that the extra energy needed is supplied by the same plant). With a typical extra energy use of 20%, emissions from the plant before capture are now 1.2 metric tons of CO₂.

If the capture efficiency is 90%, this will result in $1.2 * 90\% = 1.08$ t CO₂ captured. This is not the same as CO₂ avoided – the plant without CCS emitted 1 tCO₂, and the plant with CCS emits $1.2 - 1.08 = 0.12$ tCO₂. Thus the CO₂ avoided is $1 - 0.12 = 0.88$ tCO₂. The quantity of avoided CO₂ is clearly less than the CO₂ captured, which is a general finding. In terms of costs, costs per tCO₂ captured will be lower than costs per tCO₂ avoided. The gap between the two narrows as the share of CO₂ captured and the energy efficiency of the process increase.

For consistency with cost estimates of other CO₂ abatement measures, costs per tCO₂ avoided are used throughout the remainder of this *Issue Brief*.

Current costs

The costs of CCS depend on a range of factors including fuel, which technologies are used, how/where they are applied, location, national circumstances and whether there is a use for the captured CO₂.

Retrofitting capture equipment to existing power plants would be significantly more expensive, and less efficient, than including capture within new plants. All costs now quoted apply to new plants. Costs are largely unproven and are thus approximate. System costs require estimates of the costs of each element of the cycle (capture, transportation and storage), each of which is uncertain and is usually quoted within a range.

Cost estimates to date can be summarized as follows:¹¹

- The range is US\$ 20-270/metric ton CO₂.
- This would typically increase electricity generating costs by 1-5 US cents/kWh electricity generated (approximately 25-125% of generation costs).

- Certain early opportunities exist with substantially lower costs, but their potential is limited. They mainly concern industrial uses for captured CO₂ (for example, enhancing the recovery of either oil or methane from coal beds, by using EOR and ECBMR). These have the potential to use only a small fraction of the CO₂ emitted from the power sector and, depending on the application, net life cycle reductions of CO₂ are not always achieved. Revenues from EOR/ ECBMR could reduce costs by US\$ 20-30/metric ton CO₂ (around 1 US cents/kWh electricity generation).
- Generally more than half of estimated CCS costs are due to the cost of capture.

Future costs

CCS costs could drop significantly in the future. Estimated costs in 2030 could be in the range US\$ 25-50/metric ton CO₂. Costs will fall with experience, as choices as to the best options are refined and the integrated process is optimized.

Potential

The earlier section on storage concluded that there was sufficient capacity in geological formations to cover the demand for geological storage over the next century. CCS potential is thus a question of cost. Key drivers are:

- The size of emissions sources (economies of scale mean that sources under a certain size could not be developed economically).
- Distances between emissions sources and storage sites.
- The costs of alternative methods for avoiding CO₂ emissions.

Based on these factors, the IPCC Special Report concludes that, “by 2050, given expected technical limitations, around 20-40% of global fuel CO₂ emissions could be technically suitable for capture, including 30-60% of electricity generation and 30-40% of industrial CO₂ emissions.”¹² CCS could thus make a significant contribution, but would not be applicable to all CO₂ emissions and would always be part of a portfolio of measures.

The exact potential clearly relies on a range of assumptions relating to the costs of CCS and of other options. As we look further into the future, meeting possible increasing carbon constraints would probably lead to the exhaustion of the lowest cost options available today. A major role is thus envisaged for CCS: the IPCC review concludes that,

"in most scenario studies, the role of CCS in mitigation portfolios increases over the course of the century, and including CCS in a mitigation portfolio is found to reduce the costs of stabilizing CO₂ concentrations by 30% or more."¹³ The IPCC reports that a range of modeling studies show CCS being implemented when market carbon prices reach US\$ 25-30/tCO₂.

It is important to understand that CCS will only be applied if there is some incentive in place to mitigate carbon emissions. Even then, it has to be cost-effective in comparison with other options. CCS could be used during a transition to more sustainable forms of power generation, such as hydrogen, in the future.

INTERNATIONAL ACTIVITIES AND R&D

International activities

In response to a request from the Conference of the Parties to the UNFCCC, the IPCC released a *Special Report on CCS* in 2005. This report provides the most comprehensive body of information on all aspects of CCS prepared to date.

At the international level, the Carbon Sequestration Leadership Forum (CSLF) was created in 2003. The purpose of the CSLF is to make CCS technology broadly available internationally and to identify and address wider issues relating to CCS. The current members of the CSLF are 16 countries and the European Commission.

The CO₂ Capture Project¹⁴ (CCP) is an international effort funded by eight of the world's leading energy companies. This project addresses the issue of reducing emissions in a manner that will contribute to an environmentally acceptable and competitively priced continuous energy supply for the world. CCP1 ran from 2000-04, and CCP2 runs from 2004-07.

Research & development (R&D)

CCS R&D is by and large a government undertaking. The US and some other governments have developed large R&D programs to investigate and develop CSS options.

The IEA Greenhouse Gas R&D program, founded in 1991, is an international collaboration of governments and industries from many countries. It focuses its efforts on studying technologies to reduce greenhouse gas emissions including CCS.

The FutureGen¹⁵ power generation project, one of the US's major planned initiatives for CCS, will operate at net 275 MW capacity using IGCC technology to produce both electricity and hydrogen while sequestering 1 Mt of CO₂ per year.

REFERENCES AND NOTES

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Our **mission** is to provide business leadership as a catalyst for change toward sustainable development, and to support the business license to operate, innovate and grow in a world increasingly shaped by sustainable development issues.

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Powering a Sustainable Future is a result of collaborative work among executives from the eight member companies of the WBCSD Electricity Utilities Sector Project. This work was convened and supported by the WBCSD Secretariat. All member companies of the project have thoroughly reviewed drafts of the report. However, this does not mean that every member company necessarily agrees with every statement in the report.

