Science for Environment Policy
DG Environment News Alert Service
SPECIAL ISSUE

Carbon Capture and Storage

Issue 3 April 2008

Mitigating climate change: the role for carbon capture and storage

Carbon capture and storage (CCS) technologies are expected to play a key role in strategies to avoid dangerous climate change. They enable large reductions in CO_2 emissions, even given the almost inevitable continued use of fossil fuels. Recently, the European Commission has proposed a policy to address the environmental integrity of carbon capture and geological storage (http://ec.europa.eu/environment/climat/ccs/index_en.htm). CCS is especially important for coal-based developing economies such as China and India.

This Thematic Issue reports recent advances in CCS research, focusing on technology development, environmental impact and transportation issues.

Current technologies for CCS are ready to be demonstrated at scale as soon as possible for 'learning by doing'. With suitable incentives to encourage early movers, sufficient CCS capacity could be implemented in time to contribute to EU targets for a 20 per cent reduction in CO_2 emissions by 2020 (see 'Fast tracking CCS deployment' and 'Making new-build power plants CO_2 capture ready'). New CCS technologies are also in development that may offer significant benefits in terms of power station efficiency (see 'Driving down the cost of carbon capture').

A number of challenges remain. Safe and cost-effective transport of captured CO_2 to storage sites is one such concern (see 'Transport challenges for CCS'). Pipelines are in use in the USA and Turkey to transport CO_2 for enhanced oil recovery and in the future these are likely to be the most viable option for transporting captured CO_2 within Europe, though shipping may also have a role to play.

Key areas still being addressed are methodologies for identifying and assessing safe underground storage sites before permitting and for then monitoring them during and after CO_2 injection. Geological studies are underway to predict how different sites will respond to CO_2 storage (see 'Will CO_2 stay in the ground?') and to investigate the risks associated with long-term low level leaks at the site of injection as well as the potential impacts of larger scale point leaks from injection equipment or well failures.

With its strong technology background and the fortuitous availability of extensive offshore storage capacity deep under the North Sea, the EU is in a good position to be an early leader on CCS development and deployment. This should give EU manufacturing and engineering service industries a clear advantage in a potentially very large global market. But an even greater benefit will be achieved if EU leadership encourages subsequent CCS take-up by China, India and other key participants as part of an effective global CO_2 reduction agreement.

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EUROPEAN COMMISSION
environment

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Making new-build power plants CO_2 capture ready

Ideally, to minimise the risk of climate change, no new power plants would be built without carbon capture and storage (CCS). This must be balanced against the growing demand for energy, especially from developing countries, that cannot wait while the necessary technology, regulations and incentives for CCS are put in place. But, even if new power plants are built without CCS, a new IEA GHG report shows that they may not be locked-in to a fifty-year lifetime of carbon emissions if they are designed to be 'capture ready', so that their CO_2 emissions can be captured once the essential regulatory requirements or economic conditions are introduced.

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"The key issues for new-build capture-ready plants are allowing sufficient space and access for the additional facilities that will be required, as well as suitable transport routes to CO_2 storage sites."

New coal plants are seen as a climate threat, because there are reliable, large global supplies, especially in countries with projected high energy demands such as the USA, China and India. But conventional pulverised coal power stations can easily and cheaply be built with capture ready capabilities for subsequent retrofit using post-combustion or oxy-combustion capture. The key issues for new-build capture-ready plants are allowing sufficient space and access for the additional facilities that will be required, as well as suitable transport routes to identified CO_2 storage sites.

On 23 January 2008, the EC proposed a directive to allow capture and underground storage of CO_2 in the EU[1]. Large scale application of CCS in power plants is expected to be viable in 10-15 years, allowing it to play a role in the EU ETS (emissions trading system)[2]. Reform of the ETS will impose a cap on CO_2 emissions which will be reduced year on year and an auctioning system will replace the current system of allocating emissions credits. The power sector – forming the majority of EU emissions – will face full auctioning from the start of the new regime in 2013.

In the UK, electricity utility E.ON is planning to replace a plant at Kingsnorth with a new capture-ready pulverised coal plant. Three new natural gas power plants have already been given UK government permits on the basis of their being capture ready. The UK Government has also recently selected post-combustion technology for its first commercial-scale CCS demonstration project.

Integrated Gasification Combined Cycle (IGCC) power plants (plants which make synthetic gas) are also being considered in Europe because this technology can be combined with pre-combustion capture technology. This is a bigger jump for users, though, and it is probably only worth building IGCC plants if they have CO_2 capture incorporated at the outset. This may be too many innovations at one time. Pre-combustion technologies are being explored by the ENCAP[3] programme.

Source: IEA Greenhouse Gas Research and Development Programme (IEA GHG), (2007). CO2 capture ready plants. Report number 2007/4, accessed from: www.iea.org/textbase/papers/2007/CO2_capture_ready_plants.pdf

1. See http://www.ec.europa.eu/energy/climate_actions/index_en.htm for information on the EC's Climate Action proposal and CO2 capture.

2. See http://www.ec.europa.eu/environment/climat/emission/ets_post2012_en.htm for information on the EU ETS

3. ENCAP is a project whose objective is to develop new pre-combustion CO_2 capture technologies. It is funded by the European Commission under the 6th Framework Program. Please see http://www.encapco2.org/

Fast tracking CCS deployment

Efforts to combat climate change must take into account the huge projected increase in emissions from the energy sector over the coming decades. This increase in demand will largely come from developing countries. Using carbon capture and storage (CCS) technology to minimise carbon emissions can help cut emissions from fossil fuel generation, particularly energy generated using coal, which is growing particularly fast in India and China. Experts now believe that post-combustion CCS technology could be rolled out in time to help meet the 20 per cent reduction in CO_2 emissions required by 2020 under current EU policy.

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"Of the three procedures being considered for demonstrating CO_2 capture at power plants, post-combustion capture could be implemented most rapidly, because the systems can be retrofitted to existing power plants."

Of the three procedures being considered for demonstrating CO_2 capture at power plants, post-combustion capture could be implemented most rapidly, because the CCS systems can be retrofitted to existing power plants. Modified designs can be tested later without building new demonstration plants. When evaluating a major change or redesign for the other two systems, pre-combustion capture in Integrated Gasification Combined Cycle (IGCC) plants would probably require a new base power plant and capture plant to be built and oxyfuel (O_2 / CO_2 recycle combustion) plants would need significant alterations to the base power plants.

A two-phase approach to reduce the technology and costs associated with using post combustion CCS in power plants burning fossil fuels has been suggested: construction of small–scale plants of around 100MW output in the first phase, followed by larger, semi-commercial sized plants with around 300-500MW output, to be built in the second phase. Two phases, but necessarily over longer periods, are also needed to bring oxyfuel and pre-combustion capture to a reasonable level of maturity. The researchers advise commercial rollout initially in developed countries, but suggest the technology would be taken up by developing countries, once the benefits were proven.

To allow CCS to contribute effectively to the global effort to reduce CO_2 emissions, the two phases of demonstration plants would ideally be completed by 2020, when the 20 per cent reduction in CO_2 emissions becomes binding on EU states[1]. This rapid-learning deadline is probably most easily met using post-combustion capture. If there is early confidence in the technology, commercial development of new power plants using CCS could be advanced, with rollout in developed countries by 2015 and global rollout by 2020. For this to happen, substantial financial assistance from Governments and other sources and a supporting regulatory framework are urgently needed to ensure immediate testing and development of all CCS technologies.

The CASTOR project[2] is exploring improvements in post-combustion CO_2 capture that could to reduce the costs of CO_2 capture from 50-60 Euros per tonne to 20-30 Euros per tonne. CASTOR aims to define strategies that will allow the capture and storage of 30 per cent of CO_2 currently emitted from European power stations.

[1] See http://www.ec.europa.eu/energy/climate_actions/index_en.htm for more details.

[2] CASTOR is funded by the European Commission under the 6th Framework programme. See https://www.co2castor.com for more details.

Source: Gibbins, J., Chalmers, H. (2007). Preparing for global rollout: A 'developed country first' demonstration programme for rapid CCS deployment. *Energy Policy*. doi:10.1016/j.enol.2007.10.021.

Carbon capture: environmental impacts

Before regulators extend subsidies to carbon capture projects or require all new plants to use carbon capture technology, they should consider the environmental effects of the technologies. Recent research[1] explored the effects that carbon capture systems could have on the emissions of acid gas pollutants, such as nitrogen oxides and sulphur oxides, from power stations. New research also suggests that water consumption increases when some types of power plant are fitted with carbon capture systems.

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"Coal-fired power stations equipped with capture technologies are likely to reduce sulphur dioxide emissions by at least 96 per cent."

In the short to medium term, fossil-fuel fired power plants are expected to deploy carbon capture technologies to cut global greenhouse gas emissions, and research is underway to explore the environmental impacts of these technologies. Recent research investigated emissions of acid gas pollutants and CO_2 from power plants with and without carbon capture.

The results show that the effect on the acid gas emissions of an individual plant depends on a combination of two factors. First is the application of the capture process itself. This is unlikely to increase significantly the emissions of acid gas pollutants. On the contrary, the solvents used to capture CO_2 from the flue gases will remove some nitrogen oxides and sulphur oxides. The second is the energy penalty that the capture technology imposes. Because currently available carbon capture technologies reduce the efficiency of power plants, more fossil fuel will need to be burned to generate the same amount of energy.

The resulting increase in nitrogen oxide emissions, however, is small, estimated at 5 per cent for natural gas powered plants and 24 per cent for coal-fired plants, while at least 80 per cent of the CO_2 generated will be captured. Sulphur dioxide is produced mainly by coal combustion. The authors estimate coal-fired power stations equipped with capture technologies are likely to reduce sulphur dioxide emissions by at least 96 per cent. This will be driven by a need to avoid expensive losses of the solvents used to capture CO_2.

More important than the impact on individual plants is the effect on projected emissions from the energy sector as a whole when CCS is (a) enabled or (b) made mandatory. Recent work[2] shows that under both scenarios, emissions reduce significantly relative to a business as usual scenario, because of indirect effects such as fuel-switching.

Water consumption, however, may be an issue for carbon capture systems which rely on solvents to remove CO_2 from flue gases. A new study estimates that the amount of water used for thermal cooling at US pulverised coal plants with CO_2 capture equipment could double by the year 2030[3]. This increase in water consumption may make these systems less suited to dry regions. New technologies that reduce the demand for water need to be developed in the longer term.

Source: Tzimas, T., Mercier, A., Cormos, C. and Petevas, S.D. (2007). Trade-off in emissions of acid gas pollutants and of carbon dioxide in fossil fuel power plants with carbon capture. *Energy Policy.* 35 (8):3991-3998.

[1] This study was carried out within the multi-annual work programme of the European Commission's Joint Research Centre within the "Assessment of Energy Technologies and Systems " Action.

[2] Cofala, J., Rafal, P., Schoepp W., and Amann M. (2007) Impacts of options for CCS incentivisation. IIASA. Laxenburg.

[3] Shuster, E (2007). Estimating freshwater needs to meet future thermoelectric generation requirements. DOE/NETL- 400/2007/1304. The full report can be accessed from: http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/2007WaterNeedsAnalysis-UPDATE-Final_10-10-07b.pdf

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Will CO_2 stay in the ground?

Storing carbon deep below the earth's surface could play a prominent role in tackling climate change. But before underground CO_2 reservoirs can be deployed as viable long-term storage options, environmental concerns over leakages and the behaviour of trapped CO_2 must be addressed. A new model can help predict how different geological sites will respond to CO_2 sequestration, and the likelihood of a CO_2 plume escape, the biggest environmental concern associated with CO_2 storage.

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"In addition to the global climate change impact of CO_2 returning to the atmosphere, leakages pose risks to health and ecosystems."

Sleipner, in the Norwegian section of the North Sea, is one of three large carbon storage sites along with Weyburn in the USA and In Salah in Algeria. Since 1996, 8 million tonnes of CO_2 have been injected into the Sleipner reservoir's 200m porous layer of thick, saline-filled sand, or aquifers, and the site has been thoroughly monitored.

Scientists tracked thickness profiles for the different layers using time-lapse seismic surveys. Because the injected CO_2, which is in liquid form, is less dense than the salt water in the reservoir, it rises and is partially trapped beneath a number of thin impermeable mudstone layers before reaching the thick cap-rock overlaying the site. The study revealed that CO_2 accumulated in the upper layers, while the fraction of CO_2 trapped in the lower layers appeared to decrease with time, possibly because the CO_2 moved upwards. The authors suggest that seismic surveys provide an economically-viable tool to follow CO_2 behaviour in different sites. Such imaging can rapidly assess the suitability of a wide range of reservoirs for long-term CO_2 storage.

A range of potential carbon storage sites need to be investigated representing a wide range of different geological characteristics. Within Europe, carbon storage is being investigated in different geological sites including: RECOPOL, a project exploring CO_2 storage on land in the Silesian coal basin of Poland[1], LACQ, an industrial demonstration project in France, using the Rousse natural gas reservoir for storage and CO2SINK[2], exploring the geology in Ketzin, Germany.

Carbon storage is not risk free. In addition to the global climate change impact of CO_2 returning to the atmosphere, leakages pose local risks to health and ecosystems. For storage sites under water, there are concerns about chronic exposure of marine ecosystems to raised CO_2 levels, such as might occur near injection sites. For CO_2 storage sites on land, there are concerns that large scale leakage could harm people and wildlife in the immediate vicinity. However it should be noted that the pH changes in the North Sea predicted for the next century vastly exceed the impact of leakage from a number of Sleipner-like storage sites in the North Sea.

Deep saline aquifers, like the Sleipner reservoir, offer the largest storage capacity of all geological media, and the technology is in place for them to be used immediately. The absence of policy, legislation and a proper regulatory framework is the most critical barrier to the large-scale implementation of CO_2 geological storage.

Source: Bickle, M., Chadwick, A., Huppert, H. E., *et al.* (2007). Modelling carbon dioxide accumulation at Sleipner: Implications for underground carbon storage. *Earth and Planetary Science.* 255, 164–176.

[1] RECOPOL is co-Funded by the European Commission under the 5th Framework programme. See http://recopol.nitg.tno.nl/index.shtml

[2] CO2SINK is co-funded by the European Commission under the 6th Framework programme. See http://www.co2sink.org

Transport challenges for CCS

Carbon Capture and Storage (CCS) schemes will involve the transport of pressurised liquid CO_2 to sites where it is permanently stored. Options for CO_2 transport include pipelines and shipping. Research is underway to identify the key challenges to be overcome to ensure that CO_2 can be safely and economically transported to potential storage sites. Potential storage sites include depleted oil wells, where it could be used for enhanced oil recovery (EOR)[1], empty gas wells, coal seams which cannot be mined or porous water-bearing rock formations known as saline aquifers.

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"To date, pipelines have attracted more attention than shipping as transport options for CO_2. However, in some cases shipping may be more cost-effective."

Over 3000 km of CO_2 transport pipelines have been built, and are operational, mainly in the USA, but with one example also in Turkey. These have been used primarily to deliver CO_2 for EOR. Regulators in the USA have classified CO_2 pipelines as hazardous liquid pipelines when they operate a pressures over 73 atmospheres and have specified additional requirements such as increased depth of cover and surveillance when such pipes run close to population centres. Pipelines carrying petroleum and petroleum products are also classified as hazardous liquid pipelines. For CO_2 pipelines operating at pressures under 73 atmospheres, US regulators apply the same regulations as govern pipelines carrying natural gas.

The majority of US pipelines are laid in sparsely populated areas and there is little experience of pipelines in more densely populated areas. The researchers suggest that further work is needed to understand and regulate any risks associated with pressurised CO_2, particularly in relation to pipelines located onshore in densely populated areas. The also suggest further research into the level of toughness required for pipe materials to prevent fracture propagation in offshore pipelines (cracks that could 'unzip' a CO_2 pipeline over long distances). Calculating the level of toughness required is more complicated for offshore pipelines because the effect on the pipeline of interaction between escaping liquid CO_2 and water is not fully understood.

If water is present in the CO_2 stream, carbonic acid can form. Carbonic acid is corrosive to carbon steel pipes, which are the most economically viable material for pipeline construction. This well-known phenomenon can be avoided by drying the CO_2 (reducing water content to very low levels) before transportation. Drying adds only moderate additional costs to CCS.

To date, pipelines have attracted more attention than shipping as transport options. However, in some cases shipping may be more cost effective and/or allow lower-cost CO_2 sources and storage reservoirs to be used that cannot easily be accessed by pipelines or that may not be operational for long enough to justify the infrastructure investment. For offshore sites, ships transporting CO_2 as a pressurised, cryogenic liquid could compete economically with pipes for transport over distances greater than 700 km (assuming 6.2 Mt transported per year)[2]. However, as volumes of CO_2 to be transported increase, ships become less economically competitive with pipelines.

[1] EOR is a process whereby CO_2 is pumped into oil fields to facilitate the extraction of oil that could not otherwise be accessed.

[2] IEA Greenhouse Gas Research and Development Programme (2004). Ship Transport of CO_2, Report number PH4/30.

Source: Race, J.M., Seevam, P. N., Downie, M. J. (2007). Challenges for offshore transport of anthropogenic carbon dioxide. Proceedings of OMEA2007, 10-15 June, 2007, San Diego, CA, USA.

Driving down the cost of carbon capture

Post-combustion carbon dioxide capture technologies can already be used under certain conditions and pre-combustion separation uses technologies that are well established in other industrial sectors, such as fertiliser generation and hydrogen production. However, alternative technologies are being explored to further drive down costs and improve overall energy efficiency. New research has demonstrated how some new methods could reduce the cost of carbon capture by 20-30 per cent whilst also producing hydrogen, which could be used to fuel cars.

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"According to the Stern report, the cost of adapting to climate change will be greater than the cost of mitigating climate change. CCS could be used to achieve 15-55 per cent of cumulative CO_2 mitigation efforts by 2100."

Globally, power generation is the largest single source of CO_2 and accounts for 24 per cent of total greenhouse gas emissions. However, fitting existing power plants with carbon capture technologies inevitably reduces energy efficiency and it is estimated that existing technologies would cost perhaps 20 -60 Euros for every tonne of CO_2 removed.

New research shows that 'demonstration' technologies could reduce the cost of carbon capture by 20-30 per cent[1]. For natural gas fuelled power plants, research is underway in the CACHET[2] project to develop technologies that reduce the cost of CO_2 capture at the same time as producing hydrogen. The authors suggest that the hydrogen, a carbon-free fuel, could then be used as a clean way to power vehicles.

An expensive part of carbon capture is separating the gases. Where air is used as the oxidation source, nitrogen and residual oxygen are mixed with the CO_2, increasing the cost of separation processes and reducing energy efficiency. An alternative approach is to keep the air and the fuel apart using 'unmixed' oxidation processes, in which metal oxides react with the fuel instead of air. The research shows that nickel particles can be used to carry oxygen to the fuel and catalyse this reaction, thus avoiding contact with the air and providing a much cheaper and more energy efficient means of separating the gases.

This form of separating gases can be used in two methods explored by the research: chemical looping combustion (CLC) which allows CO_2 separation with essentially no additional energy cost, and chemical looping reforming (CLR) which allows CO_2 separation and hydrogen production at the same time.

According to the Stern report, the cost of adapting to climate change will be greater than the cost of mitigating climate change. Estimates vary, but CCS could be used to achieve 15-55 per cent of the cumulative CO_2 mitigation efforts by 2100. While post-combustion approaches may allow retrofitting carbon capture technologies to existing power stations to meet early mitigation targets, experimental technologies such as CLC and CLR may prove to be effective approaches for future generations of power stations built with capture from the outset, especially when using clean fuels such as natural gas.

[1] IPCC (2005). Carbon dioxide capture and storage. http://www.ipcc.ch

[2] CACHET is funded by the European Commission's 6th Framework programme. See http://www.cachetco2.eu/

Source: Johansson, M., Mattisson, T., Lyngfelt, A. *et al.* (2008). Using continuous and pulse experiments to compare two promising nickel-based oxygen carriers for use in chemical-looping technologies. *Fuel*. 87 :988-1001

A selection of articles on Carbon Capture and Storage from the *Science for Environment Policy* News Alert

Research to Develop New Policies for Carbon Sequestration Technology (4/10/07)

In a recent study, American scientists analysed the research areas that can support the development of regulatory and legal frameworks to ensure the safe implementation of carbon capture and sequestration. A better understanding of the magnitude and mechanisms of potential leakage as well as the development of monitoring, mitigation and remediation methods are essential for the large scale deployment of this technology.

Carbon Capture and Storage: how is it perceived in Europe? (26/04/07)

Carbon capture and storage is one of the solutions that can be used to decrease concentrations of CO_2 in the atmosphere. An EU-funded survey of about 500 stakeholders in Europe was recently performed in order to find out the current acceptance and perception of such storage technologies. The results show that about three quarters of the respondents think that carbon capture and storage is definitely or probably necessary to achieve deep reductions in CO_2.

Prospective Scenarios for Renewable Energies and Carbon Capture and Storage (29/03/07)

A German team of scientists has recently compared the structural, economic and environmental aspects of carbon capture and storage (CCS) with renewable energy technologies. Even if CCS technologies emit more carbon dioxide than generally assumed and considerably more than renewables, CCS could lead to a significant absolute reduction of greenhouse gas emissions within the electricity supply system. However, depending on market forces, renewables could develop faster and become cheaper.

Deep-Sea Sediments - an Innovative Solution for Storing CO_2 Safely (05/10/06)

American scientists have recently evaluated the feasibility of injecting man-made carbon dioxide into deep-sea sediments. They show that this innovative solution could provide virtually permanent, unlimited and safe storage for this gas, a major driver of global climate change in the last decades.

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