Carbon Capture and Storage

Carbon capture and storage (**CCS**) is an approach to mitigate global warming by capturing carbon dioxide (CO_2) from large point sources such as fossil fuel power plants and storing it instead of releasing it into the atmosphere. Technology for large scale capture of CO_2 is already commercially available and fairly well developed. Although CO_2 has been injected into geological formations for various purposes, the long term storage of CO_2 is a relatively untried concept and as yet (2007) no large scale power plant operates with a full carbon capture and storage system.

CCS applied to a modern conventional power plant could reduce CO_2 emissions to the atmosphere by approximately 80-90% compared to a plant without CCS[1]. Capturing and compressing CO_2 requires much energy and would increase the fuel needs of a plant with CCS by about 11-40%[1]. These and other system costs are estimated to increase the cost of energy from a new power plant with CCS by 21-91%[1]. These estimates apply to purpose-built plants near a storage location: applying the technology to preexisting plants or plants far from a storage location will be more expensive.

Storage of the CO_2 is envisaged either in deep geological formations, , or in the form of mineral carbonates. In the case of deep ocean storage, there is a risk of greatly increasing the problem of ocean acidification, a problem that also stems from the excess of carbon dioxide already in the atmosphere and oceans. Geological formations are currently considered the most promising sequestration sites, and these are estimated to have a storage capacity of at least 2000 Gt CO_2 (currently, 30 Gt per year of CO_2 is emitted due to human activities[2]). IPCC estimates that the economic potential of CCS could be between 10% and 55% of the total carbon mitigation effort until year 2100 (Section 8.3.3 of IPCC report[1]).

Cost of CCS

Capturing and compressing CO_2 requires much energy, significantly raising the running costs of CCS-equipped power plants. In addition there are added investment or capital costs. The process would increase the energy needs of a plant with CCS by about 10-40%. The costs of storage and other system costs are estimated to increase the costs of energy from a power plant with CCS by 30-60%, depending on the specific circumstances.

Costs of energy with and without CCS (2002 US$ per kWh)

	Natural gas combined cycle	Pulverized coal	Integrated gasification combined cycle
Without capture (reference plant)	0.03 - 0.05	0.04 - 0.05	0.04 - 0.06
With capture and geological storage	0.04 - 0.08	0.06 - 0.10	0.06 - 0.09
With capture and Enhanced oil recovery	0.04 - 0.07	0.05 - 0.08	0.04 - 0.08
All costs refer to costs for energy from newly built, large-scale plants. Natural gas combined cycle costs are			

based on natural gas prices of US$2.80–4.40 per GJ (LHV based). Energy costs for PC and IGCC are based on bituminous coal costs of US$1.00–1.50 per GJ (LHV. Note that the costs are very dependent on fuel prices (which change continuously), in addition to other factors such as capital costs. Also note that for EOR, the savings are greater for higher oil prices. Current gas and oil prices are substantially higher than the figures used here. All figures in the table are from Table 8.3a in [IPCC, 2005][1].

The cost of CCS depends on the cost of capture and storage which vary according to the method used. Geological storage in saline formations or depleted oil or gas fields typically cost US$0.50–8.00 per tonne of CO_2 injected, plus an additional US$0.10–0.30 for monitoring costs. However, when storage is combined with enhanced oil recovery to extract extra oil from an oil field, the storage could yield net benefits of US$10–16 per tonne of CO_2 injected (based on 2003 oil prices). However, as the table above shows, the benefits do not outweigh the extra costs of capture.

Comparisons of CCS with other energy sources can be found in wind energy, solar energy, and Economics of new nuclear power plants.

Environmental effects

The merit of CCS systems is the reduction of CO_2 emissions by up to 90%, depending on plant type. Generally, environmental effects from use of CCS arise during power production, CO_2 capture, transport and storage. Issues relating to storage are discussed in those sections.

Additional energy is required for CO_2 capture, and this means that substantially more fuel has to be used, depending on the plant type. For new supercritical pulverized coal (PC) plants using current technology, the extra energy requirements range from 24-40%, while for natural gas combined cycle (NGCC) plants the range is 11-22% and for coal-based gasification combined cycle (IGCC) systems it is 14-25% [IPCC, 2005]. Obviously, fuel use and environmental problems arising from mining and extraction of coal or gas increase accordingly. Plants equipped with flue gas desulfurization (FGD) systems for SO_2 control require proportionally greater amounts of limestone, and systems equipped with SCR systems for NO_X require proportionally greater amounts of ammonia.

IPCC has provided estimates of air emissions from various CCS plant designs (see table below). While CO_2 is drastically reduced (though never completely captured), emissions of air pollutants increase significantly, generally due to the energy penalty of capture. Hence, the use of CCS entails a reduction in air quality.

Emissions to air from plants with or without CCS (kg/(MW·h))

	Natural gas combined cycle	Pulverized coal	Integrated gasification combined cycle
CO_2	43 (-89%)	107 (−87%)	97 (−88%)
NO_X	0.11 (+22%)	0.77 (+31%)	0.1 (+11%)
SO_X	-	0.001 (−99.7%)	0.33 (+17.9%)
Ammonia	0.002 (before: 0)	0.23 (+2200%)	-

Based on Table 3.5 in [IPCC, 2005]. Between brackets the increase or decrease compared to a similar plant without CCS.

CO_2 capture

Capturing CO_2 can be applied to large point sources, such as large fossil fuel or biomass energy facilities, industries with major CO_2 emissions, natural gas processing, synthetic fuel plants and fossil fuel-based hydrogen production plants. Broadly, three different types of technologies exist: Post-combustion, pre-combustion, and oxyfuel combustion.

- In **post-combustion**, the CO_2 is removed after combustion of the fossil fuel - this is the scheme that would be applied to conventional power plants. Here, carbon dioxide is captured from flue gases at power stations (in the case of coal, this is sometimes known as "clean coal"). The technology is well understood and is currently used in niche markets.
- The technology for **pre-combustion** is widely applied in fertilizer, chemical, gaseous fuel (H_2, CH_4), and power production [3] In these cases, the fossil fuel is partially oxidized, for instance in a gasifier. The resulting syngas (CO and H_2) is shifted into CO_2 and more H_2. The resulting CO_2 can be captured from a relatively pure exhaust stream. The H_2 can now be used as fuel; the carbon is removed before combustion takes place.
- In **oxyfuel combustion** [4] the fuel is burned in oxygen instead of air. To limit the resulting flame temperatures to levels common during conventional combustion, cooled flue gas is recirculated and injected into the combustion chamber. The flue gas consists of mainly carbon dioxide and water vapour, the latter of which is condensed through cooling. The result is an almost pure carbon dioxide stream that can be transported to the sequestration site and stored. Power plant processes based on oxyfuel combustion are sometimes referred to as "zero emission" cycles, because the CO_2 stored is not a fraction removed from the flue gas stream (as in the cases of pre- and post-combustion capture) but the flue gas stream itself. It should be noted, however, that a certain fraction of the CO_2 generated during combustion will inevitably end up in the condensed water. To warrant the label "zero emission" the water would thus have to be treated or disposed of appropriately. The technique is promising, but the initial air separation step demands a lot of energy.

An alternate method, which is under development, is chemical looping combustion (CLC). Chemical looping uses a metal oxide as a solid oxygen carrier. Metal oxide particles react with a solid, liquid or gaseous fuel in a fluidized bed combustor, producing solid metal particles and a mixture of carbon dioxide and water vapor. The water vapor is condensed, leaving pure carbon dioxide which can be sequestered. The solid metal particles are circulated to another fluidized bed where they react with air, producing heat and regenerating metal oxide particles that are recirculated to the fluidized bed combustor.

A few engineering proposals have been made for the much more difficult task of capturing CO_2 directly from the air, but work in this area is speculative and conceptual at this point. Capture costs are estimated to be much higher than from point sources, but may be feasible for dealing with emissions from diffuse sources like automobiles and aircraft [5].

CO_2 transport

After capture, the CO_2 must be transported to suitable storage sites. This is done by pipeline, which is generally the cheapest form of transport. A conveyor belt system or ships can also be used. These methods are currently used for transporting CO_2 for other applications.

CO_2 storage

Various forms have been conceived for permanent storage of CO_2. These forms include gaseous storage in various deep geological formations (including saline formations and exhausted gas fields), liquid storage in the ocean, and solid storage by reaction of CO_2 with metal oxides to produce stable carbonates.

Geological storage

Also known as *geo-sequestration*, this method involves injecting carbon dioxide, generally in supercritical form, directly into underground geological formations. Oil fields, gas fields, saline formations, unminable coal seams, and saline-filled basalt formations have been suggested as storage sites. Here, various physical (e.g., highly impermeable caprock) and geochemical trapping mechanisms would prevent the CO_2 from escaping to the surface. CO_2 is sometimes injected into declining oil fields to increase oil recovery (enhanced oil recovery). This option is attractive because the storage costs are offset by the sale of additional oil that is recovered. Disadvantages of old oil fields are their geographic distribution and their limited capacity.

Unminable coal seams can be used to store CO_2 because CO_2 adsorbs to the surface of coal. However, the technical feasibility depends on the permeability of the coal bed. In the process of absorption the coal releases previously absorbed methane, and the methane can be recovered (Enhanced Coal Bed Methane recovery). The sale of the methane can be used to offset the cost of the CO_2 storage.

Saline formations contain highly mineralized brines, and have so far been considered of no benefit to humans. Saline aquifers have been used for storage of chemical waste in a few cases. The main advantage of saline aquifers is their large potential storage volume and their common occurrence. This will reduce the distances over which CO_2 has to be transported. The major disadvantage of saline aquifers is that relatively little is known about them, compared to oil fields. To keep the cost of storage acceptable the geophysical exploration may be limited, resulting in larger uncertainty about the aquifer structure. Unlike storage in oil fields or coal beds no side product will offset the storage cost. Leakage of CO_2 back into the atmosphere may be a problem in saline aquifer storage. However, current research shows that several *trapping mechanisms* immobilize the CO_2 underground, reducing the risk of leakage.

For well-selected, designed and managed geological storage sites, IPCC estimates that CO_2 could be trapped for millions of years, and the sites are likely to retain over 99% of the injected CO_2 over 1,000 years.

Ocean storage

Another proposed form of carbon storage is in the oceans. Two main concepts exist. The 'dissolution' type injects CO_2 by ship or pipeline into the water column at depths of 1000 m or more, and the CO_2 subsequently dissolves. The 'lake' type deposits CO_2 directly onto the sea floor at depths greater than 3000 m, where CO_2 is denser than water and is expected to form a 'lake' that would delay dissolution of CO_2 into the environment. A third concept is to convert the CO_2 to bicarbonates (using limestone) or hydrates.

The environmental effects of ocean storage are generally negative, but poorly understood. Large concentrations of CO_2 kills ocean organisms, but another problem is that dissolved CO_2 would eventually equilibrate with the atmosphere, so the storage would not be permanent. Also, as part of the CO_2 reacts with the water to form carbonic acid, H_2CO_3, the acidity of the ocean water increases. The resulting environmental effects on benthic life forms of the bathypelagic, abyssopelagic and hadopelagic zones are poorly understood. Even though life appears to be rather sparse in the deep ocean basins, energy and chemical effects in these deep basins could have far reaching implications. Much more work is needed here to define the extent of the potential problems.

The time it takes water in the deeper oceans to circulate to the surface has been estimated to be on the order of 1600 years, varying upon currents and other changing conditions. Costs for deep ocean disposal of liquid CO_2 are estimated at US$40−80/ton[*vague*]. (2002 USD) This figure covers the cost of sequestration at the powerplant and naval transport to the disposal site. [2]

The bicarbonate approach would reduce the pH effects and enhance the retention of CO_2 in the ocean, but this would also increase the costs and other environmental effects.

An additional method of long term ocean based sequestration is to gather crop residue such as corn stalks or excess hay into large weighted bales of biomass and deposit it in the alluvial fan areas of the deep ocean basin. Dropping these residues in alluvial fans would cause the residues to be quickly buried in silt on the sea floor, sequestering the biomass for very long time spans. Alluvial fans exist in all of the world's oceans and seas where river deltas fall off the edge of the continental shelf such as the Mississippi alluvial fan in the gulf of Mexico and the Nile alluvial fan in the Mediterranean Sea.

Mineral storage

"Carbon sequestration by reacting naturally occurring Mg and Ca containing minerals with CO_2 to form carbonates has many unique advantages. Most notably is the fact that carbonates have a lower energy state than CO_2, which is why mineral carbonation is thermodynamically favorable and occurs naturally (e.g., the weathering of rock over geologic time periods). Secondly, the raw materials such as magnesium based minerals are abundant. Finally, the produced carbonates are unarguably stable and thus re-release of CO_2 into the atmosphere is not an issue. However, conventional carbonation pathways are slow under ambient temperatures and pressures. The significant challenge being addressed by this effort is to identify an industrially and environmentally viable carbonation route that will allow mineral sequestration to be implemented with acceptable economics."[6]

In this process, CO_2 is exothermically reacted with abundantly available metal oxides which produces stable carbonates. This process occurs naturally over many years and is responsible for much of the surface limestone. The reaction rate can be made faster, for example by reacting at higher temperatures and/or pressures, or by pre-treatment of the minerals, although this method can require additional energy. The IPCC estimates that a power plant equipped with CCS using mineral storage will need 60-180% more energy than a power plant without CCS. [7]

The following table lists principal metal oxides of Earth's Crust. Theoretically up to 22% of this mineral mass is able to form carbonates.

Earthen Oxide	**Percent of Crust**	**Carbonate**	**Enthalpy change (kJ/mol)**
SiO_2	59.71		
Al_2O_3	15.41		
CaO	4.90	$CaCO_3$	-179
MgO	4.36	$MgCO_3$	-117
Na_2O	3.55	Na_2CO_3	
FeO	3.52	$FeCO_3$	
K_2O	2.80	K_2CO_3	
Fe_2O_3	2.63	$FeCO_3$	
	21.76	All Carbonates	

Leakage

A major concern with CCS is whether leakage of stored CO_2 will compromise CCS as a climate change mitigation option. For well-selected, designed and managed geological storage sites, IPCC estimates that CO_2 could be trapped for millions of years, and are likely to retain over 99% of the injected CO_2 over 1000 years. For ocean storage, the retention of CO_2 would depend on the depth; IPCC estimates 30–85% would be retained after 500 years for depths 1000–3000 m. Mineral storage is not regarded as having any risks of leakage. The IPCC recommends that limits be set to the amount of leakage that can take place.

It should also be noted that at the conditions of the deeper oceans, (about 400 bar or 40 MPa, 280 K) water–CO_2(l) mixing is *very* low (where carbonate formation/acidification is the rate limiting step), but the formation of water-CO_2 hydrates is favorable. (a kind of solid water cage that surrounds the CO_2). [3]

To further investigate the safeness of CO_2 sequestration, we can look into Norway's Sleipner gas field, as it is the oldest plant that sequesters CO_2 in an industrial scale. According to an environmental assessment of the gas field which was conducted after ten years of operation, the author affirmed that geosequestration of CO_2 was the most definite way to store CO_2 permanently. [4]

"Available geological information shows absence of major tectonic events after the deposition of the Utsira formation [saline reservoir]. This implies that the geological environment is

tectonically stable and a site suitable for carbon dioxide storage. The solubility trapping [is] the most permanent and secure form of geological storage." [4]

Phase I of the Weyburn Project in Weyburn, Saskatchewan, Canada has determined that the likelihood of stored CO_2 release is less than one percent in 5,000 years.[8]

Example CCS projects

As of 2007, four industrial-scale storage projects are in operation. Sleipner [4] is the oldest project (1996) and is located in the North Sea where Norway's StatoilHydro strips carbon dioxide from natural gas with amine solvents and disposes of this carbon dioxide in a deep saline aquifer. The carbon dioxide is a waste product of the field's natural gas production and the gas contains more (9% CO_2) than is allowed into the natural gas distribution network. Storing it underground avoids this problem and saves Statoil hundreds of millions of euro in avoided carbon taxes. Since 1996, Sleipner has stored about one million tonnes CO_2 a year. A second project in the Snøhvit gas field in the Barents Sea stores 700,000 tonnes per year. [9]

The Weyburn project Weyburn is currently the world's largest carbon capture and storage project.[10] Started in 2000, Weyburn is located on an oil reservoir discovered in 1954 in Weyburn, southeastern Saskatchewan, Canada. The CO_2 for this project is captured at the Great Plains Coal Gasification plant in Beulah, North Dakota which has produced methane from coal for more than 30 years. At Weyburn, the CO_2 will also be used for enhanced oil recovery with an injection rate of about 1.5 million tonnes per year. The first phase finished in 2004, and demonstrated that CO_2 can be stored underground at the site safely and indefinitely. The second phase, expected to last until 2009, is investigating how the technology can be expanded on a larger scale.[11]

The fourth site is In Salah, which like Sleipner and Snøhvit is a natural gas reservoir located in In Salah, Algeria. The CO_2 will be separated from the natural gas and re-injected into the subsurface at a rate of about 1.2 million tonnes per year.

A major Canadian initiative called the Integrated CO_2 Network (ICO2N) is a proposed system for the capture, transport and storage of carbon dioxide (CO_2). ICO2N members represent a group of industry participants providing a framework for carbon capture and storage development in Canada.

In October 2007, the Bureau of Economic Geology at The University of Texas at Austin received a 10-year, $38 million subcontract to conduct the first intensively monitored, long-term project in the United States studying the feasibility of injecting a large volume of CO_2 for underground storage[12]. The project is a research program of the Southeast Regional Carbon Sequestration Partnership (SECARB), funded by the National Energy Technology Laboratory of the U.S. Department of Energy (DOE). The SECARB partnership will demonstrate CO_2 injection rate and storage capacity in the Tuscaloosa-Woodbine geologic system that stretches from Texas to Florida. The region has the potential to store more than 200 billion tons[*vague*] of CO_2 from major point sources in the region, equal to about 33 years of U.S. emissions overall at present rates. Beginning in fall 2007, the project will inject CO_2 at the rate of one million tons[*vague*] per year, for up to 1.5 years, into brine up to 10,000 feet (3,000 m) below the land surface near the

Cranfield oil field about 15 miles (25 km) east of Natchez, Mississippi. Experimental equipment will measure the ability of the subsurface to accept and retain CO_2.

Currently, the United States government has approved the construction of what is touted as the world's first CCS power plant, FutureGen.

Examples of carbon sequestration at an existing US coal plant can be found at utility company Luminant's pilot version at its Big Brown Steam Electric Station in Fairfield, Texas. This system is converting carbon from smokestacks into baking soda. Skyonic plans to circumvent storage problems of liquid CO2 by storing baking soda in mines, landfills, or simply to be sold as industrial or food grade baking soda. GreenFuel Technologies Corp. is piloting and implementing algae based carbon capture, circumventing storage issues by then converting algae into fuel or feed.

Carbon Trap Technologies, L.P., ("CTT") was formed in early 2007 to develop and to market a technology to chemically sequester carbon dioxide emissions from fossil fuel combustion, while producing useful products with significant market value.

In the Netherlands, an 68 MW oxyfuel plant ("Zero Emission Power Plant") is being planned and is expected to be operational in 2009[13].

References

- [IPCC, 2005] *IPCC special report on Carbon Dioxide Capture and Storage*. Prepared by working group III of the Intergovernmental Panel on Climate Change. Metz, B., O.Davidson, H. C. de Coninck, M. Loos, and L.A. Meyer (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp. Available in full at www.ipcc.ch
- *Environmental Challenges and Greenhouse Gas Control for Fossil Fuel Utilization in the 21st Century*. Edited by M. Mercedes Maroto-Valer *et al.*, Kluwer Academic/Plenum Publishers, New York, 2002: "Sequestration of Carbon Dioxide by Ocean Fertilization", pg 122. by M. Markels, Jr. and R.T. Barber.
- Nobel Intent: Carbon Dioxide Lakes in the Deep Ocean, September 19, 2006 @ 11:08AM - posted by John Timmer http://arstechnica.com/journals/science.ars/2006/9/19/5341
- Solomon, Semere. (July, 2006). Carbon Dioxide Storage: Geological Security and Environmental Issues Case Study on the Sleipner Gas Field in Norway. The Bellona Foundation. Retrieved November 7th, 2006, from http://bellona.no/filearchive/fil_Paper_Solomon_-_CO2_Storage.pdf

1. ^ *a b c d e* [IPCC, 2005] *IPCC special report on Carbon Dioxide Capture and Storage*. Prepared by working group III of the . Metz, B., O.Davidson, H. C. de Coninck, M. Loos, and L.A. Meyer (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp. Available in full at www.ipcc.ch
2. ^ Volcanic Gases and Their Effects. Retrieved on 2007-09-07.
3. ^ http://www.netl.doe.gov/publications/brochures/pdfs/Gasification_Brochure.pdf
4. ^ *Winner: Restoring Coal's Sheen*, William Sweet, IEEE Spectrum, January 2008. Available in full at [1]
5. ^ http://wpweb2.tepper.cmu.edu/ceic/theses/Joshuah_Stolaroff_PhD_Thesis_2006.pdf

6. ^ Goldberg, Chen, O'Connor, Walters, Ziock. (1998). "CO_2 Mineral Sequestration Studies in US", National Energy Technology Laboratory. Retrieved June 7th, 2007 from: http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/6c1.pdf
7. ^ [IPCC, 2005] *IPCC special report on Carbon Dioxide Capture and Storage*. ch.7, p.321, p.330, Prepared by working group III of the Intergovernmental Panel on Climate Change. Metz, B., O.Davidson, H. C. de Coninck, M. Loos, and L.A. Meyer (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp. Available in full at www.ipcc.ch
8. ^ Allan Casey, *Carbon Cemetery*, Canadian Geographic Magazine, Jan/Feb 2008, p. 61
9. ^ Allan Casey, *ibid*, p. 63
10. ^ Allan Casey, *ibid*, p. 63
11. ^ Allan Casey, *ibid*, p. 59
12. ^ "Bureau of Economic Geology Receives $38 Million for First Large-Scale U.S. Test Storing Carbon Dioxide Underground" [2]
13. ^ "Demonstration project The Netherlands: Zero Emission Power Plant" [3]
    - ICO2N - The Vision [[5]]

See also

Energy Portal

- Carbon dioxide sink
- Mitigation of global warming
- Low-carbon economy
- Solvay process industrial process used in the production of soda ash (sodium carbonate)

External links

- Intergovernmental Panel on Climate Change IPCC Special Report on Carbon Dioxide Capture and Storage.
- Carbon Sequestration News Recent news articles on CO_2 capture and storage.
- Gulf Coast Carbon Center University of Texas at Austin research center that investigates geologic storage of anthropogenic carbon dioxide in the Gulf Coast region.
- Stanford University Collection of recent news articles on CO_2 capture and storage.
- The Big Sky Carbon Sequestration Partnership The Big Sky Carbon Sequestration Partnership (BSCSP)
- Webcasts, Reports and Articles Relevant Climate Change Action Posts
- DOE Fossil Energy Department of Energy programs in carbon dioxide capture and storage.

- CO_2 Capture and Storage International Energy Agency Greenhouse Gas Research Programme (includes CSS project summaries)
- CO_2 Capture and Geologic Storage National Energy and Technology Laboratory summary of worldwide projects
- [6] ICO2N - Canadian Carbon Dioxide Capture and Storage initiative
- European Union (2006-03-14). "World's largest CO2 capture pilot plant inaugurated in Denmark". Press release. Retrieved on 2007-07-13.
- Scottish Centre for Carbon Storage Current Carbon Capture and Storage Research being undertaken in Edinburgh, Scotland.
- UK Carbon Capture and Storage Consortium Overview of the UK academic consortium focused on researching issues related to Carbon Capture and Storage.
- Storing CO_2 Underground
- Can geosequestration save the coal industry?