Carbon Capture and Storage (CCS) techniques

Research report
January 2007

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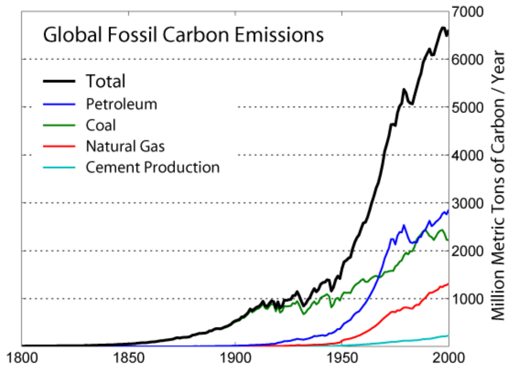
Carbon dioxide – At a glance

Carbon dioxide is a chemical compound composed of one carbon and two oxygen atoms. It is often referred to by its formula CO_2. It is present in the Earth's atmosphere at a low concentration and acts as a greenhouse gas.

The initial carbon dioxide in the atmosphere of the young Earth was produced by volcanic activity; this was essential for a warm and stable climate conducive to life. Nowadays volcanic releases are about 1% of the amount of CO_2, which is released by human activities.



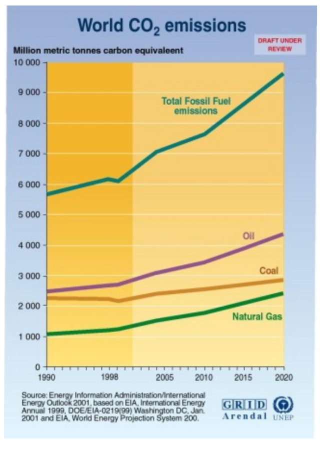
Since the start of the *Industrial Revolution*, the atmospheric CO_2 concentration has increased by approximately 110 μL/L or about 40%, most of it released since 1945. **Burning fossil fuels such as coal and petroleum is the leading cause of increased man-made CO_2; deforestation is the second major cause**. Around 24,000 million tons of CO_2 are released per year worldwide, equivalent to about 6,500 million tons of carbon.

Various techniques have been proposed for removing excess carbon dioxide from the atmosphere in carbon dioxide sinks. A carbon dioxide sink is a carbon reservoir that is increasing in size, and is the opposite of a carbon "source". This concept of CO_2 sinks has become more widely known because the Kyoto Protocol allows the use of carbon dioxide sinks as a form of carbon offset. Carbon sequestration is the term describing processes that remove carbon from the atmosphere. To help mitigate global warming, a variety of means of artificially capturing and storing carbon – as well as of enhancing natural sequestration processes – are being explored.

The **Global Warming Theory** (GWT) **predicts that increased amounts of CO_2 in the atmosphere tend to enhance the greenhouse effect and thus contribute to global warming**. The effect of combustion-produced carbon dioxide on climate is called the *Callendar effect*.

How does CCS work?

Carbon capture and storage (sometimes referred to as *carbon capture and sequestration*; abbreviated CCS) **is an approach to mitigating climate change by capturing carbon dioxide** (CO_2) **from large point sources such as power plants and subsequently storing it away safely instead of releasing it into the atmosphere**. Technology for capturing of CO_2 is already commercially available for large CO_2 emitters, such as power plants. Storage of CO_2, on the other hand, is a relatively untried concept and as yet no power plant operates with a full carbon capture and storage system.



Approximately **one third of all CO_2 emissions due to human activity come from fossil fuels used for generating electricity**, with each power plant capable of emitting several million tons of CO_2 annually. A variety of other industrial processes also emit large amounts of CO_2 from each plant, for example oil refineries, cement works, and iron and steel production. These emissions could be reduced substantially, without major changes to the basic process, by capturing and storing the CO_2. Other sources of emissions, such as transport (accounting for approx. 24% of CO_2 emissions) and domestic buildings, cannot be tackled in the same way because of the large number of small sources of CO_2.

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. Capturing and compressing CO_2 requires much energy and would increase the fuel needs of a plant with CCS by about 10-40%.

These and other system costs are estimated to increase the cost of energy from a power plant with CCS by 30-60% depending on the specific circumstances.

Storage of the CO_2 is envisaged either in deep geological formations, deep oceans, or in the form of mineral carbonates. Geological formations are currently considered the most promising, and these are estimated to have a storage capacity of at least 2000 Gt CO_2. The IPCC (Intergovernmental Panel on Climate Change) estimates that the economic potential of CCS could be between 10% and 55% of the total carbon mitigation effort until year 2100.

Cost of technology

Capturing and compressing CO_2 requires much energy, significantly raising the costs of operation, apart from the added investment costs. **It would increase the energy needs of a plant with CCS by about 10-40%.** This, 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)	0,031 - 0,050	0,043 - 0,052	0,041 - 0,061
With capture and geological storage	0,043 - 0,077	0,063 - 0,99	0,055 - 0,091
With capture and enhanced oil recovery	0,037 - 0,070	0,049 - 0,081	0,040 - 0,075

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 2.8 – 4,4 US$ per GJ (LHV based). Energy costs for PC and IGCC are based on bituminous coal costs of 1,0 – 1,5 US$ per GJ (LHV. Note that the costs are very dependent on fuel prices (which have changed since), 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]

The costs of CCS are dominated by costs of capture. According to a study by Fraunhofer Institut of March 2005, the use of **CCS would double electricity production costs** of fossil fuel power plants, **adding costs of 0,015 – 0,025 € per kWh**. Furthermore, the study concludes that the costs of CO_2 capture would be around 20 – 50 € per tonne.

The storage is relatively cheap, geological storage in saline formations or depleted oil or gas fields typically cost 0,5 – 8 US$ per tonne of CO_2 injected, plus an additional 0,1 – 0,3 US$ 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 10 – 16 US$ 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.

Environmental impacts of CCS

The major merit of CCS systems is the reduction of CO_2 emissions, which is typically on the order of 90%, depending on plant type.

The substantial extra amounts of energy required for CO_2 capture means that more fuel has to be used, how much depends on the plant type. For new supercritical pulverized coal 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%, according to IPCC. Obviously, fuel use and environmental problems arising from mining and extraction of coal or gas increase accordingly.

IPCC has provided estimates of air emissions from various CCS plant designs (see table hereunder). 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 some sacrifice of air quality.

Emissions to air from plants with or without CCS (kg/MWh)	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, major CO_2 emitting industries, natural gas production, synthetic fuel plants and fossil fuel-based hydrogen production plants. Broadly, three different types of technologies exist:

- 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. In these cases, the fossil fuel is gasified and the resulting CO_2 can be captured from a relatively pure exhaust stream.

- An alternate method, which is under development, is the chemical looping combustion (also called “**oxyfuel combustion**” or simply “oxy-combustion”). 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.

CO_2 transport

After capture, the CO_2 must be transported to suitable storage sites. Those storage sites are not necessarily located in the same area as the CO_2 emitting plants. Hence, transportation remains issue and pipelines, which are generally the cheapest form of transport, or ships (when no pipelines are available) are required for CO_2 transportation. Note that both methods are currently used for transporting CO_2 for other applications.

In order for CO_2 transportation to be economically viable, especially for the huge volumes produced by emitting plants, CO_2 would need to be compressed and liquefied. According to the Fraunhofer Institute, the liquefaction of CO_2 from atmospheric pressure to 110 bar would require 0,12 kWh per tonne of CO_2.

CO_2 storage

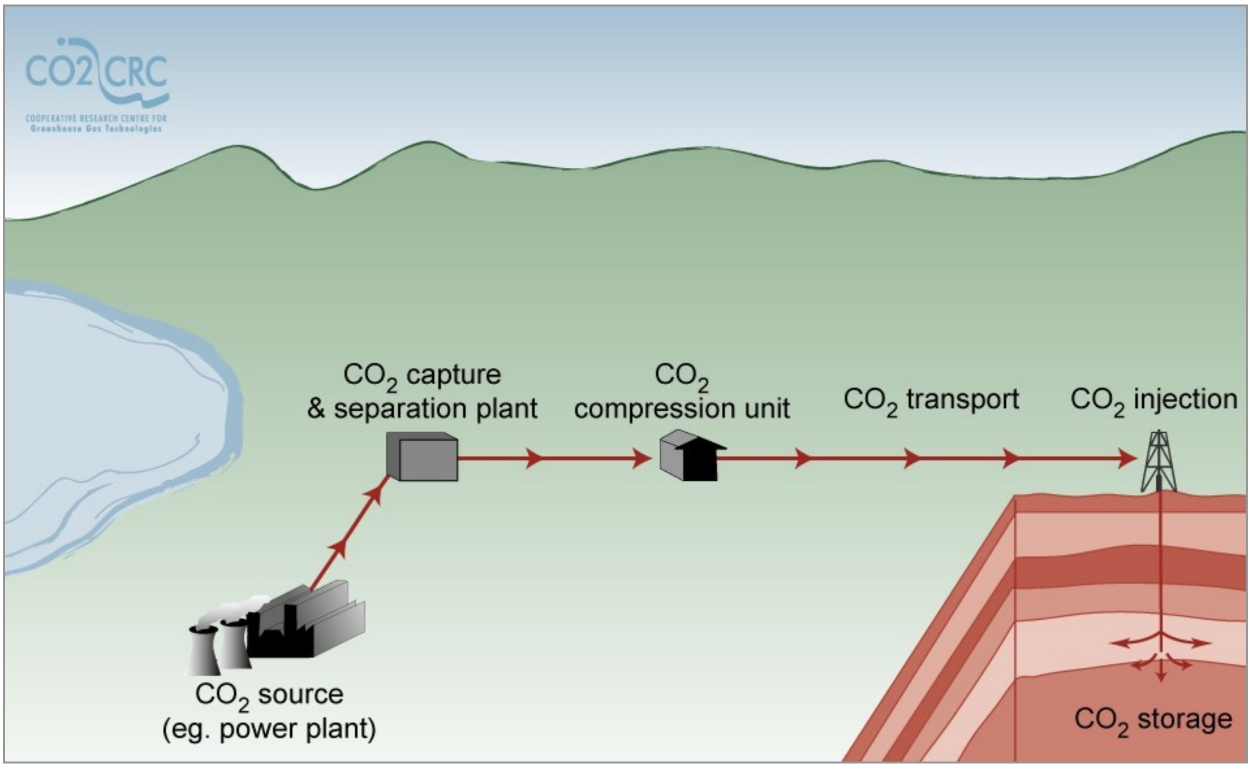
Various forms of more or less permanent storage of CO_2 isolated from the atmosphere have been conceived. These are storage in various deep geological formations (including saline formations and exhausted gas fields), ocean storage, and reaction of CO_2 with metal oxides to produce stable carbonates.

As of 2005, it is estimated that saline formations would offer storage capacities for approx. 50-100 years. However, tectonic movements may have significant impacts on the usability and durability of those storage sites. Also, the geographical location of some saline formations may make transportation of CO_2 difficult – or even impossible.

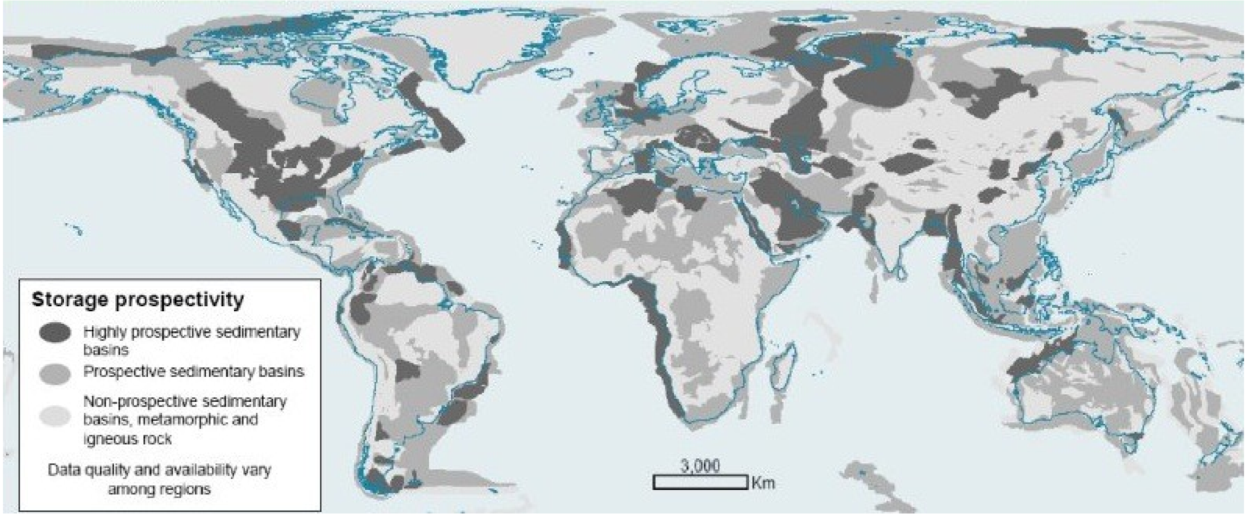
I. Geological storage

Also known as *geo-sequestration*, **this method involves injecting carbon dioxide directly into underground geological formations** (usually in depths of approx. 1,000–2,500 meters). Oil fields, gas fields, saline formations, and unminable coal seams have been suggested as storage sites. Here, various physical (e.g., highly impermeable cap rock) 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. 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 coal surface, but the technical feasibility depends on the permeability of the coal bed. In the process it releases methane, that was previously adsorbed to the coal surface, and that may be recovered. Again 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 oilfields. 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.



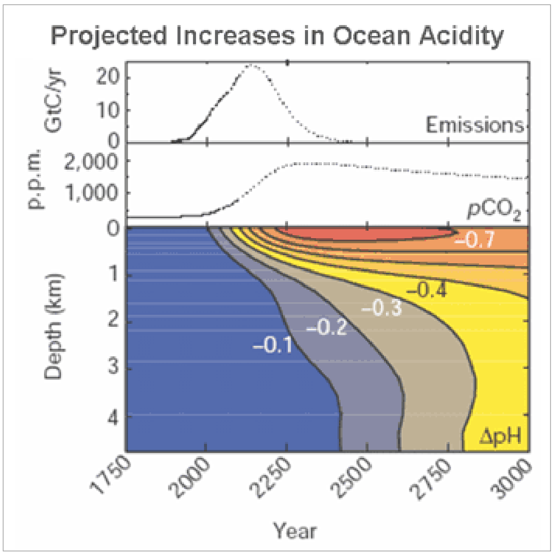
For well-selected, designed and managed geological storage sites, IPCC estimates that CO_2 could be trapped for millions of years, and the sites are likely to retain over 99% of the injected CO_2 over 1,000 years.

II. Ocean storage

Another proposed form of carbon storage is in the oceans. The following two main concepts exist:

- The **dissolution** type injects CO_2 by ship or pipeline into the water column at depths of 1,000 meters or more, and the CO_2 subsequently dissolves.

- The **lake** type deposits CO_2 directly onto the sea floor at depths greater than 3,000 meters, 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. Large concentrations of CO_2 kill 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.

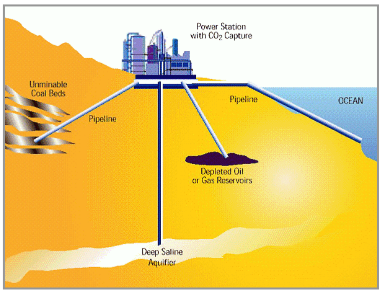
The time it takes water in the deeper oceans to circulate to the surface has been estimated to be on the order of 1,600 years, varying upon currents and other changing conditions. Costs for deep ocean disposal of liquid CO_2 are estimated at $40-80 per ton. This figure covers the cost of sequestration at the power plant and naval transport to the disposal site.

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 impacts.

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.

III. Mineral storage

Mineral storage aims to trap carbon in stable minerals, and CO_2 would be forever trapped. In this process, CO_2 is reacted with (abundantly available) metal oxides, which produces stable carbonates. This process occurs naturally and is responsible for much of the surface limestone. However, the natural reaction is very slow and has to be enhanced by pre-treatment of the minerals, which is very energy intensive. 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.



Current issues of CCS technology

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 1,000 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 1,000-3,000 meters.
- Mineral storage is not regarded as having any risks of leakage.

The IPCC recommends that limits be set to the amount of leakage than can take place.

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 conducted after 10 years of its operation, the author affirmed that geographic sequestration of CO_2 was the most definite way to store CO_2 permanently.

According to a case study published by The Bellona Foundation, *"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."*

Examples of industrial-scale CCS projects

Norway, Sleipner

Sleipner is the oldest project (on stream since the autumn of 1996) and is located in the North Sea where Norway's Statoil strips carbon dioxide from natural gas with amine solvents and disposes of this carbon dioxide in a saline formation. Sleipner stores about one million tons CO_2 a year. Every day 2800 tons of CO_2 are removed from the natural gas produced from Sleipner West. The carbon dioxide is re-injected and stored in the sandstone formation Utsira, instead of being emitted into the atmosphere.

Canada, Weyburn

The ***Weyburn*** project started in 2000 and is located in 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 tons per year.

Algeria, In Salah

The third site is ***In Salah***, which like *Sleipner* is a natural gas reservoir located in *In Salah*, Algeria. Statoil and BP work with Sonatrach, Algeria's state-owned oil and gas company, on the gas and condensate field, which came on stream in 2004. The CO_2 will be separated from the natural gas and re-injected into the subsurface at a rate of about 1.2 million tons per year.

United States, FutureGen

In 2003, United States government has approved the construction of world's first CCS power plant, ***FutureGen***, while BP has indicated that it intends to develop a 350 MW carbon capture and storage plant in Scotland, in which the carbon from natural gas will be stripped out and pumped into the Miller field in the North Sea.

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