The problems of carbon dioxide capture and storage

Unwanted Abundance

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Today, human activity is significantly altering the climate system by increasing the concentration of greenhouse gases in the atmosphere. The largest contributor amongst the gases inducing an enhanced greenhouse effect is carbon dioxide (CO_2). This gas is emitted into the terrestrial atmosphere by the burning of fossil fuels such as coal, oil and natural gas, as well as by the burning of forests during land clearance, and by certain industrial and resource extraction processes.

With the continuance of observed past and recent trends of energy use and carbon emissions, the world is clearly not on a path towards reducing global greenhouse gas emissions below current levels, and certainly not towards greenhouse gas stabilization. Between 1995 and 2001, the average global CO_2 emissions grew at a rate of 1.3% per year, which is faster than the growth rate in the use of primary energy, and higher than the growth rate in emissions in the 5 prior years. Electric power generation remains the single largest source of CO_2 emissions, larger than the total amount of emissions from the industrial sector, while transportation is the fastest-growing emissions sector. In most scenarios that do not assume climate change mitigation action, future global emissions are expected to be significantly higher than today's level unless drastic action is taken.

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Sources of carbon dioxide

CO_2 emissions arise from a number of different sources, but predominantly from the combustion of fossil fuels in the power generation, industrial, residential and transportation sectors. In the former two sector types, emissions are typically generated in large plants or industrial facilities, usually with large emission volumes. This makes them amenable to CO_2 capture technologies. Other sectors, such as those of transportation and buildings, also produce significant amounts of CO_2. Here, however, the individual sources tend to be small and often mobile,

Pre-combustion CO_2 capture at a coal gasification plant in North Dakota, USA. The plant separates 3.3 million tons of CO_2 per year

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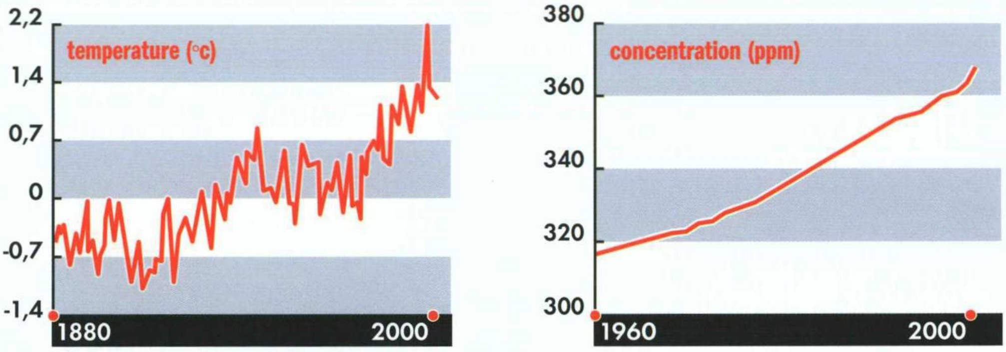


Global mean temperature change and CO_2 carbon dioxide concentration at the South Pole (parts per million)

so that these sectors are much less suitable for capture. If, on the other hand, electricity or hydrogen were used as a transportation fuel, carbon capture and storage (CCS) could be applied to the energy sources of these energy carriers.

How to capture CO_2

The purpose of CO_2 capture is to produce a concentrated stream of CO_2 in a dense supercritical state that can readily be transported to a CO_2 storage site. Today, CO_2 is separated at some large industrial plants, among them natural gas processing and ammonia production facilities. These plants, however, remove CO_2 to meet process demands and are not designed for storage purposes. An exception is the Sleipner gas field in the North Sea where some 20,000 tons per week of carbon dioxide are captured and then injected into a sandstone layer, rather than vented to the atmosphere.

Generally, there are three main approaches to CO_2 capture:

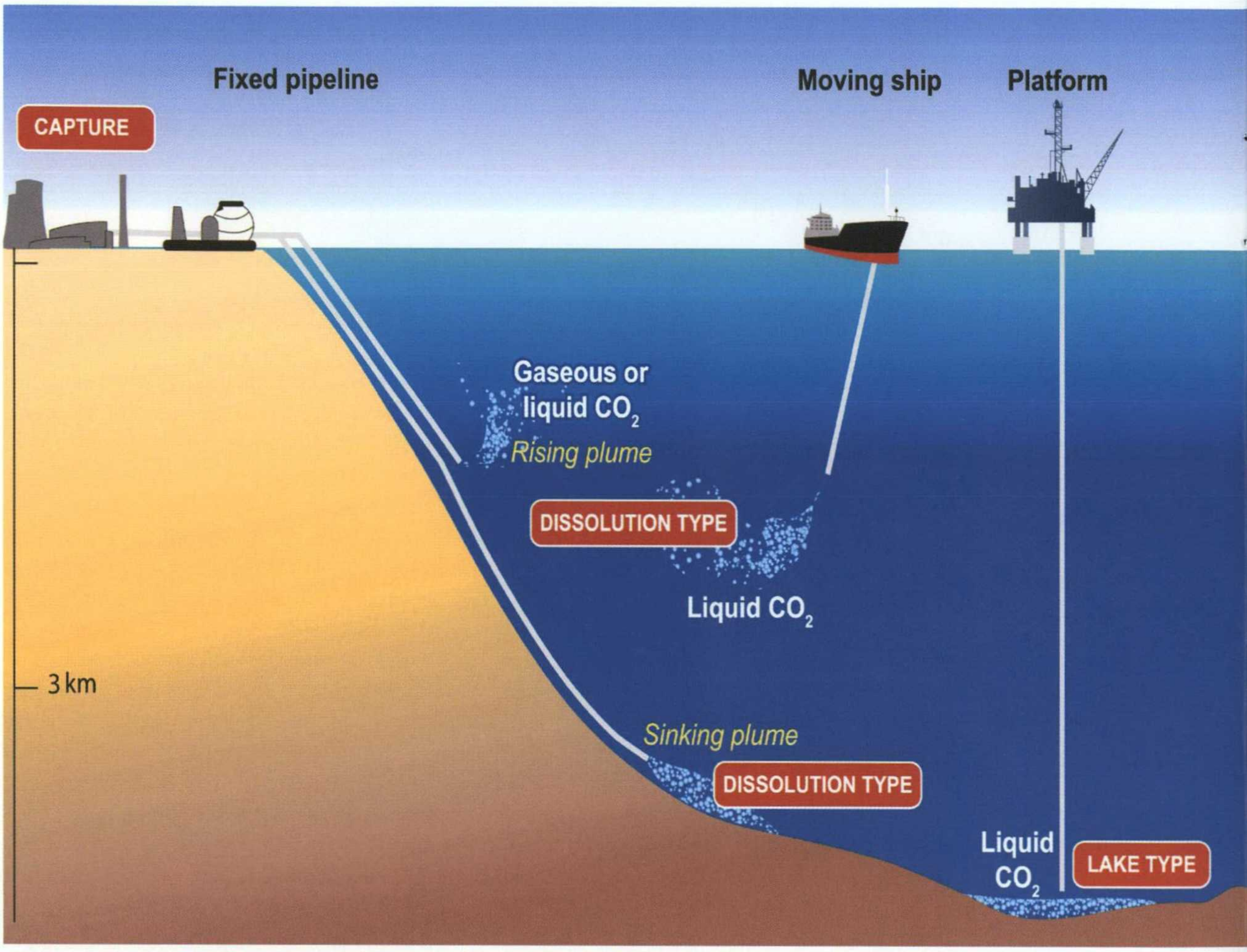
- *Post-combustion* systems, which separate CO_2 from the flue gases produced by the combustion in air of a primary fossil fuel (coal, natural gas or oil) or biomass fuel.
- *Pre-combustion* systems, which process the primary fuel in a reactor in the presence of steam or oxygen to produce separate streams of CO and then CO_2 for storage, and hydrogen that is used as an energy carrier.
- *Oxyfuel combustion* systems, which use oxygen instead of air for combustion to produce a flue gas that is mainly water and CO_2, which is subsequently removed for storage.

There are several commercially available technologies which in principle can be used for CO_2 capture from flue gases. However, comparative assessment studies have shown that absorption processes based on chemical solvents are currently the preferred option for post-combustion CO_2 capture. At this point in time, they offer high capture efficiency and selectivity, the lowest energy use and lowest cost per ton of CO_2 avoided when compared with the other post-combustion capture processes.

A pre-combustion capture process typically comprises a first stage of reaction producing a mixture of hydrogen and carbon monoxide (commonly termed *syngas*) from a primary fuel. The two main routes are to add steam, in which case the process is called *steam reforming*, or oxygen to the primary fuel. In the latter case, the process is often called *partial oxidation* when applied to gaseous and liquid fuels and *gasification* when applied to a solid fuel, but the principles are the same. The two reactions are followed by the shift reaction to convert CO to CO_2 by the addition of steam.

It is possible to envisage two applications of pre-combustion capture. The first is in producing a fuel (hydrogen) that is essentially carbon free. Secondly, pre-combustion capture can be used to reduce the carbon content of fuels, with the excess CO_2 being made available for storage. It has to be pointed out that producing hydrogen from fossil fuels with carbon capture and storage is less costly than doing so using nuclear or renewable energy.

The oxyfuel combustion process eliminates nitrogen from the flue gas by combusting a hydrocarbon or carbonaceous fuel in either pure oxygen or a mixture of pure oxygen and a CO_2-rich recycled flue gas. The flame temperature is fixed by the proportion of the recycled flue gas. It could vary from about 1,300°C with a large recycle flow to



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Various methods for the ocean storage of CO_2, nowadays a controversial proposal

over 3,500°C with no recycle and pure oxygen used for combustion. Oxyfuel combustion, in contrast to the two former options (pre-combustion and post-combustion capture systems) is still in the demonstration phase. It has been performed on a pilot scale and uses high-purity oxygen instead of air. This results in high CO_2 concentrations (in excess of 80 vol. %) but, simultaneously, in increased energy requirements associated with the production of pure oxygen.

Transportation options

CO_2 can be transported via pipelines, by tank wagons and by ships. In practice, because of the huge volumes involved, only pipelines and ships are cost-effective options. Costs depend strongly on the quantities and, to a lesser extent, on the distances involved. Generally, transportation costs are considered to be small compared to the overall capture costs. Transportation cost estimates range from 1 to 10 USD/t CO_2, provided the pipeline transports more than 1 Mt of CO_2 per year and the distance is less than 500 kilometers. Per unit of weight the costs of CO_2 transportation are much lower than for natural gas or hydrogen because CO_2 is in a liquid or supercritical state, with a density 10 to 100 times higher. Therefore, per unit of weight, CO_2 transportation is more akin to oil transportation in terms of cost than to natural gas or hydrogen. Carbon dioxide is already transported in high pressure pipelines - more than 2,000 km of long-distance CO_2 pipelines are in use today.

Storage of carbon dioxide

Long-term storage of carbon dioxide underground is a widespread geological phenomenon, with natural accumulations of CO_2 remaining trapped underground for millions of years. This suggests that injecting CO_2 into deep geological formations may similarly result in its storage for millions of years, provided that the sites are carefully selected and that human activity underground or other external factors do not disturb the reservoir's stability. At depths below 800 to 1,000 m, supercritical CO_2 has a liquid-like density that provides the potential for efficient utilization of underground storage space in the pores of sedimentary rocks. Oil and gas reservoirs (potentially depleted), possibly coal formations and particularly saline formations (deep porous reservoir rocks filled with brackish water or brine) can be used for the storage of CO_2.

CO_2 injected into suitable, depleted oil reservoirs can typically enhance oil recovery by 10-15% of the original oil in place in the reservoir. This is an established technique, called CO_2-EOR (enhanced oil recovery). The additional oil production could, in certain circumstances, more than offset the cost of CO_2 capture and injection. CO_2-EOR could also replace other energy-intensive enhanced oil production techniques, resulting in further greenhouse gas emission benefits.

There are also many underground water-filled strata (aquifers) that could potentially be used to store CO_2. The aquifers that would be used for CO_2 storage are deep underground, containing saline water unsuitable for extraction as potable water. CO_2 would partially dissolve in the water in the aquifer. In some formations, CO_2 would slowly react with minerals to form carbonates, which would essentially lock up the CO_2 permanently. Suitable aquifers would have a cap rock of low permeability to minimize CO_2 leakage. Injection of CO_2 into deep saline reservoirs would use techniques similar to those for depleted oil and gas fields and many of the aspects described above will also apply to aquifer storage.

Another potential storage medium is unmineable coal. Carbon dioxide can be injected into suitable coal beds where it will be adsorbed onto the coal, locking it up permanently, provided the coal is never mined. Moreover, it preferentially displaces methane that exists along with the coal. Methane is already extracted from coal beds by depressurisation but this typically recovers only about 50% of the gas in place. Injection of CO_2 enables more methane to be extracted, while at the same time sequestering CO_2. Coal can adsorb about twice as much CO_2 by volume as methane, so even if the recovered methane is burned and the resulting CO_2 is reinjected, the coal bed can still provide net storage of CO_2.

Ocean injection of carbon dioxide is controversial. Advocates of storage in the deep ocean point out that atmospheric CO_2 passes continuously into the ocean surface, as the air and ocean system seeks chemical equilibrium. Slowing the increase of CO_2 levels in the air will reduce the amount dissolving into the surface water. Thus, deep-ocean injection would shift some CO_2 from the surface waters to the lowest layers, reducing environmental impacts near the surface, where most marine life is found. Opponents of ocean storage cite international law that protects the oceans from certain kinds of industrial uses and the difficulties in monitoring carbon dioxide transport after injection. In many parts of the world opponents tap into a strong cultural preference for leaving the oceans alone.

Closing remarks

When William Shakespeare took a breath, 280 molecules out of every million entering his lungs were carbon dioxide. Each time we draw breath today, 380 molecules per million are carbon dioxide. That proportion climbs about two molecules every year. Nothing, however, says that CO_2 must be emitted into the air. The atmosphere has been our prime waste repository, because discharging exhaust up through smokestacks, tailpipes and chimneys is the simplest and least costly thing to do. The good news is that the technology for capture and storage already exists and that the obstacles hindering implementation seem to be surmountable. ■

Further reading:

Metz B. et al. (Eds) (2005). *Carbon Dioxide Capture and Storage.* Cambridge: Cambridge University Press.

Thomas D.C., Benson S.M. (Eds) (2005). *Carbon Dioxide Capture for Storage in Deep Geological Formations.* Oxford: Elsevier.

Pacala S., Socolow R. (2004). Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. *Science 305*: 968-972.

International Energy Agency (2004). *Prospects for CO_2 Capture and Storage.* Paris: OECD/IEA.

IEA Greenhouse Gas R&D Programme: *www.ieagreen.org.uk*