10 Carbon sequestration

If there are no alternative routes to making the metals, and if we continue to expand production, could we reduce total emissions not by saving energy, but by separating CO_2 from other gases emitted in production, capturing it and burying it underground?

We had an argument about writing this chapter: "We have to have more pictures"; "I don't like the colours"; "This is too political"; "That joke about the Belgian, the strawberry and the treacle is totally inappropriate"… and so on. But we've had a lot of arguments now, and all that stuff from the relationship councillors about airing our different opinions and respecting each other just seems like too much effort—so we're going to bury our resentments, and carry on with gritted teeth.

Welcome to the world of carbon sequestration (also known as storage): we've got an environmental problem? Don't worry—let's bury it. Nuclear waste? Hole in the ground. Red mud? Open lakes out of sight. Toxic chemicals? Down the drain. We have a long history of literally burying our problems, so if we're worried about carbon emissions, why not just trap the CO_2 and push it underground?

Which rather sounds as if we're avoiding facing up to the real problem, and by hiding CO_2 underground it looks as if we're creating a short delay and leaving an even worse problem behind for our children. But to some extent, we have no choice but to consider burying at least part of the problem. Behind all discussion on carbon sequestration is the big black hand of coal. Globally we're currently using more and more coal for electricity generation, and 75 % of the world's coal reserves are held by just five countries: the United States, Russia, China, India and Australia[1]. To date, Russia, China and India have steadily increased their use of coal to drive their economic development, and there is not yet sufficient political will in the USA or Australia to inhibit further coal development. Coal gives more CO_2 emissions for each unit of energy produced than any other form of electricity generation[2]. (The UK's emissions reductions in the 1990's which allowed Prime Minister Tony Blair to be first to sign the Kyoto Protocol occurred mainly because of a switch from coal to gas fired electricity generation.) If we're inevitably going to increase coal combustion, the only way we can reduce associated emissions is if we capture the CO_2 and bury it.

What does that have to do with materials production? Well, if we can't avoid emitting CO_2 when producing materials, and we've seen that that's the case for primary production of both steel and aluminium, maybe we can join the bandwagon of the 'clean coal' movement, and having separated the CO_2 using one of the novel processes in the previous chapter, we could also compress, transport and store it.

Carbon Capture and Storage (CCS) technologies are at a very early stage of development, and certainly we would be taking a grave risk if we bank all our hopes for emissions reductions on this unproven approach. Therefore in this chapter we aim to review current thinking on the second part of CCS: what are the main options for storage? what are the risks? what are the costs? If we can make a balanced assessment of those questions, we'll be in a better position to evaluate our options for reducing emissions from future materials production.

Where can CO_2 be stored?

The world's natural carbon cycle involves continuous exchange of carbon between four major 'pools': the atmosphere, oceans, plants and soils. These flows are large, much larger than the additional emissions arising from fossil fuel combustion, but essentially balanced. For example, each year plants absorb around 120 billion tonnes of carbon from the atmosphere through photosynthesis, release about 60 billion tonnes through respiration, and store about 60 billion tonnes as biomass in soils. In turn, soils release about 60 billion tonnes of carbon to the atmosphere through respiration. In parallel, the oceans exchange about 90 billion tonnes of carbon with the atmosphere each year. These two cycles are essentially balanced so, as George Bush said, "what's the problem? Emissions from fossil fuels are tiny compared to nature's emissions." Well, that's right, but emissions from fossil fuel combustion are not balanced by an equivalent withdrawal from the atmosphere. So, when we talk here about storage, we're specifically thinking about storing additional carbon beyond what's always happened within the Earth's natural cycles. Incidentally, in case George is reading, we should also flag another common confusion: this paragraph has described tonnes of carbon, where the rest of the book considers carbon dioxide, or CO_2. Which is heavier —a tonne of carbon or a tonne of CO_2? Of course they're the same weight (well done George), but a tonne of CO_2 contains only 270 kg of carbon, because an oxygen atom is a third heavier than a carbon atom. So to convert carbon emissions into CO_2 emissions, we need to multiply by 11/3, or about 3.7.

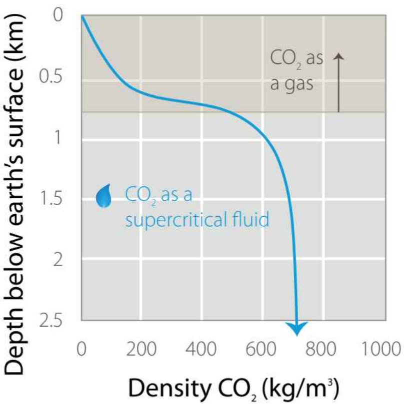


Figure 10.1—**Behaviour of CO_2 at increasing depth and pressure**

What else can we do to store emissions from industrial processes? Some options depend on photosynthesis to extract carbon from the atmosphere, but we'll ignore these general approaches as our focus is specifically on burying emissions captured at materials processing factories. Other options involve burying the gas below the earth's surface, and the graph illustrates the benefit of this: as you descend below the earth's surface, either in the ocean, or under the 'water table', the surrounding pressure increases. This compresses the CO_2 gas and eventually its becomes a liquid with a volume 370 times less than the gas at atmospheric pressure.

There are three main storage options: we can pump CO_2 under ground into current or past oil and gas reservoirs, into coal seams or into other porous rocks; we can dissolve CO_2 in the ocean or store it as a 'lake' at great depths; we can convert CO_2 gas into a solid through mineral carbonation, consume it in industrial processes or use it to grow algae for bio-fuel.

Oil and gas have been stored under the earth's surface for millennia, so presumably we can replace them with stored CO_2. This could either happen during extraction (it may be easier to extract the oil if we 'push it out' with an injection of CO_2 called 'enhanced oil recovery'), or it could occur after a field has been exhausted. In effect we could run the extraction process backwards, and push CO_2 back in. Both approaches have been tried in practice, see the box story on the following page for more details. Oil and gas fields are potentially attractive storage sites because their geology is already well studied, they are below sealing layers of impermeable rock, and some of the required infrastructure (wells, pipelines) is in place. However, a lot more development would be required to switch from oil extraction to carbon storage[3].

The coal industry is particularly interested in injecting CO_2 into deep coal seams, especially those that can't be mined profitably. As the CO_2 is absorbed into the coal, methane (natural gas) is emitted. If we then collected this gas we could burn it to offset some of the cost of CO_2 injection, although doing so would release CO_2 and hence reduce the net amount stored[4]. Obviously if the seam were subsequently mined, and the coal burnt, the exercise would be pointless.

CO_2 could equally be pumped into any porous rock covered by an impermeable layer, as illustrated in Figure 10.2. Abandoned mines, salt caverns, basalt layers and shale formations have all been tested but found unsuitable for large scale storage. The most promising locations appear to be salty lakes (saline aquifers) deep within porous rock formations where the CO_2 would be physically trapped by the rock and would over time dissolve into the water. Several estimates suggest that we have sufficient capacity worldwide to store the CO_2 emitted during several centuries of human activity[4]. However in contrast with fossil fuel geologies, the relevant rock layers are less well mapped and understood, and we do not know how the carbon dioxide would react with the surrounding minerals and microbes.

Sea water absorbs CO_2, and the deep layers of oceans are the earth's largest natural pool (or 'sink') of carbon storage. We could pump CO_2 deep into the oceans (a thousand metres or more below the surface), and release it to bubble up through the ocean and be absorbed into the water. The gas could be released using existing oil transport systems, for example from fixed pipelines with diffuser valves or from pipes trailing behind huge tankers. We do not know how this form of storage would affect marine life over a few hundred years, the oceans would release the stored carbon and eventually reach an equilibrium with the atmosphere. Trials of this type of storage have been attempted off Norway and Hawaii but were halted due to local opposition.

CO_2 storage test sites

There are three sites worldwide where storage of CO_2 has been tested at scale (i.e. more than 1 million tonnes per year for at least five years). Each project is expected to store 20 Mt CO_2 in total:

- At the Sleipner West field in the Norwegian North Sea, CO_2 separated from gas has been injected into a saline formation (lying above the gas layer) since 1996.
- At the Weyburn oil field in Canada, CO_2 is injected to increase oil production and then stored. The CO_2 comes from the gasification of coal across the border in North Dakota and is transported via a 320km pipeline. Similar schemes are operating at a smaller scale in Texas.
- At the In Salah gas field in Algeria, CO_2 separated from the gas is re-injected back into the field, albeit into a saline formation adjacent to the gas reservoir.

These examples suggest that for fixed-location sources like steel and aluminium plants, storage is feasible. However we would require 2,800 such facilities to store our current carbon emissions from steel and aluminium (2.8Gt per year divided by a facility capacity of 1 Mt/year). Even if compressed to 800 kg/m^3 —the highest density at which CO_2 is injected —this would require 3.5 billion m^3 of storage, equal to three quarters of the volume of crude oil we currently extract each year. And this is only the emissions for steel and aluminium, which are only 10 % of the total emissions from energy and processes…

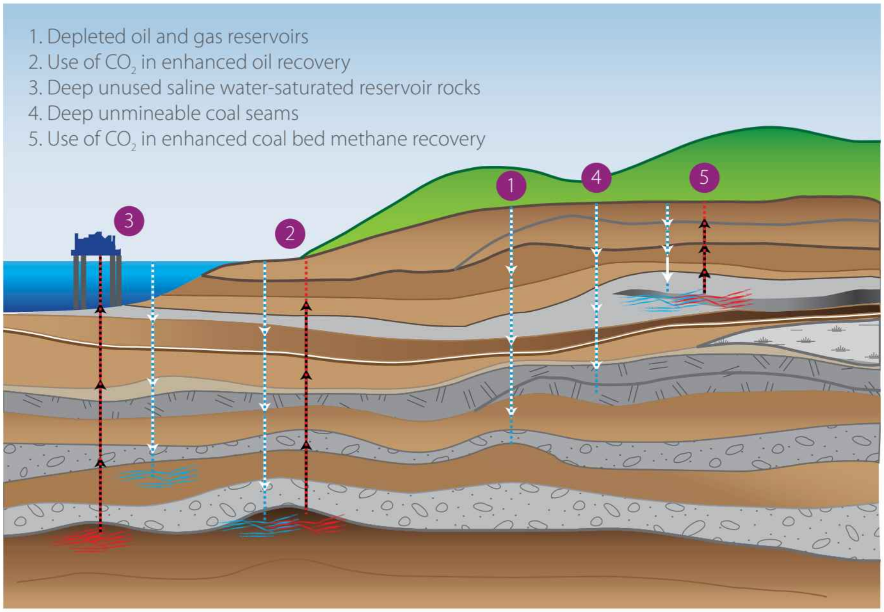


Figure 10.2—**Ground storage options for CCS**[11]

At higher pressures, liquid CO_2 has a greater density than sea water, so below about 3,000 metres will form a liquid lake that sinks. CO_2 stored in this way would dissolve into the water slowly so might remain in storage for 10,000 years as the oceans are more stable at these depths. This approach hasn't yet been tested, and if deep sea currents stir up the CO_2 lake, the storage time could be cut to as few as 30 years[3].

Many of the earth's surface rocks are silicates (compounds of silicon and oxygen atoms) containing metal oxides, which over a very long time react with carbon dioxide to form limestone or other carbonates (compounds which include a carbon atom bonded to three oxygen atoms). This process can be accelerated dramatically at raised temperature or pressure, so could be used as a means to store CO_2 as a solid material. The attraction of mineral carbonation is that the resulting solid is indefinitely stable, so the CO_2 will not be re-released. However it is energy intensive, to the point that it might consume virtually all the energy generated by a power station, and the weight of silicate required is 2–4 times greater than the weight of CO_2 stored. In order to sequester all 28 Gt of our current yearly emissions we would have to mine 84 Gt of silicates per year, equivalent to about seven times our current extraction of fossil fuels[5]. The process also uses intense intermediate chemicals such as hydrochloric acids so it isn't yet a clear environmental winner. A demonstrator project has been initiated in New South Wales to combine carbon dioxide with the serpentinite rock abundant in the area. This would store the CO_2 as magnesium carbonate which could be used as a building material. However, significant technology improvements are required before mineral carbonation becomes a viable option.

Some industrial processes use CO_2, for example as a solvent or refrigerant. It would be sensible if, rather than investing energy in manufacturing CO_2 for these purposes, we used captured CO_2 instead. Unfortunately the total volumes of CO_2 required by industry are small, no more than 200 Mt per year, and the CO_2 is often released again within a year, so this approach would have little benefit[4].

Finally, we could bubble a stream of CO_2 through a pool to stimulate growth of algae, which can be harvested and converted to biofuels. This approach is at an early stage, currently has a low yield, and as well as needing sunlight, and water, also uses a large area of land. We would need a 50 km^2 pool to store the carbon output from a (small) 100 MW power station[6] so the approach may well be prohibitively expensive.

Current global emissions from energy use and processes are around 28 Gt CO_2/year or just under 8 Gt C/year. Table 10.1 shows that the options above could potentially have sufficient capacity to store this amount of CO_2 for many years but how risky is this, and what will it cost?

Storage option	**Lower estimate of worldwide capacity ($GtCO_2$)**	**Upper estimate of worldwide capacity ($GtCO_2$)**	**Storage integrity ('permanence')**	**Environmental Risk**
Oil & Gas Reservoirs	675	900	High	Low
Coal Seams	3–25	200	Medium	Medium
Saline aquifers	1,000	Possibly 10,000	Medium	Medium
Oceans	1,000	Every 2,000 increases acidity by 0.1 pH	Medium	High
Mineralisation	Theoretically very high but high energy cost and raw material requirement		Highest	High
Industrial Processes	0.1	0.2	Low	Low
Algae	Limited by land requirements		Low	Medium

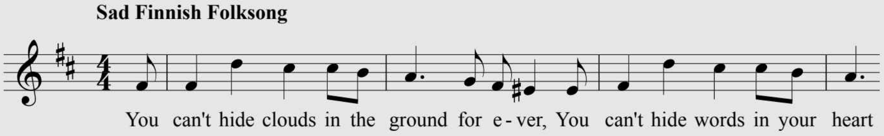
Table 10.1—**Estimated global capacity for different storage options**

Lake Tanganyika

What are the risks of storing CO_2?

If you sit on a balloon, eventually it bursts. If we blew up a balloon at atmospheric pressure with the world's annual 30 thousand million tonnes of CO_2, it would contain about 16,700 cubic kilometres: enough to cover Belgium to a depth of half a metre, or roughly the same volume as Lake Tanganyika, the world's second largest freshwater lake. If we compress it 370 times, as discussed earlier, we're down to a volume of just 45 cubic kilometres per year: around eleven times our current oil production. What happens to that if we sit on it for ever?

The obvious danger of storing this high pressure balloon underground is that it might leak out. It could do that at the place where the CO_2 was pumped into storage, or it could escape through the rock—slowly by permeating the porous rock, or rapidly if it encountered a geological fault[3]. The effect of such a leak would be twofold: firstly, the emissions would return to the atmosphere and contribute to global warming; secondly because carbon dioxide gas is slightly denser than air, when released as a concentrated cloud it initially stays close to the surface of the earth, until dispersed by the wind. Our lungs can only reject CO_2 at a certain rate, so if the concentration of CO_2 in the atmosphere becomes too high, we are eventually unable to take in enough oxygen, and die. Tragically, on 21st August in 1986, a 1.6 million tonne (or 1.2 cubic kilometre) bubble of CO_2 was spontaneously released from Lake Nyos in Cameroon—a lake which naturally has high concentrations of CO_2. Before this bubble could disperse, around 1,700 people lost their lives. Clearly no one will invest in carbon storage unless they have high confidence that this disaster will not repeat, so extensive modelling and experiments have explored the expected safety of storage. Models predict that it is very likely that more than 99% of CO_2 stored would remain in storage for 100 years[3]. However, this figure depends on assumptions —and safety will remain a concern until we have more practical experience.



If we need to transport CO_2 from where we made it to where we want to store it, will it leak out of the pipes? We already have some experience in this area, transporting CO_2 in pipelines in the USA for use in enhanced oil recovery. So far the pipelines have proved to be as safe as those used for natural gas, but sulphur and other impurities in the flow increase the rate at which the pipes corrode so they must regularly be inspected.

Finally, if CO_2 is stored in oceans, it may change the acidity of the water and in turn change the living habitat of certain species. We don't yet understand how increases in either carbon content or water acidity will affect marine life, but high levels of either will cause death, as in mammals. Experiments in which various species were exposed to CO_2 produced mixed results ranging from avoidance to attraction to death. Potentially, because deep sea fish respire more slowly and have fewer young than their near surface relatives, they might be less affected by increases in carbon or acidity, but this also remains unknown[3]. It is hardly surprising that the marine protection treaty organisation OSPAR[7] announced a decision in 2007 to prohibit the storage of carbon dioxide on the sea-bed[4].

Process	Approximate Energy Use (GJ/tCO_2)
Post-combustion separation (chemical absorption)	2.7–3.3
Pre-combustion separation (physical or chemical absorption)	2.3–5.0
Oxyfuel	3.2–5.1
Compression	0.4
Mineralisation	1.1

Table 10.2—**Energy estimates to operate different carbon capture and storage processes**

What are the energy and money costs of storing CO_2?

Because CO_2 storage is still only in development, we cannot predict its costs with great certainty. But we know that it entails equipment and infrastructure similar to existing gas extraction, storage and distribution systems, and if you've ever been in charge of the balloons at a 5-year old's birthday party, you'll be aware that it's also going to take a good deal of energy.

Dealing with energy first, Table 10.2 shows that most methods of capture have similar energy requirements[8]. After capture, energy is required to compress the gas from about 10 to over 200 times atmospheric pressure, but this combined with the energy required for transport, is small compared to the energy of capture[3]. The only storage route requiring significant energy input is mineralisation as discussed above.

Site and Capture technology	Cost US$/t captured (2002$)
Steel Blast Furnace	
Pre-combustion (DRI)	10–25
Post-combustion	18–30
Power Stations (for Steel and Aluminium Electric Furnaces)	
Pre-combustion	11–35
Post-combustion	23–35
Oxy-combustion	16–50

Table 10.3—**Cost estimates for different carbon capture technologies**

The costs of operating this system include the capital and operating costs of separation and capture, the additional energy costs to drive the process and the capital and operating costs for storage. Again, these can only be estimated, but Tables 10.3 and 10.4 present a range of current estimates from the IPCC[3].

As well as costs, we also need to consider the scale of the change required to introduce sufficient storage to influence our net global emissions. We mentioned earlier that our annual volumes of CO_2, once compressed at high pressure to liquid, would be about 11 times greater than our current oil production. So if we want to address our emissions target (50% absolute cut in emissions by 2050,

Storage Option	Cost Estimate (US$/t stored) (2002 dollars)
Oil & Gas Reservoirs	0.5 - 13
Coal Seams	0.5 - 8
Saline aquifers	0.2 - 30
Oceans:	5 - 30
Mineralisation	50–100
Industrial Processes	-
Algae	Land cost

Table 10.4—**Storage cost estimates**

while demand doubles) we have 39 years remaining to set up an industry that must operate at 10 times the scale of the current oil industry. This took one hundred years in development and had powerful economic drivers. Challenging…

Outlook

We started the chapter in an argument, and against the advice of our counsellor decided to bury it under the carpet, to avoid dealing with the issues. In exploring carbon storage we've seen that our relationship analogy conveys some truth: storage aims to allow us to continue emitting CO_2 at whatever rate we wish, rather than reducing our emissions. However, that's only part of the story. On the one hand, storage looks like the only viable approach to deal with emissions from coal combustion, and unless a very strong driving force changes their behaviour, it's likely that the countries with the largest coal reserves are going to burn them. On the other hand, carbon storage is in its infancy: only three sites operate at scale, and most of what we have discussed about technology, risks and costs is based on prospective research. A pilot electricity generating plant in Schwarze, Germany demonstrates that carbon can be captured effectively, but as yet it is released and not stored—see the box overleaf. We have seen that there are many possible storage options, but to implement them at sufficient scale to make a big difference requires implementation at an unprecedented rate.

The 'Batillus' built in 1976 for a subsidiary of Shell Oil, was one of the largest boats ever with a net tonnage of 275,268 tons, being 414m long and 63m across at her widest point. Fully laden, she could carry almost five million barrels of oil, or about 7% global production for one day. If we were to transport our annual CO2 emissions by ship we would need over 56,000 tankers of this size, which, if laid end-to-end would stretch from pole to pole.

Commercially and politically, storing carbon has a particular attraction: if we could make it happen, we could address our concern about emissions without requiring any change in the behaviour of consumers or voters. It appears to offer unlimited capability to take the problem away, and while we are discussing but not really implementing it, the question of "who pays" can happily be reduced to "I'm not going to pay, you'll have to." By not answering the question of who pays, everyone can recommend CCS as a key part of our future: incredibly, for a technology that barely exists, the International Energy Agency projects that 19% of our emissions will be sequestered in the year 2050[9], and this is a cornerstone of all their projections for emissions abatement.

For both the steel and aluminium industries, storing carbon, whether from primary processes or from electricity generation, is equally attractive as a 'catch all' solution that would solve the problem, if only someone else pays for it. In Europe, where we have set aggressive targets for emissions reduction but not offered any border protection to our industries, it is inevitable that the steel industry in particular must pursue storage: they have no chance to achieve emissions reductions targets and stay in business without it. This position would change with border controls that ensured that steel makers anywhere supplying customers in Europe were subject to the same targets as producers in Europe.

But back once more to our opening argument: we actually have great evidence from relationship counsellors that the way to solve problems is not to hide them, but to address them. All over the world, for the past 30 years, we've been teaching our manufacturing students that the great secret behind Toyota's commercial success is their production system which aims to make problems visible, to find their root causes, and then to solve them so well that the problems can't ever recur. If the problem is that we're emitting too much CO_2, isn't it better to emit less than to bury it? Oh no it isn't. Oh yes it is...

Schwarze Pumpe CCS demonstrator[12]

In 2008, at Schwarze Pumpe in Germany, a pilot plant was commissioned to demonstrate oxyfuel combustion of coal generating 30 MW of steam (sold to a neighbouring paper mill) and a relatively pure stream of CO_2 for carbon capture and storage. The demonstrator has achieved a carbon capture rate of 90 % but although liquefied CO_2 is stored onsite in tanks and can be transported by trucks, it is currently released into the atmosphere. Failure to resolve long term liability for storage has prevented its implementation[10].

Notes

1. Data from the annual BP publication (BP, 2011).
2. Data from the International Energy Agency shows that while 27 % of the total primary energy supply comes from burning coal, 43 % of emissions due to generating this energy are from coal, more than any other source. 'CO_2 emissions from fuel combustion — highlights', IEA (2008b).

Where can CO_2 be stored?

3. The Intergovernmental Panel on Climate Change produced a special report addressing CCS, IPCC (2005). It goes through capture, transport and storage options in great detail, giving data on processes, logistics, risks and costs.
4. The International Energy Agency has produced reports investigating the feasibility and scale of CO_2 storage. The information in these paragraphs is from 'CO_2 Capture and Storage: A Key Carbon Abatement Option', IEA (2008b).
5. Vaclav Smil's book 'Energy Myths and Realities' (Smil, 2010) neatly summarises the current state of many carbon storage technologies and computes figures to put the issues in perspective.
6. Outline calculations for algae biomass storage of CO_2 have been done by the IPCC (2005).

What are the risks of storing CO_2?

7. The OSPAR Convention (OSPAR, 1998) is the current treaty regulating environmental protection in the North-East Atlantic. It builds on previous accords limiting marine pollution. The OSPAR Commission, made up of government representatives) carries out work under the convention.

What are the energy and money costs of storing CO_2?

8. These values are primarily drawn from examples of gas and coal-fired power plants with CCS. The exact energy consumption will depend on the configuration of the power plant, exact technology used for capture, and carbon dioxide concentration in the gas stream to be separated. The typical range for CO_2 concentration in these examples is 3–14 %; ULCOS blast furnaces are aiming for CO_2 concentrations around 40vol% in the gas entering the separator and therefore should be able to achieve lower energy use for carbon capture according to Danloy et al. (2008). For comparison current blast furnaces have a concentration of 22vol% as detailed in the blast furnace mass and energy balance found on http://www.steeluniversity.org.

Outlook

9. IEA (2010b) includes projected energy use, carbon emissions and 'technology roadmaps' that outline what improvements and savings could be made to reduce them.

Box stories

10. Details of the project are provided on the company's website (Vattenfall, 2011) and a more detailed analysis of initial results has been carried out by Strömberg et al. (2009).

Images

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