Carbon storage

Carbon capture and geological storage beneath the UK – status and prospects

With its depleted offshore oil and gas fields, Britain ought to be leading the world in the long-term storage, following capture, of carbon dioxide. And the first full-scale trial plant may not be far away, writes Professor Stuart Haszeldine of the Scottish Centre for Carbon Storage (SCCS).

Last December, the Chancellor of the Exchequer gave his clearest indication yet that a full scale electricity generation plant, complete with carbon capture, will be built in the UK. The pre-budget report did not go nearly as far as many industry proponents would have liked in unequivocally supporting a rapid roll-out of carbon and capture and storage (CCS). However, the report did very explicitly continue the Treasury interest, and work in progress together with the DTI, towards clean and green fossil-fuelled electricity, with CCS, in the UK. The two main strands of this current work are firstly to cooperate with Norway in planning and optimising an offshore pipeline network for carbon dioxide transport, and secondly to undertake an assessment with consulting engineers, of the value for money of different CCS options for the first-ever demonstration plant in the UK, partly enabled by public funds.

What are the underlying principles of CCS, what are the development challenges, and how does the deep subsurface (a mystery to many) enable the UK to play a leading role in CCS deployment?

Why bother?

It is now well established that increased carbon dioxide in the earth’s atmosphere can be linked to increased temperatures, and hence to climate change occurring both now and in the future. Less well appreciated, but potentially much more significant and dangerous, is the impact that elevated concentrations of atmospheric carbon dioxide will have by simple equilibrium chemical dissolution into the upper ocean. It is simple kitchen chemistry to determine that this will mean an acidification of pH. Calculations imply that acidity will increase from the stable pH of 8.25 equilibrium of the past 20 million years, dropping to an unprecedented 7.65. This means five times more acidity. About 1 million tonnes per hour of carbon dioxide dissolves in the ocean from the atmosphere.

Ocean wildlife, from plankton to crustaceans and hence to fish, will be affected in, as yet, unknown ways. Athletic squid face respiration problems. Corals in particular face total extinction because rising ocean carbon dioxide will cross the chemical stability boundary from aragonite to calcite, to make a coral skeleton dissolve. It is a fact that, even though about half of the world’s cheap oil has already been burned, the total amount of fossil hydrocarbon available to burn from gas, coal, and hydrate has barely been touched. If fossil hydrocarbon continues to be used to generate power, then a remedy must be found to carbon dioxide emissions, or else the earth faces a future similar to Venus, with its high carbon dioxide hot atmosphere.

CCS – capture

CCS comprises a range of technologies which enable fossil fuel (typically coal, lignite or natural gas) to be combusted in a ‘clean’ manner. This goes beyond the scrubbing of sulphur, trapping of dust emissions, or elimination of mercury vapour, to the ultimate lack of emissions. The key element is the capture of carbon dioxide (CO₂). This can be achieved in the flue gas after combustion by amine absorption; or by chemical splitting and re-forming the fuel feedstock into syngas or hydrogen before combustion, plus carbon dioxide which is separated off; or by fuel combustion in a controlled oxygen-rich atmosphere to produce only water and carbon dioxide.

This capture step currently comprises 70% of the additional CCS cost and a 10–30% energy penalty. Consequently, worldwide efforts by industry and research institutes are underway to dramatically reduce that penalty. The separated carbon dioxide is pressurised, to become much more dense, and form a fluid at greater than 70 atmospheres. The dry fluid, at greater than 95% purity, is then suitable for transport by pipeline, by marine tanker, or even by rail, to its underground storage site.

CCS – transport

Transport of pressurised fluid carbon dioxide has been undertaken since the 1970s in the US, to supply carbon dioxide from natural sources to oilfields subjected to enhanced oil recovery (EOR) in Texas. This experience provides confidence that many established techniques can be adapted to the UK. What differs for the UK is that the Health and Safety Executive is in the process of establishing a suite of standards, rules, and protocols which will be needed to grant permits for high-pressure onshore pipelines to pass close to populated areas. The HSE also needs to establish novel knowledge such as: what would actually happen if a pipe crack developed into a catastrophic fracture? How should 24/7 monitoring of engineering facilities be undertaken to detect leakage? And, how can a volume of carbon dioxide released be translated into a hazard with a defined impact? Not least are the safety constraints for operating offshore platforms, where EOR operations could require handling of carbon dioxide pressurised to 400 atmospheres.

For a full scale implementation of CCS, to capture and store emissions from the 20 or 30 largest onshore power plants, then a network of carbon dioxide transport pipelines onshore is needed. The largest storage sites for the carbon dioxide lie offshore. So an onshore gathering network needs to focus, through selected headlands, to feed an offshore distribution network for injection into a diversity of sites. The UK has an established network of offshore pipework, which will become legacy material during decommissioning of gas and oil fields. However, it remains an open question as to the viability of reusing existing pipes, because of their location, the pipeline past history, and uncertain guarantees of future safety. To make full efficient use of geological storage beneath the UK offshore, then a network of large trunk, and smaller branch, pipelines may be efficient.

Neither will cross-boundary linkage to Norway be excluded, as those geological storage sites are of equal volume to the UK. Norway will only produce carbon dioxide from nine new gas power plant, meaning that UK, or world, carbon dioxide could find its final resting place in the geology of a Norwegian pore network.

However, the means to develop a pipe transport network for carbon dioxide remains unclear. Will this be piecemeal from individual developers, or will this be centrally planned – as the Norwegians favour? How will the emergence of such a network be managed and built by public or private funds, before full economies of scale are reached?
Carbon dioxide trapping

Carbon dioxide remains as a dense fluid at pressures greater than 70 atmospheres. Because pressure increases with increased depth below ground, this equates to more than 700 metres depth (just like diving deeper in a swimming pool). This fluid carbon dioxide has a density similar to crude oil, and consequently rises buoyantly through the ambient salty water, which occurs in deeply buried porous aquifers. To retain carbon dioxide into the far-off future, the dual combination of a porous aquifer (sandstone or limestone), overlain by an impermeable cap rock seal (mudrock, shale or salt) is needed. This combination is ubiquitous in areas hosting oil and gas, and is also common in shallower sectors of the North Sea and widespread beneath the onshore UK.

There are three established mechanisms for trapping of carbon dioxide. Firstly, the significant short-term problem is to trap buoyant fluid carbon dioxide. For this a good seal is needed. This can be best demonstrated in depleted oilfields, or at an even better quality of sealing in depleted gas fields. Secondly, when carbon dioxide moves through the pores of a rock, microscopic bubbles of carbon dioxide remain stranded and isolated after the main body of carbon dioxide has moved onwards inside individual pores of the aquifer. These disconnected micro-bubbles cannot move further, and are trapped securely. Thirdly, carbon dioxide dissolves in saline water, to form a salty version of bottled carbonated table water. This water is acid and can dissolve additional minerals from the rock. During hundreds of years, this acidity will become chemically neutralised by those dissolution reactions. Fourthly, carbon dioxide and minerals dissolved in water can gradually combine to form new crystals – like artificial limestone; this is true permanent sequestration.

UK Storage sites – oil and gas

The UK is especially fortunate in its endowment with a large offshore oil and gas province and associated industries. These oil and gas fields are some of the best-known geological sites on the earth. Depleted fields are obvious targets for carbon dioxide storage, because they demonstrably have had an effective seal overlying a porous aquifer. However, it is important to know that seals are semi-permeable membranes, and each has its pressure of leakage.

This is rather like Gore-tex outdoor waterproofs sealing out (not transmitting) mild rain, being forced to transmit extremely heavy rain (because of the greater pressure of entry), and being permeable to (able to transmit) water vapour (because of its lower viscosity). Carbon dioxide is harder to retain than either oil or gas, so that a seal effective for oil will retain much less pressure of carbon dioxide, meaning less vertical height of carbon dioxide and only one third of the volume. However the seals of North Sea oil fields overlying a reservoir are routinely capable of retaining much greater columns of oil have been naturally present, so that prediction of carbon dioxide retention is still plausible if measurements have been made.

The largest risks here are: firstly that the seal may be fractured by small faults, or fractures, invisible to conventional surveying. Such fractures could provide unexpected short-cuts for carbon dioxide to bypass the seal and leak. Secondly, that the boreholes used to exploit the oil and gas, and to emplace the carbon dioxide, have inevitably destroyed the seal, and so high quality, chemically resistant, long lasting cements are being developed to ensure that these pathways of potential rapid leakage are robustly secured.

Volumes of storage in depleted oil and gas fields are the best-known, because there is a lot more information. The most recent estimates, from a 2006 DTI-funded study, are 7,500mm tonnes of carbon dioxide storage in depleted oil, condensate or gas fields offshore. Compared to a present emission rate of 132 Mt CO₂/yr from just the 20 largest UK power plants, that is 53 years worth, and could reduce total UK carbon dioxide emissions by 23% per year. If all UK large power plants are included, then a 33% cut by 2050 could be anticipated.

Enhanced oil recovery is often discussed as a profitable entry option for CCS. However, it is also an expensive option. The 2005 IPCC special report on CCS shows that EOR offshore injection costs may be £20 per tonne of carbon dioxide. This is because of the large infrastructure needed. The offshore platform equipment also has to be converted to resist corrosion, because of the operational injection, production, and re-injection of wet (acid) carbon dioxide.

This 'water alternating gas' (WAG) method is the option which seems to intrigue large oil companies, with a prize of producing an extra 4-12% of the original oil resource. This could store 1800 Mt CO₂ in the UK sector. But even at base price of $40 barrel oil it is manifestly not economic in its own right. The operational costs offshore are so high that a 'bread-and-

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butter' revenue is needed from a carbon dioxide price, to enable the 'jam' of EOR to be halted. So, there is a race between decommissioning dates for offshore fields versus the development of an abundant and secure carbon dioxide supply, at a stable price, sufficient for reliable EOR supplies.

Early UK target fields might be Fulmar, Forties or Ninian. According to a 2005 study by Exploration Consultants Ltd for DTI, the first key date is 2011, after which suitable fields start to be decommissioned rapidly, with a linear decline to 2030 – unless EOR comes. Given the lack of power plant with firmly-committed CCS in 2007, timing and aligning the need for 80 Mt CO₂/yr to be provided, with the requirement to start producing the additional 1.9000 m barrels of oil from 2011 seems destined to be sub-optimal.

If conventional EOR does not occur, the oil remains in the ground – about 55% of North Sea resources. The UK would still be able to deploy a longer-term method of EOR extraction, by re-engineering specifically for EOR, using cheap offshore facilities, and using the 'gravity stable gas injection' method. In such a case, carbon dioxide can be injected at the top of a reservoir, and pushes the oil downwards to production boreholes. Because immiscible carbon dioxide is such a good solvent, the viscosity of the oil is greatly reduced, sometimes by a factor of 10. Then 60-90% of the original resource can be recovered, and a much greater proportion of carbon dioxide is stored.

The disadvantage, of course, is that this takes many decades rather than years, and works less well where a reservoir has been flooded by water. Research on EOR developments, at the SCCS in Edinburgh, can undertake the detailed assessment needed for individual fields to optimise injection sites and WAG ratios and, more generally, to extend the EOR application into shallower and more complex fields.

UK Storage sites – aquifers
At shallower depths than oil and gas fields are many very extensive sandstones filled with saline water – saline aquifers. Many of these are overlain by mudrock seals, which may retain carbon dioxide. In the UK, the most promising horizons are the Bunter Sandstone of the southern North Sea, the similar Sherwood Sandstone of the Irish Sea, and the much younger Pliocene age Usitha Sandstone of the northern North Sea. In these cases, much less is known in detail about the aquifer or seal, but substantial data can be used from proxy or analogue examples where similar rocks are known from Irish Sea or Southern North Sea gas fields.

The Usitha area is the site of Statoil's carbon dioxide injection pilot, operating since 1996. This lies only a few km across the political boundary, and if a carbon dioxide pipe grid were to be established, then carbon dioxide derived from UK sources could be transported. Injection into saline aquifers offshore is established at €3.5 t CO₂, much cheaper than EOR. Storage volumes are also much larger, with estimates ranging 15,000 to 25,000 Mt CO₂ (compare to 150 Mt CO₂/yr from all heat and power generation in the UK).

These estimates need to be refined, by detailed reservoir simulations of carbon dioxide injection, in a similar way to oilfields. Research at SCCS has shown that optimising injection rate into an aquifer site can double, or halve, the storage volume – so that the most rapid injection is not the best strategy. The legal status of both aquifer and gas field injection of carbon dioxide has been under doubt, as carbon dioxide was not included as a permitted substance in the Annex to the worldwide London Convention, which regulates marine dumping.

However, following work led by the UK and Australia, carbon dioxide was added to the list of permitted substances in November 2006, to become legally active in 2007. This will open the UK possibility of very cheap, and close to shore, aquifer sites from Middlesbrough, past offshore Lincolnshire, to Great Yarmouth.

UK Storage sites – onshore/nearshore aquifers
It is frequently repeated that the largest opportunities lie offshore for carbon dioxide storage. Whilst this is true, it also misses a point that much of east Scotland and east England and the near coastal zones are underlain by saline aquifers deeper than 700 metres – albeit on a much smaller scale than offshore. These may prove to be important in enabling the start-up of the CCS value chain. In the transition from now, to a CCS future, there will be a period when some plant could be fitted with CCS, but are not connected to a national CCS pipe grid. Building a speculative pipe connection for hundreds of millions of pounds is not viable. When power generators renew, or retrofit, plant sites for CCS, then local storage may be a valuable interim asset.

SCCS research is investigating the possibility of developing storage sites local to the plant. Such sites could store 5 to 10 years of carbon dioxide production, i.e 20 to 80 Mt CO₂. Even when a full carbon dioxide pipe grid is operational, these local sites may have value as 'buffer' storage (analogous to natural gas storage), to flatten out the carbon dioxide supply from a typical 30% variability of operation for a coal plant.

Monitoring, seepage, leakage and traces
The timescales required for carbon dioxide retention are short by geological standards – just 10,000 years. It is already possible to monitor fluid carbon dioxide by seismic reflection technology from oil and gas fields, modified to image carbon dioxide. Under development are electro-magnetic techniques, which should be able to image dissolved carbon dioxide. One purpose of these is to detect any movement of carbon dioxide from its intended sub-surface position. The discussions on regulation of carbon dioxide storage, most developed in Australia and underway in the UK, seem inclined to treat the 'storage site' as including not just the aquifer or reservoir, but also the entire overburden section of sediment.

This means that more knowledge is needed on the pathways and rates of carbon dioxide ascent towards the surface. SCCS research is tackling this by study of natural carbon dioxide reservoirs, from the North Sea, US, and Italy – where there are examples of both intact and leaking carbon dioxide retention over tens of thousands or millions of years.

An issue sometimes overlooked, is identification of carbon dioxide ownership, if a leak occurs. The gas itself carries minimal information. Particularly if the carbon dioxide is derived from two sources of coal combustion, the isotopic signatures of carbon will be very similar. Consequently, it will be difficult for a regulator to prove in a legal contest that a carbon dioxide leak is from your storage operation. That cuts two ways. If two power plants have injected into the same EOR operation, or the same saline aquifer, at different sites or different times, it is difficult to determine which carbon dioxide belonged to which operator. So there is a possibility of your liability for another operators leak. A simple remedy is to fingerprint your carbon dioxide, by spiking with a distinctive natural or artificial gas.

Research at SCCS is investigating the performance of fingerprint gas tracers in natural and laboratory settings.

2007 and beyond
Prediction is difficult, but it seems that CCS now has an unstoppable momentum. The UK will build at least one full-scale pilot plant. Although choosing this for 'value' sets expensive pre-combustion gas reforming to make hydrogen, cheaper to run, more expensive to build, coal IGCC. Are apples better 'value' than bananas? The UK can be a close follower of Norway, which has consistently blazed a CCS trail in aquifer storage and soon will with EOR in the Halten (StatoilShell) project. The Zero Emission Power (ZEP) strategy in the EU proposes 12 demonstration plants by 2015. These are likely to include the diverse range from retrofit up to oxyfuel. Australia will start to inject carbon dioxide in 2007. Canada is not far behind. And the Deaf and EU projects with China plan to operate plants by 2014.

For the UK to prosper with CCS not just one demonstration is needed, but several deployments, as there are diverse niches in existing sites even within our small country. All of aquifers, gas fields and EOR are now available. The EUETS will probably include CCS from 2012. By to satisfy cautious bankers and enable release of investment funds, it would certainly help for the Treasury to set a floor price for domestic carbon dioxide in the UK. We have some of the best geological assets, now we need some courage to develop them.

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