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CARBON CAPTURE AND STORAGE: SUSTAINABILITY IN THE UK ENERGY MIX

Workshop Report, 7th July 2006

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Workshop Background

Climate change is real, but the acceptable limits of fossil fuel emissions are uncertain. The effects on oceans may be terminal, with unknown consequences for humans. The UK Government promises to place the climate agenda at the centre of all actions. Sweden anticipates oil freedom by 2021, Norway is a world leader in CO_2 geo-storage, Canada is world leader the construction of full-size low CO_2 coal power stations, Germany has 20-100 x more power from diverse renewables than the UK. By contrast, UK CO_2 emissions are rising, sales of aviation fuel increase, and nuclear electricity renewal dominates news media (and potentially, expenditure) to reduce just 8% of power sector CO_2, whilst renewables and CCS languish with lower-tier Government funding, or lack of immediate business and industrial value.

This meeting follows on from the UK Energy Research Centre annual assembly, and brings speakers from leading national positions, who can provide perspectives on success, failure, and future pathways. Will the UK be a leader in climate stabilisation? Or is that moment about to pass?

The focus is on CCS (carbon capture and storage). This is suite of technologies to capture CO_2 at power stations and other concentrated sources, liquefy and transport the CO_2, and inject into rock pores deep below ground. The Intergovernmental Panel on Climate Change produced a special report on CCS in 2005, where a worldwide analysis showed that CCS could halve the increase of CO_2 emissions by 2100 – especially in coal-using countries. The UK has claim to a world-class opportunity for CCS, utilising reservoirs deep beneath the North Sea. Will technology, industry, and Government enable this opportunity to be taken?

About the Organisers and Sponsors

The subject of this workshop was proposed by Stuart Haszeldine of University of Edinburgh, CCS topic leader within UKERC's Future Sources of Energy theme, with project colleague Jon Gibbins at Imperial College London. This workshop has been coordinated and sponsored by the UKERC Meeting Place.

The UK Energy Research Centre's mission is to be the UK's pre-eminent centre of research, and source of authoritative information and leadership, on sustainable energy systems. UKERC undertakes world-class research addressing whole-systems aspects of energy supply and use, while developing and maintaining the means to enable cohesive UK research in energy. A key supporting function of UKERC is the Meeting Place, based in Oxford, which aims to bring together members of the UK energy community and overseas experts from different disciplines, to learn, identify problems, develop solutions and further the energy debate.

Core Organising Team

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Morning Session

1) Introduction: CCS and sustainability

Stuart Haszeldine of the UK Energy Research Centre, and University of Edinburgh, explained that the meeting had been created by himself (from UKERC) and Jon Gibbins (from the UK Carbon Capture and Storage Consortium). The format of the meeting, would comprise short informative presentations grouped thematically together, with long periods for free-ranging discussion after each presentation group. The Chatham House Rule would apply, so that comments could be freely made, but will not be attributable to an individual. The meeting funding and style was operated by the Meeting Place function of UKERC, its remit being to bring together members of the Energy community from the UK and overseas to identify problems and further the Energy debate. The aim of the day is to examine if Carbon Capture and Storage (CCS) adds to "Sustainability", defined as ***'development which meets the needs of the present without compromising the ability of future generations to meet their own needs'***, or is CCS simply "***an excuse for Business as Usual?"***

The flow of presentations and discussion was intended to move from the scientifically general on climate and environment effects, to the specifics of CCS experience and possible future developments, particularly those relevant to the UK. The UK, like other industrialized countries can group its CO_2 emissions roughly equally into Transport, Home and Industry, and Electricity generation. CCS is particularly appropriate for reducing emissions from the electricity sector, as they are localized, abundant and long-lasting. The UK has made progress towards Greenhouse Gas reductions. However, CO_2 emissions had decreased from 1990 but would now increase because of increased burning of cheap coal fuel. Many other "Kyoto Annex 1" countries were even further from their 2010 targets than the UK. Can CCS provide a sustainable means of mid-term progress?

There are several concepts of CCS, but this meeting focuses only on deep hydrocarbon fields, and deep saline aquifers. Numerous scientific and industrial pilots for CCS exist around the world, and the North Sea has emerged as a hot spot of proposed developments during 2005-06. However, many of these propositions need explicit Government support, or a value for CO_2 from mechanisms such as the EU-ETS. CCS has its negative points, such as increased fuel consumption, because of the energy costs of capture. Set against this, CCS can also be argued to have positive security of supply aspects, in that it could enable 7 – 15% more oil to be extracted from existing North Sea fields, as well as its main attribute – the direct reduction of fossil CO_2 emission rates. There is much talk, and some action, of co-firing biomass with fossil fuel, so that CCS enables a real carbon neutral system (or potentially carbon negative). Finally, it is startling to recall that the present-day rise of atmospheric CO_2 has been caused by industrialized burning of just 50% of the easily available oil. There is much, much, more fossil hydrocarbon available to the world, albeit at a progressively higher price. In the geologically very near future to 2100, some of this may be deliberately burned, such as Alberta tar sands – and CCS undertaken. Some may be accidentally released by un-anticipated climate change – such as ocean hydrates, or onshore permafrost. The consequences are poorly known.

So the question may also be: ***should the world avoid CCS, but at its peril?***

2) Some thoughts on climate science, carbon capture and policy

Dr Dave Frame, Oxford University Centre for the Environment talked about **"Climate forecasting on the scale of decades to centuries using numerical models".** Existing climate models are unwieldy, very slow and large. These produce forecasts, which are probabilistic in nature, and lead to a stabilisation scenario. However, we do not know the unknown terms in the equations. Thus, probabilistic forecasts for "stabilisation" depend on the modelling assumptions and paradigms. This work focuses more on the **transient effects**, and warming **rates**. We know the amount of global warming in the 20th Century is approx 1°C, but this is just a transient effect. How do we model the long term assuming no further human interference? Warming and cooling rates are potentially more robust outputs from modelling, being sometimes linear and hence more predictable. Models suggest a maximum temperature rise of 1.5 to 1.75 °C. If warming is linear, then prediction on short time scales is easy, but predictions further into the future are more difficult. Quantifying the uncertainties in the models is difficult. However this can be important to show, for example, that a rapid spike of 2.6 °C warming with x 2 CO_2, then followed by cooling, is too short to melt a Greenland icecap. Crucially, the maximum warming depends more on the total carbon burned than the exact timing. This may change emphasis on global temperature targets or atmospheric concentration. These provide good tools to inform us about the total fossil carbon allowed, and to regulate that via a carbon price, for example.

Several scenarios are evaluated, all trending to 'zero' carbon emissions in 2300, but with different calendar timing "peaking early" or "peaking late". These produce a modal warming of 2 °C, with a maximum probable warming of 3.8 °C. The total amount of carbon burned is critical. The coupling of atmospheric CO_2 forcing remains poorly understood, and is very model dependent – for example the cross-talk of ocean to atmosphere. Much more firm information is needed for the carbon cycle, as this significantly changes the volume of the modelled carbon wedge.

Models can be used to predict carbon emissions targets for acceptable degrees of climate change. To be effective, the models must include the carbon cycle and ocean-atmosphere interaction. Quantifying the equilibrium response to an elevated CO_2 concentration has proved elusive. The maximum warming remains the same, if the same amount of carbon is burned, however the transient rate of temperature change can be quite different. This is much more tractable than seeking to measure 'stabilisation scenarios" of GHG worldwide. Dave therefore suggested that we refocus on Transient Climate Response, which is much easier to quantify and may provide more robust, and nuanced, information to policy makers.

3) Effects of CO_2 Increase on Oceans

Carol Turley, Plymouth Marine Laboratory (ct@pml.ac.uk) With the World's oceans covering over 70% of the planet's surface, and contributing to half the primary production on the planet, and containing an enormous diversity of life, it is not surprising that they provide invaluable resources to human society. Climate change is already having an impact in the oceans as well as on land. Of particular concern are the loss of marginal sea ice biomes, expansion of the low productivity central oceanic gyres, the loss of warm water coral reef ecosystems and regime shifts such as that seen in the North Sea in the late 1980s. These impacts are thought to be due to increasing seawater temperature, and as this increases in the future the impacts are predicted to get more severe.

Oceans play a vital role in the Earth's life support system through regulating climate and global biogeochemical cycles through their capacity to absorb atmospheric carbon dioxide. Put simply, climate change would be far worse if it wasn't for the oceans. However, there is a cost to the oceans. When carbon dioxide reacts with water it produces carbonic acid, so when more CO_2 is taken up by the surface of our oceans the more surface ocean pH decreases (pH is a measure of acidity). This is called "ocean acidification" and is happening at a rate that has not been experienced for at least 400,000 years and probably for the last 20 million years. The effect of ocean acidification on marine ecosystems and organisms that inhabit them has only recently been recognised and is of growing concern to scientists and policy makers involved in climate change, biodiversity and the marine environment.

The world's oceans currently absorb on average about one metric tonne of CO_2 produced by each person every year. It is estimated that the surface waters of the oceans have taken up about 500 Gt CO_2, about half of all that generated by human activities since 1800. This additional CO_2 is already reducing ocean pH and it is also affecting the carbonate chemistry through the reduction of the carbonate ions, aragonite and calcite, which are used by many marine organisms to build their external skeletons and shells.

If the current trends in CO_2 emissions continue to increase due to human activities, by the end of the century pH of surface seawater could decrease by about 0.5 units. This change in the chemistry of the oceans is quantifiable and predictable. The consequences of acidification on marine organism are much less certain as results from research are just emerging. These studies suggest that it is a real threat for the survival of some important marine ecosystems and many marine species.

Ocean acidification leads to a decrease in carbonate ion concentration, a crucial element in the construction of the external skeleton or shells of many marine calcifying organisms. By the middle of this century, ocean acidification will affect the calcification process which allows organisms such as corals, molluscs and calcareous phytoplankton, to build their external skeleton or shells. Tropical corals might be heavily damaged, which will threaten the stability and longevity of many organisms and impact the human populations that depend on them. Cold-water corals are also likely to be strongly affected before they have even been fully explored.

Predictions based on numerical models suggest that in 50 years, surface waters in the Southern Ocean will be corrosive to aragonite, an element that constitutes the shell of the pteropods. These small planktonic snails may therefore not be able to survive in polar waters. As they occur in high numbers and are an important food source for many species, from zooplankton to whales and commercial fishes such as salmon, their disappearance may have a substantial knock-on effect on the whole Southern Ocean ecosystem.

Surface ocean acidification is happening now, and will continue as humans emit more CO_2 into the atmosphere. It is happening at the same time as the world is warming. Organisms and ecosystems are going to have to deal with a number of major rapid global changes at once – unless we urgently introduce effective ways to reduce CO_2 emissions. These changes are happening on human time scales so that our children and grandchildren will experience them. Avoiding even more serious ocean acidification is a powerful additional argument to that of future dangerous climate change for the urgent reduction of global CO_2 emissions.

For more information see the Royal Society Report on Ocean Acidification (http://www.royalsoc.ac.uk/document.asp?id=3249).

4) Climate change, EU policy and CO_2 storage security

Dr Jason Anderson, Institute for European Environmental Policy discussed some of the economic and political aspects of global climate change and emissions reductions. Jason stressed the need for urgent action on global emissions. The sooner emissions start to fall, then the less drastic the rate of reduction has to be. A peak in emissions by 2020 would be acceptable, otherwise the subsequent rate of emissions reductions will have to be very rapid indeed. A limit to global warming of 2 °C above pre-industrial levels has been endorsed by the European Council, the European Parliament and the European Commission, as well as many stakeholders. This currently means an 8% decrease of Greenhouse Gas (GHG) emissions within the EU, with implication for 30% decrease by 2030, and a minimum of 50% decrease by 2050.

A suite of mitigation policies are, and can be, in operation within the EU. But Europe will only meet its Kyoto targets by buying carbon credits, a process that the audience (of this workshop) clearly thought was cheating, but which is allowable under the protocol. The IEA (2006) estimate that a cost of 20€ per ton would be bearable, and could reduce 16% GHG. At $25 per ton CO_2 the IEA estimate that GHG can be kept to their present level within the EU. Energy efficiency is the cheapest method. CCS is a beneficial part of the CO_2 reduction portfolio at the higher cost end, towards $35/ton CO_2. The reduction in emissions required depends on the target of maximum atmospheric CO_2. By contrast, van Vuuren et al (2006) estimate that atmospheric stabilisation could cost much more, with permits at $200/ton carbon in 2050 for a relatively high peak of 650 ppm, and a 550 ppm peak costing double at $400 /ton carbon, increasing again to $600 /ton carbon to meet a 450 ppm peak. To achieve these, a full portfolio of energy solutions will be required, including energy efficiency.

Legally within the EU, there are numerous Regulations and Directives to meet and harmonise before CCS is routinely achievable. The DG Environment is currently completing its European Climate Change Policy (ECCP) consultation, and will build CCS into that, for communication at the end of 2007. Jason discussed the EU Emissions Trading Scheme, where the UK is proposing CCS be included. The European Commission will delay any decision until after the ECCP communication. Placing CCS within the Clean Development Mechanism is proposed, to buy emissions credits from outside the EU. This still seems a long way from approval in Jason's opinion. Other incentives and obligations will probably emerge as the ECCP gains shape. Public acceptance of new technology is important, with good public support for solar and wind power. Supplied with information, the public seem to favour CCS, while nuclear power has a poor public image. CCS as an option may lower barriers to public agreement on more stringent targets. Or CCS may reduce pressure for targets by giving the impression of a fallback solution, for example in the USA. CCS will probably displace other CO_2 mitigation options. Assessment of site performance could use a risk-based approach, but will need to be site-specific. It remains unclear if CCS is a bridge to the low carbon future, or if CCS will remain part of the future – once CCS is phased in, it will be hard to phase it out.

DISCUSSION

The discussion had a general theme of **'Is it too late to prevent disastrous climate change?'**

Are we past the point of no return for climate change? Needless to say, there was no clear answer to this question! There is no known safe limit for CO_2 in the atmosphere, except for the pre-industrial level of 270 ppm. The major problems are the 'non-linear' effects, e.g. climate warms a little, then the Greenland ice sheet may melt catastrophically, or the Gulf Stream may stop. These effects cannot be reversed on short timescales by reversing the atmospheric changes, e.g. cooling the Earth wouldn't rebuild the Greenland ice sheet, certainly not on any human time scale. What would happen if there was no progress with global emissions reductions, i.e. the Business As Usual scenario? There could be a global climate warming of 5.5 – 6 °C in next 100 years. This is huge, with much hotter summers, and especially nights. Many ecosystems would die, including some human ones. There could be a major, worldwide, extinction, perhaps similar to those that geologists see in the fossil record. James Lovelock has suggested that 'civilisation' might survive only in the polar regions. There is a major political aspect to all climate change predictions that makes objective assessment difficult.

In view of the possible effects of ocean acidification, should we have targets for ocean pH change instead of having emissions targets for atmospheric CO_2? No 'safe' ocean pH limit is known, though we could use the annual variation (0.1 - 0.2 pH units) as a guide. This suggests that the predicted pH change for 2050 (0.3 pH units) is 'unsafe' i.e. will result in significant extinctions such as the present day coral bleaching. However there are many factors involved that are poorly known, in fact there are probably 'unknown unknowns'! We have 10 – 15 years to act, or our children's children may never have the chance to see a coral reef.

Can we take CO_2 out of the atmosphere by artificially mixing the oceans using huge vertical pumps? No, it may be technically possible but it's too dangerous to mess with global ocean circulation. There may be 'natural' enhanced vertical mixing as storms in the Southern Ocean intensify as the climate deteriorates – better modelling would help. Artificially locking the CO_2 up as a solid mineral precipitate within the oceans is also impractical – we would need to re-make the White Cliffs of Dover.

How do we reconcile the timescales of politicians (1 – 5 years) with climate change timescales (decades, centuries)? Scientists and policy makers need to talk to the public about their children and grandchildren, about human deaths due to global warming and collapsing eco-systems that are happening now, not that might happen in 50 or 100 years. People won't accept emissions reductions scenarios (e.g. tax on aviation fuel) unless they understand what it means to them as individuals now. Unfortunately, we can predict the fate of whole ecosystems, but we cannot predict lifestyle. We can't predict what life would be like in a 550 ppm CO_2 world as we can't anticipate technological change. Education is crucial, the UK Government is playing a leading role in global publicity; academics and industry must help.

Still on the subject of timescales, the world energy industry does think on a 50 year time scale – this is roughly the time from finding an oil field to depleting it. So do insurers – would you insure the rebuilding of New Orleans? There is a trust issue here – can we set long-term targets and seriously expect Government or industry to stick to them? The fuel we burn now will affect the climate in the latter half of this Century – there is a long lag in the climatic system.

What will happen after 2012, when the Kyoto agreement expires? The point was made that Kyoto agreement isn't much use anyway, sticking to it won't significantly limit climate change, and many countries have no intention of sticking to it; Spain and Italy haven't even set targets. There is probably even less chance of a global agreement post-Kyoto, though the Kyoto agreement isn't global even now. A lot depends on the USA and industrialising countries such as China and India. Europe can only lead by example, i.e. action not words.

Can we engineer our way out of this predicament, after all that's how we got here? Efficiency is slowly improving, driven by technological advances and attempts to reduce energy costs. The optimistic view is that a combination of better engineering and cost-cutting will eventually save the day. Is the hydrogen economy a solution? Probably not, as hydrogen has to be generated somewhere, you simply shift the pollution from (say) your car to (say) your fossil fuel powerplant. CCS could make energy, almost pollution free, for a hydrogen economy while still allowing burning of fossil fuels.

5) CCS in Canada – Experience, sources, uses and storage

Malcolm Wilson, Energy INet and University of Regina, discussed a variety of topics in the area of CCS experience in Canada. The Energy Inet organisation is a joint industry-public partnership, seeking to help maximise Canada's energy research and development impact. This included the differing energy uses within states in Canada and from this an indication of the sources of CO_2 supply, location and relative purity. The presentation also outlined the key areas of developing experience in capture, use in Enhanced Oil Recovery (EOR), Enhanced Coal Bed Methane production (ECBM) and acid gas injection.

The presentation then addressed the pilot work in Canada on post combustion capture using amine solvents in conventional columns and the progress that has been made in this area. It also noted the work on oxy-fuel combustion. Of particular note is the development of a new lignite-fired 450MW power station in Canada that will have fully integrated capture and will be on-stream by 2012, producing approximately 7,000 tonnes per day of CO_2 for use in EOR or for storage. This Boundary Dam plant will have oxy-fuel burners and post-combustion CO_2 capture.

Canada's primary potential for EOR or storage is in Western Canada, with an estimated storage potential of some 1000 Gt CO_2, most of this being in saline aquifers of Alberta and Saskatchewan, but with approximately 1000 Mt CO_2 potential for EOR. Tar sand production in Alberta is not conveniently sited for CCS. Ontario may build pipes to reach the Michigan Basin, whereas Nova Scotia may use offshore aquifers and coals. While there is some work on ECBM, the work has not progressed to the same point as EOR and there is still much to learn of the potential for coals. Similarly, the concept of Enhanced Gas Recovery has been discussed, but little research undertaken.

The discussion then moved to the Canadian flagship project, the Weyburn Monitoring and Storage Project sited in the Canadian sector of the Williston Basin. The IEA Greenhouse Gas Programme cite this as the worlds largest full-scale Monitoring and Verification programme. CO_2, with 96% purity and 1% H_2S, is transported by a 320km pipe from North Dakota. This project injects some 5,000+ tonnes per day of CO_2 into a moderately large oil reservoir. The incremental oil from this reservoir now sits at 18,000 barrels per day. 7 Mt CO_2 have already been injected, and 26 Mt CO_2 are planned to be injected by 2035. The key to this being a good research project is the fact that there is an extremely good historical database in place and the research programme was able to undertake a full baseline survey prior to any CO_2 being injected. The monitoring technologies in use by 4D seismic, geochemistry and tracers were discussed and the successes noted. Also discussed was the modelling underway to determine the reservoir performance over the time period to complete dissolution of the CO_2 in reservoir fluids. Projecting 5,000 yr into the future using flow models, shale rock seals were considered highly effective, such that only 0.02% of the CO_2 is expected to rise above the reservoirs, and zero % will reach the surface. Leaky wells are predicted to account for 0.14% of leakage upward, and since CO_2 dissolved is denser than water some 18% CO_2 may dissolve and migrate downwards. The end results indicate the climate change effectiveness of the technology and the integrity of the storage "container" – the Weyburn reservoir.

Alberta also has extensive experience of acid gas injection (CO_2 + H_2S), with 2Mt CO_2 in 5 years from over 40 sites. ECBM is also operational, but remains unknown for its future role. EOR will probably take most of the future effort, producing hundreds Mt /yr oil, also with attention to tar sands processing. Future issues for CCS are regulations, cost reductions of capture, public support, and full-scale demonstration projects. CCS is progressing slowly, so will not deliver the CO_2 reductions needed by Canada for 2010 Kyoto compliance.

6) CCS and Enhanced Oil Recovery: developing Norwegian value.

Aage Stangeland, Bellona Foundation, and a member of the **EU zero emission power FP7 working group,** explained that Bellona are an environmental NGO, with expertise in energy issues within Norway. They believe that new build powerplants must use CCS. However, this will only be effective as part of a comprehensive strategy of CO_2-emission reduction measures. The Norwegian Petroleum Directorate had published work indicating that CCS was un-economic. The Bellona report on CCS was published one month before the last election, and this approach has been adopted by the new Norwegian Prime Minister.

Norway is predicted to require increasing amounts of energy, but there is no potential for new hydro-power stations. Gas-powered stations are the preferred option, producing 16Mt CO_2 per year. This will be taken offshore by pipeline for geological disposal. Crucial issues are the requirement for investment by the Norwegian Government, and the need for a long term regulatory framework against which investment can take place.

In the Bellona model, there the four separate companies involved in electricity generation. An oil company supplies natural gas. A generating company generates electricity. A capture company removes the CO_2 from the waste gases from the power station, and a transport company moves the CO_2 from the power station to the site of disposal by the oil company. The transport company is non-profitable, and has to be state owned. In exchange, the increased revenues from oil production are taxed by the state, which makes a net profit. Bellona suggests that the price of CO_2 could be tied to the price of oil or gas, this helps to spread the risk amongst all the stakeholders.

Bellona recommends that the Norwegian government establish two companies: one for capture of CO_2, and one for the distribution and sale of CO_2 to be used for enhanced oil recovery (EOR) purposes. The price mechanism in the proposed economic model places the risk on the part with the largest proportion of revenues in the value chain, i.e. the government, and thereby makes capture of CO_2 for EOR purposes a very profitable operation.

The government can, according to the economic model, contribute to the necessary investments in the CO_2 value chain. Thereafter, all private actors will profit from CO_2 for EOR projects, even at oil prices considerably lower than today. The calculations also show that the Norwegian State will profit from the CO_2 value chain even at oil prices as low as 18 US$ per barrel, when state tax on the enhanced oil production and the avoided CO_2 permit cost are accounted for.

DISCUSSION

There were several questions about the fate of the injected CO_2 in the Weyburn project. The stated leakage of CO_2 at 0.14% of the total injected was clarified as being over 5000 years. However, more leakage was expected over much shorter time scales up well-bores. This was thought to be relatively simple to remediate, but could not be modelled using the existing methods. CO_2 also escapes from the reservoir when it is produced along with the oil. All of this is recovered, dehydrated, and re-injected, as it is the cheapest CO_2 available. Hence all the CO_2 that has been bought is underground at the present day. As the company is paying 17 – 18 US$ per tonne (delivered at pressure) it isn't economic to allow any to escape to the atmosphere.

Although the Weyburn project is world famous as a model for CCS, it was designed entirely as an EOR exercise. There have been no concessions to CCS in the design, so the quantity of carbon buried has been minimised. This contrasts with a CCS scenario where the aim is to maximise carbon buried, with oil production as a possible side-effect to offset costs.

Can we re-use existing pipelines to move CO_2 from sources to the storage sites, or do we have to build costly new pipelines? What effect does H_2S have, and how dangerous is it? We can potentially use existing infrastructure but the predicted volumes are so high that new pipelines will inevitably be required. By 2050, 50 billion tonnes will have to have been buried. The CO_2 will be dry when pumped, so is not corrosive. The H_2S makes the CO_2 much more dangerous. Canadian planning law means that the pipelines must not pass closer than 400m from a house, and 800m from a community.

The fate of the CO_2 underground was modelled for 10,000 years. What were the uncertainties? There were many uncertainties! Present day models cannot even predict accurately the behaviour of the fluids in a reservoir over the life of the reservoir (30 years).

The Bellona financial model for CCS/EOR in Norway was also discussed. The financial model has a transport company, which is distinct from the oil company and the power generating company. The transport company both collects the CO_2 from the power station, and delivers it to the site of geological storage. This company loses money and is Government owned. Why not charge the power and oil companies to cover this loss, perhaps in conjunction with a carbon tax? The reply was that this model spreads the investment, and removes both risk and start-up costs from the private industry. Without this assurance they would not be prepared to invest. The Government eventually recovers its investment in the transport company through taxation of the extra oil produced, though the Norwegian government has not yet committed itself to this role. This model will not work where there is no state involvement in the energy industry, so not in the USA. The model was developed for Norway.

With the financial model of separate transport company and power generating company, the power plant and the CO_2-capture plant are separated. Does this work physically, as conventionally the two are integrated? The reply was that while integration is normal in pre-combustion and oxy-fuel plants, this is not important to the financial model.

When a private company buried CO_2, where does its liability end, especially if the CO_2 subsequently leaks? The Norwegian view is that the State must take all long-term liability, or the private companies will not be prepared to take the risk. Even with this proviso, the private energy companies will need incentives and a dependable regulatory framework to make a stable basis for investment. However, in Canada, there are no long term regulations. There are existing rules for the abandonment of EOR facilities, with liability being handed over to the state. The company retains liability for negligence for eternity, or until it ceases to exist, as most companies do in the long term – the world's oldest companies are only 300 – 400 years old. Alberta has a 'orphan well' fund that deals with leaking wells after the demise of the parent company.

Can the Bellona model work with just CCS, not EOR? No. Can you put a financial value on the environment, to offset costs of CCS? You can, but unless someone is prepared to pay it, the energy companies aren't going to be interested.

Canada is committed to a 6% reduction in emissions through the Kyoto agreement, but is predicted to be 20% over target by 2012. Will CCS close the gap? Reductions are hoped for, in equal proportions, from the public, from external purchases of carbon credits, and from the final emitters. The new Canadian Government will probably opt for CCS rather than lifestyle change, but probably still will not make the target.

Linking CCS to EOR means it is inextricably linked to extra carbon emissions, not to a reduction. What can be done? Long term, these extra emissions need to be stopped. Storage becomes more practical as CO_2 cost drops. If CO_2 has a 35 $/ton value then CCS works. Costs may be reduced by the GE H_2 production method, to 15 $/ton or mid 20 $/ton CO_2; Kvaerner in Norway has an operating post-combustion method already producing 23 $/ton CO_2.

How important is immediate, practical, experience in building and running CCS schemes? Very important! China for example will not follow advice from the west unless we can show that we are taking our own medicine. We need full scale plants, not just pilots. If we decide to go ahead today, a CCS scheme will come on-stream in 2012, so there is a considerable delay. It is also very expensive. It is the responsibility of scientists to inform politicians.

Afternoon Session

7) Hydrogen power and carbon capture and storage

Lewis Gillies of BP Alternative Energy talked on **"Hydrogen power and carbon capture and storage"** to open the afternoon session. Lewis's overview explained that we cannot, as yet, conceive a world which does not rely on fossil fuels. Recently, BP realised that a great deal of research had been undertaken on reducing emissions from the transport sector, such as fuel cell cars. However, very little research had been completed on the power generating sector. This is a major source of global CO_2 emissions and currently accounts for 40% of UK emissions. BP made a conscious decision to target reduction of the power sector emissions having noted that three of the wedges from the Princeton model for stabilising global CO_2 levels are in the power sector. 35 Decarbonised Fuel projects have been identified worldwide. BP aims to invest $8bn in the next 10 years to become the largest solar and wind generating energy company in world.

Lewis then went on to outline the details of the Peterhead Project. This will use natural gas to produce hydrogen which will then be used as fuel for a new purpose built power station. CO_2 will be separated from the natural gas prior to combustion. After processing and compressing, a 250 km pipeline will transport the CO_2 to the Miller field in the North Sea whereupon it will be injected to enhance oil production (commonly known as Enhanced Oil Recovery - EOR). BP proposes to inject up to 1.8 Mt of CO_2 per year and to recover 50-60 million barrels of oil. Lewis stressed that there was nothing in the project which doesn't already operate at this scale but the technology has never before been integrated on a single site and the challenge is to make it all work together.

In the final portion of the talk Lewis outlined why the UK needs to consider carbon capture and storage (CCS). Primarily this is because the UK government has a legal commitment to the Kyoto treaty and reducing CO_2 emissions. The CO_2 reduction from the 475 MW output Peterhead power plant with CCS would be equivalent to ALL of the onshore wind farms in the UK during 2005. It is also an opportunity for the UK to set an example to China, India and other developing nations that CCS is viable on a large scale. Lewis stressed that at present the infrastructure for carbon storage is in place at the Miller platform which will be decommissioned in the next 2 years. Building a new pipe from Peterhead to Miller would have cost $350 million. Use of Miller will save $200 million in decommissioning costs, which would be required to develop a non-producing field.

Lewis finished by outlining that the project is at present cost competitive with wind generation and that these costs could be further halved in the near future. BP has spent $50 million on researching the economics of the Peterhead project and Miller field, and they are confident that this is real viable project, not just a desk study. However, this is dependent on the energy produced by the project being purchased from them at a price equivalent to that of wind power. Electricity cost would be $90 MWhr initially, reducing to $45 MWhr through learning. The CO_2 costs $10 per ton to deliver to Miller, and the EOR oil price used was $40/barrel. The project will also provide BP and the UK with experience of working with hydrogen, a gas which will be extremely important as we reduce our fossil fuel consumption. Construction of the plant could begin as early as February 2007.

Lewis's take home message was that a government framework is needed (for low carbon electricity – like ROC for renewables), and public support is required to make the Peterhead project viable. Willingness to spread the cost of the more expensive low carbon electricity over the entire population would only add pennies to the general public's energy bills.

8) CO_2 storage, leakage and verification.

Dr. A. K. (Tony) Booer of Schlumberger Carbon Services focused on **"CO_2 storage, leakage and verification".** This second talk of the afternoon commenced by explaining that subsurface CO_2 capture stretches the usual oil field practises of characterisation and monitoring through extension of space scales (from rock pores to the reservoir, as a focus of interest, to the overburden and wider basin-scale extent) and requires much longer time scales than previously considered in oil fields. He went on to state that although CO_2 in the surface has favourable properties to enable measurements, the challenge of limited access (from the surface or wells) makes direct measurements and interpretation difficult. Modelling is used to fill in the blanks, but this brings limits to what can be predicted in terms of performance.

Tony highlighted that full characterization is an essential part of the selection process. Importantly, he made clear that there is little point in monitoring if the system being monitored is not well understood. However, the process of selecting a suitable storage site will mean that the system should be well understood. The storage site selected will be the fundamental influence on performance and monitoring strategies. Performance and risk analysis will drive, and will be driven by, measurement techniques which are backed up by modelling and simulation.

A key consideration of monitoring technologies is that storage sites are not designed to leak, and leakage, if it does occur, arises from unknowns that can't be modelled deterministically. Thankfully, Schlumberger believe that the risks can be determined statistically. Caprock, fractures and wells are all possible points of failure, but leakage along wells (particularly old, abandoned ones) is seen as the most likely. The better characterised the site, the better designed, the lower the risk. Existing wells are probably the highest risk leakage paths. However, wells can be instrumented for leaks although mature oil & gas reservoirs may have a large number of oil wells.

Tony highlighted that acoustic methods are especially suited to monitoring gas in the subsurface, since modest amounts of CO_2 can make significant differences in acoustic velocities or impedance. He then went on to mention other monitoring methods including seismic surveys, which are useful in monitoring wide scale distribution of the CO_2 plume in reservoirs and ultrasonics which can be utilized in boreholes to monitor casing and cement condition and potential hydraulic leakage paths. He mentioned that cross-well electromagnetic surveys can also be used to monitor the displacement of a fluid between two wells. However, although high quality images can be obtained, the geometric constraint of requiring two wells with an intersecting piece of reservoir between them can be limiting. Micro-seismicity is another acoustic technology which can be used to map the boundaries of growing fractures – perhaps useful for caprock integrity monitoring. In addition he mentioned that it is also possible to obtain physical samples of fluids from the formation around a borehole enabling direct measurement of the rocks' physical properties. He stated that conventional logging methods, such as the spectral analysis of gamma rays, could also be used to identify carbon and oxygen signatures from formations around wellbores.

In the final section of his talk Tony focused on the role that modelling has to play in interpretation of monitoring measurements and confirmation of performance and risk parameters. During the lifetime of a storage site operation it is hoped that the needs for regular monitoring may decline steadily as greater certainty about subsurface conditions and the migration of CO_2 develops. A final survey to verify safe storage of the site is expected to be required before the presumed transfer of ownership and liability of the site back to the state.

Tony's take home message was that CCS is the world's most viable opportunity to reduce CO_2 emissions from fossil fuel and therefore we should start now and we will learn by doing.

9) Bio-fuels for co-firing: assessing the environmental cost

Dr. Richard Tipper of the Edinburgh Centre for Carbon Management talked on: **Bio-fuels for co-firing: assessing the environmental cost.** This third talk of the afternoon session outlined that bio-energy is the worlds 4^{th} largest energy resource which accounts for ~14% primary energy worldwide and much more in developing countries (70% of primary energy in Africa is from bio-energy). Another example is Brazil where bio-ethanol is used for transport and electricity generation. Bio-fuels represent a considerable global resource which could be equivalent to burning 1 billion tonnes of oil. In the UK policies are being implemented that will require fuel companies to supply more than 5% of transport fuel from bio sources.

Richard then moved on to talk about the key choices that need to be made to increase bio-energy production. These included what land should be used for growing additional crops taking into account productivity, rainfall, other crop uses, proximity to demand and alternative land uses. Other key choices mentioned were which crops should be grown, what form of energy should they be used to produce (heat, transport or power) and by what process (combustion, fermentation, esterification, gasification, pyrolysis). He went on to say that co-firing capability is now installed in most UK power stations and that the majority of biomass burnt in the UK is from waste. Currently wood chippings are only slightly more expensive than coal (wood is £50 per tonne, coal £31) but due to uncertain government policy and a resulting lack of investment wood chippings remain a relatively unpopular fuel source. In 2005, the UK burned 1.4 Mt of biomass, generating 1.5GW electricity. Coal costs £10 / MWhr plus £1.43/MWhr Climate Change Levy; wood costs £35 /MWhr with a £40/MWhr ROC available.

Richard also outlined the environmental concerns associated with biofuels including carbon balance (land use changes, intensive farming), Biodiversity (monoculture), sustainability of management (are trees being replanted fast enough?), water resources and local pollution. Another important consideration is the actual carbon emission reduction per tonne of biomass which primarily depends on what bio-fuel is used and what it is replacing. He stated that co-firing can avoid almost 2 tonnes of CO_2 for 1 tonne of burnt biomass compared with coal and the best use of biomass is for local heating, instead of electricity. Also there is a strong possibility that bio-fuels could be combined with CCS for additional carbon reduction benefits

In his summary section, Richard highlighted that optimising CO_2 reduction from bio-energy is not an easy task. His take home message was that whilst local sustainability issues are extremely important and should be taken into account, bio-energy needs to be considered as part of the energy mix both in this country and globally.

10) "CCS developments in China".

Dr. Jon Gibbins from the **UK consortium on carbon capture and storage, Imperial College, London,** talked on "**CCS developments in China**". In this final talk of the session, Jon highlighted that China is an example of potential 'carbon lock-in' as a large number of fossil fuel power stations are being built between now and 2020. China has a key role to play in the drive to move the world to a low carbon economy, and the Chinese know this. The Chinese government are prepared to co-operate with the developed nations on CCS and this has resulted in a number of meetings, both international and Chinese. One of these was the APEC study completed in 2005 which identified CO_2 sources and possible sinks in China and concluded that there is a reasonable match between sources and sinks in the country. However the complex geology would require a detailed survey prior to any project being undertaken.

Jon went on to highlight some of the other collaborative projects which have been undertaken including the joint UK, China and EU near zero emissions coal project and the COACH project which investigated the potential to produce hydrogen. Jon also highlighted that there are a number of projects ongoing in China regarding conversion of coal to liquids and that by 2020 the country expects to account for a quarter of their oil demand in this way! 500 gasifers will be required for this and without CCS this will significantly increase the country's CO_2 emissions.

In his summary Jon pointed out that China is not going to put any of its own money into reducing CO_2 emissions at the minute as it will weaken their position in post Kyoto negotiations and also that the country has far more urgent priorities than CCS. However, the country is keen to take action, has a 'can do' attitude and will accept international support. At present any projects are in the early stages but goals and stakeholders have been identified and project selection criteria is in the process of being implemented, with an intention to generate electricity with a demonstrator by 2014. Jon stated that in order for any project to go ahead, confidence needs to be build up to prove that someone will actually pay the going rate for near zero emission coal in China. Another critical factor in China's decision-making is the agenda on CCS in the UK/EU and US. China is keen to be seen to be 'using state of the art' technologies and would welcome any examples set by the developed nations.

DISCUSSION

In the discussion, the question of what the speakers thought the UK should be doing with regard to CCS in an ideal world was raised. There was a common consensus between all the speakers that the UK should take advantage of the North Sea and act on potential collaboration with Norway and other European nations to set up real projects on saline aquifers. Enhanced Oil Recovery will not be useful forever and therefore potential sites for specific CO_2 storage need to be investigated. It was agreed that the opportunity to implement CCS is here now and therefore needs government action now. Action means that the government should facilitate build up of CCS plants, and whilst the country may need another energy review in next 5 years, CCS can buy us time and open up options for the future. It was agreed that the government needs to set up a simple policy on the future role of CCS.

The question of sub-sea CO_2 leakage and the possible effects this leakage on the marine environment was raised by the floor. This was answered by the panel by explaining that a program to monitor the effects of CO_2 off the Norwegian coast is already in place and a reassurance that, with a proper monitoring system, leaks can be detected. It was also highlighted that North Sea is a well known site in terms of geology but also of ecosystems, the locations of vulnerable sites are known and can be monitored.

A number of concerns were raised over bio-fuels including damage to the environment through the increased growth of plants and if there actually was a need to combine bio-fuels with CCS. This was addressed by the panel explaining that the nitrogen and carbon cycle are closely linked and that it is not likely that trace elements would be depleted by using bio-fuels. It was highlighted that climate change will also effect plant productivity, possibly by increasing productivity but also potentially causing more droughts. It was noted that it would make more sense to combine bio-fuels with CCS in order to take CO_2 out of the atmosphere on a large scale.

The issue of whether China would see the reason to build CCS ready power stations when the rest of the world has not done so was also raised by the floor. This was answered with a reassurance that China are aware of the reasons that exist for reducing CO_2 emissions and provided they do not have to spend their own money they are happy to collaborate with international investors on CCS.

The issue of whether pre-combustion, as outlined for the Peterhead project, is the cheapest method for carbon capture was raised. This was answered by stating that BP had chosen the technique on space grounds (requiring a seventh of the area needed for post-combustion capture) and because they believe it has the best opportunity for cost reduction in the future. It was pointed out that at present very few carbon separation plants exist and that the price of CO_2 capture is predominantly dependent on handling the CO_2 and refractor failures; knowledge transfer and technique development can improve both of these issues and it is anticipated that the costs will fall.

Finally the question of whether existing technologies are sufficient to monitor CO_2 storage sites for thousands of years was raised. This was answered by the panel stating that models still need to be further developed as there are many different scenarios of CO_2 migration that need to be considered. Running simulations for the longer timescales required for carbon storage is a unique challenge which needs to be addressed. Geochemical models also need to be developed to predict CCS specific scenarios, for example, potential salt deposits in injection fluids which could inhibit injection. On the issue of monitoring timescales it was highlighted that monitoring should not be for its own sake and could be tapered as the time from CO_2 injection increases and possibly could be stopped altogether if the site was believed to be fully understood. An analogy of smoke detectors in the home was given by the panel: hopefully they'll never be used but it's useful to have them just in case and similar principles will apply in monitoring potential CO_2 leakage!

The meeting was closed by Prof. Stuart Haszeldine who praised the wide range of subjects covered by the talks and the short term and long term ideas and projects that were detailed by the speakers.

Finally, in a return to the initial question posed at the start of the day, a motion on whether CCS is a technology that could add to sustainability of the UK energy mix was proposed and put to the vote. The motion was carried by approximately 80% of the attendees.

Documentation:
Morning: Dr Mark Wilkinson (University of Edinburgh / UKERC)
Afternoon: Dr Stuart Gilfillan (University of Edinburgh / SCCS)
Editorial: Professor Stuart Haszeldine (University of Edinburgh / UKERC)

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