DECC Science Advisory Group
Briefing Note on Carbon Capture and Storage

This SAG briefing note considers a suite of topics relevant to the development and deployment of carbon capture and storage (CCS) for low carbon electricity generation in the UK. Some of these topics have immediate urgency; others need to be attended to within timescales of about 5 years.

The purpose of CCS development in the UK is four-fold:

- *firstly* to enable a rapid and deep decarbonisation of electricity and heat generation in the UK by evolving from existing technologies
- *secondly* to provide exemplars that these technologies are commercially possible, to support UK global policy on CO_2 emissions reduction for climate change target
- *thirdly* to create a very controllable and flexible option for low carbon electricity generation in the UK, which can assure continuous power production in a carbon-constrained market responding to variable demand and otherwise supplied by high cost and variable offshore wind power and lower cost, but essentially fixed output, nuclear power
- *fourthly* to create a profitable market for storage of CO_2 from other EU nations and to give the UK a lead in CCS technologies that can be exported as goods and services.

Funding CCS through EMR

This is urgent because policy is being determined at present. It is generally accepted that Electricity Market Reform (EMR) should support deployment of renewables, nuclear and CCS in the UK. The characteristics of CCS differ from those of other low carbon generation and therefore CCS needs a financing package in the EMR which can deal with: 1) variable fuel prices as a large component of final electricity price, 2) maintenance and operation of reserve generation capacity to infill between wind generation shortages, and so operating at 30-60% capacity annually, 3) adaptation of pricing during the timespan to 2030 within the same constant policy framework, to reduce the subsidy as carbon base price increases through time.

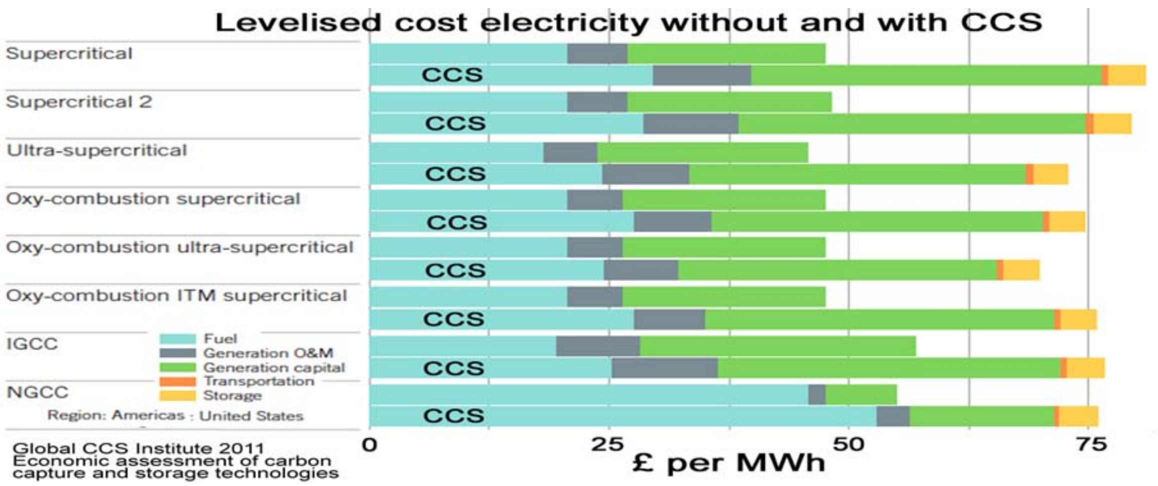
CCS is an emerging generation technology, which is not yet commercially deployed, and which is expected to see considerable learning-by-doing following deployment. Consequently CCS needs support that will: 4) compensate for the first-of-a-kind costs and risks taken by early developers as well as lesser profit for later (lower risk) developers, 5) encourage the deployment of new technologies, 6) provide appropriate levels of return for transport and storage and the scope for these to act as separate business; storage in particular may require a much higher rate of return to balance technical and regulatory risks than operating power plants.

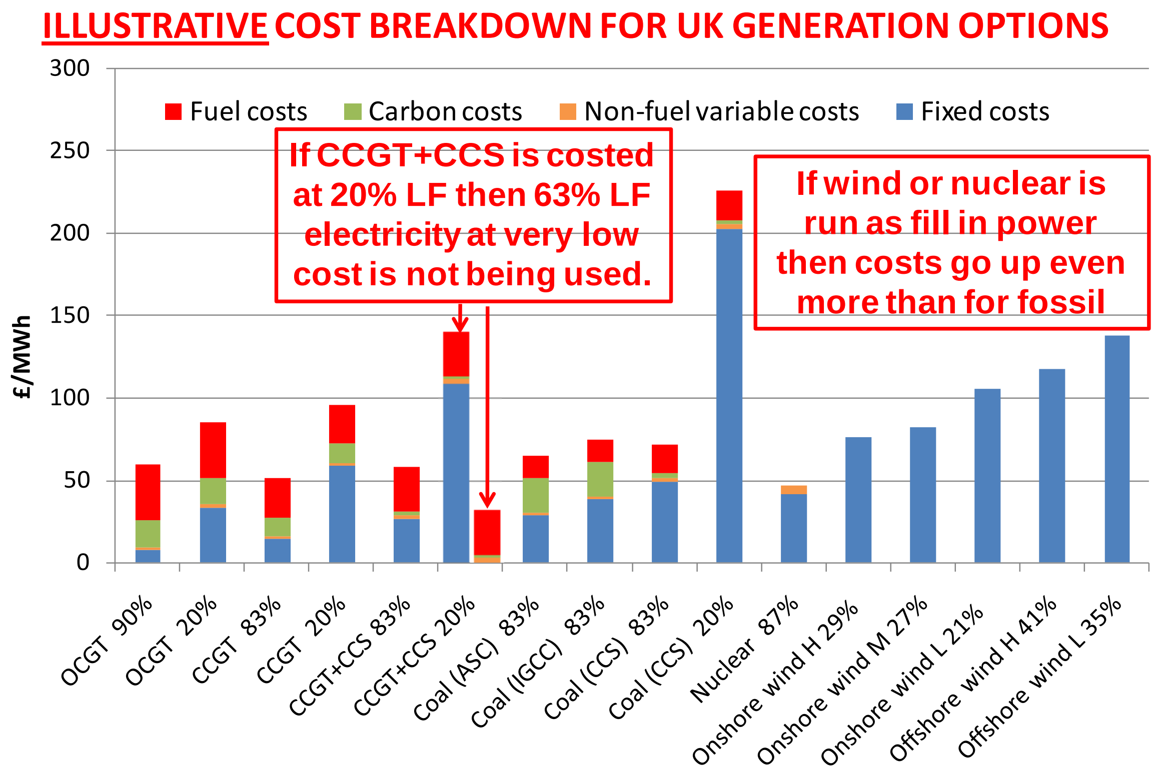
If government support does not provide suitable incentives for early developers with the first 4 to 8 UK projects, then there may be no CCS development in the UK.

Pricing CCS, as CO_2 or kWh?

Although CCS costs are often quantified in terms of cost of CO_2 abated (e.g. £ per tonne of CO_2) an alternative method is to price the low-carbon electricity provided in pence per kWh. This provides comparability and a level playing field compared to other low carbon generation technologies. The total effect of generation and subsidy costs (such as Renewable Obligations (ROC), or Contract for Difference) can be summed into a final electricity price for simple comparison. This is also more relevant for a commodity where a liquid market is willing and able to make purchases.

The CCS landscape can be potentially confusing, because rival CO_2 capture and power plant technology variants need to be evaluated. However, by chance, the final electricity costs from the three main coal fired technologies and post-combustion capture from natural gas plants appear to be similar [e.g. IEAGHG, 2006]. Inevitably these calculations are made on assumed modal fuel process and annual hours of plant availability, and into the future these will vary. But this does open the possibility of pricing CCS on mechanisms based on electricity price rather than on CO_2, and then leaving the judgments on capture type and fuel source to individual developers. A price per kWh also enables easy comparison with estimated costs for other renewable energies (e.g. RedPoint 2009, Mott MacDonald 2010), where it can be seen that CCS is bracketed as costing more than onshore wind, but less than all offshore renewables.





Based on *Redpoint: Decarbonising the GB power sector: evaluating investment pathways, generation patterns and emissions through to 2030, A Report to the Committee on Climate Change, September 2009.*
2008 capital costs, assumed £30/tCO_2 carbon price, gas price £12.5/MWh_{th}, coal price £6.25/MWh_{th}. 10% interest rate
(J. Gibbins presentation to SAG 15/7/11)

Build Rate for CCS

Following consideration by the CCC (Committee on Climate Change) 3rd budget report (2010), the UK has now undertaken a commitment to reduce CO_2 equivalent emissions by 50% from 1990 levels by 2025[1], with the option of international emissions trading kept open. This was chosen to be on the pathway to 80% decarbonization by 2050. As part of this, the CCC recommends that GHG emissions from electricity generation should become an average of 60 g of CO_2 per kWh (gCO_2/kWh) by 2030. This is a difficult challenge, even with proposed new build nuclear plant, and proposed abundant wind and potentially wave power. Current knowledge shows that wind power produces a variable output of electricity, which could not be compensated for by nuclear plant without running the latter at reduced load factors, requiring significant additional construction costs and also inherently higher capital charges per unit electricity[2]. Energy storage is insufficiently developed in the UK (which lacks a large indigenous hydroelectric capacity) to fill this gap in between supply and demand, so that a large fleet of fossil fuelled power plant will still be required to balance supply and demand into the foreseeable future. If the assumption is made that nuclear provides baseload for 50% of UK demand (30GW), and wind power operates at 33% capacity, then fossil fuel with CCS will be required to provide an average 50% capacity for 66% time. Consequently on these assumptions[3] a capacity of 30 GW fossil will be needed – more if a large nuclear

[1] That is, on average over the period 2023 to 2027
[2] Dump condensers could be added to nuclear power stations which would allow them to respond very fast, but this would add cost.
[3] Other combinations of installed capacity and load factor would be possible

build is not realized or the projected increase in demand from electric vehicles is not reduced by efficiency gains in domestic buildings. As an analogue for the feasible build rate of CCS plant, good data exist (DUKES, 2010 Ch 4) for gas plant construction during the 'dash for gas', 1990-2000. This shows 23.3 GW of capacity was built during 10 years, ie an average build rate of 2,400 MW/yr.

How could 30GW of CCS be constructed in the UK by 2030? Several forward-looking projections have been made, based on assumptions of CCS price, build rate, and storage availability. Poyry (2009) work for the CCC predicts 18GW of CCS capacity by 2030, using only gas and oilfield storage. Element Energy for DECC states that 35GW of gas fuelled plant could be operated as CCS by 2030, A CCC median scenario for 2030 predicts just 10 GW CCS. All of these predictions are passive consequences to the types of legislation currently existing in the UK, and consequently are capable of being accelerated if there is a strategic requirement and preparations are made early enough – which means in the very near future if there is to be an option of high rates of build. For the purpose of this discussion, four scenarios illustrate possible pathways.

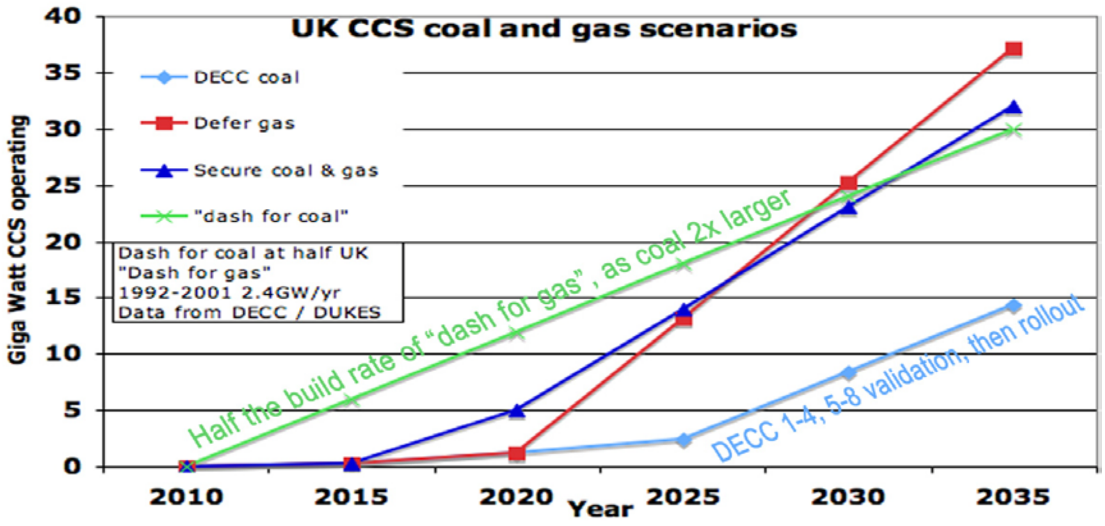
1) This scenario builds on Government's commitment to public sector investment in CCS technology for four power stations. It is expected that all four projects will be operating by 2020. Assuming these projects are doubled by 2025 to validate results with reference plant designs, resulting in 3.2 GW of CCS. New coal and new gas is then constructed with operational CCS. The rate of build is projected to be half that of the dash for gas to recognize that the size and cost of coal plant per MW generation capacity is approximately double that of gas. That produces about 8 GW of CCS by 2030. That pathway is shown by the pale blue line on the graph below. This delivers much less than 30 GW CCS by 2030.

2) In a second scenario there is also one 400 MW demonstrator, followed by three additional CCS projects operating by 2020. At this time, the capital costs of coal plant are large, and the international availability of gas is reliable and cheap due to continuing unconventional gas production. Industry elects to continue a dash for gas, resulting in retrofitting of 25GW natural plant with CCS by 2030. This is the red pathway on the graph below. This achieves the target, but results in the UK using imported gas with no imported coal. Additional coal plants, linked to the CCS infrastructure that would then be in place, would probably have to be built subsequently to reduce reliance on gas.

3) Scenario three assumes policy changes to specifically encourage and incentivise new build coal plant with CCS with immediate effect. At a build rate half that of the dash for gas (recognizing the size and cost of coal plant being larger than gas plant), about 25 GW become available by 2030. This is the green pathway on the graph below. At present this policy change seems unlikely to occur: without it this scenario illustrates the impossibility of reaching the CCS target using coal alone.

4) In scenario four, DECC policy continues with four demonstration plants being built, as at present, with CCS on coal and gas. These are augmented by an additional eight units (possibly by cloning on the same sites), to reach 5GW of CCS by 2020. A similar build rate, with a mix of new coal and retrofitted gas operating with CCS (this mix determined by the then-prevailing relative costs of coal and gas), continues, to

reach 25GW of mixed generation with CCS by 2030. This is the dark blue pathway on the graph below. It achieves UK policy by both advancing low-carbon fossil fuel generation technologies and maintaining a mix of fuel sources to enhance energy security. However this will only be feasible there are sufficiently strong signals of government ambitions on CCS, backed up by the necessary financial and other support, to encourage industry to plan, construct and operate around 5GW of CCS capacity by 2020. ..



CO_2 Storage

Most attention has so far focused on the capture steps in the CCS chain, and the associated costs and implications for commercial operation of power plant. However CCS requires geological storage to be operational at the same time and to have been identified in advance of capture and transport investments. This cannot yet be guaranteed at the required scale for large-scale deployment of CCS, but with suitable validation work it is expected that an abundance of storage can be made available beneath UK offshore waters.

Regulatory issues: All storage of CO_2 within the EU will be governed by the CCS Directive (2009). This tends to over-specify and over-regulate CO_2 storage at this early stage. The first of these is a requirement that *"all available evidence indicates that the stored CO_2 will be completely and permanently contained".* That is coupled with *"(a) conformity of the actual behaviour of the injected CO_2 with the modelled behaviour; (b) the absence of any detectable leakage; (c) the storage site is evolving towards a situation of long-term stability".*

The first statement is geologically impossible to guarantee for timescales of millions of years into the future. An adjustment has been made by the EC issuing guidance document 4 on March 2011. This creates two options i) for Member States to take devolved judgements on the quality of evidence needed to assure storage; ii) for Member States to take on liability for any future leakages of CO_2 outwith the designated subsurface volume of the storage site. However, the UK (and DECC as license giver) will need to adjust policy to deal with the implications, and create capacity to undertake this work required.

If the UK wishes to enable and accelerate the storage of CO_2 required for CCS, then decisions that address both the quality of evidence required and liability for leakage will be needed.

Monitoring: To undertake the types of detection required by the CCS Directive, then accurate and precise monitoring of CO_2 locations in the deep subsurface is required. Although some 20 experiments of CO_2 injection have been undertaken worldwide, all of these have been beneath a land mass, such that a diverse suite of low-cost monitoring techniques are available and are being developed. However if CO_2 is stored around the UK in geological settings beneath the chalk, or beneath evaporite salt deposits, then most existing onshore monitoring techniques are excluded, and the established high-quality seismic reflection imaging widely used offshore not give sufficiently precise results. During the global process of technique and tool evolution, it will be necessary to create test facilities in rocks offshore. The UK government will need to allocate funds suitable to enable these developments to occur. These laboratory test facilities could be in UK waters, or anywhere globally, at costs of £20-60M. As with all such items, the hosting country benefits most from the IP spinoffs, and is most likely to recoup its investment.

A UK program of R&D work is needed to adapt existing sensors and to create new sensors and simulation tools specific to CO_2 beneath the seabed.

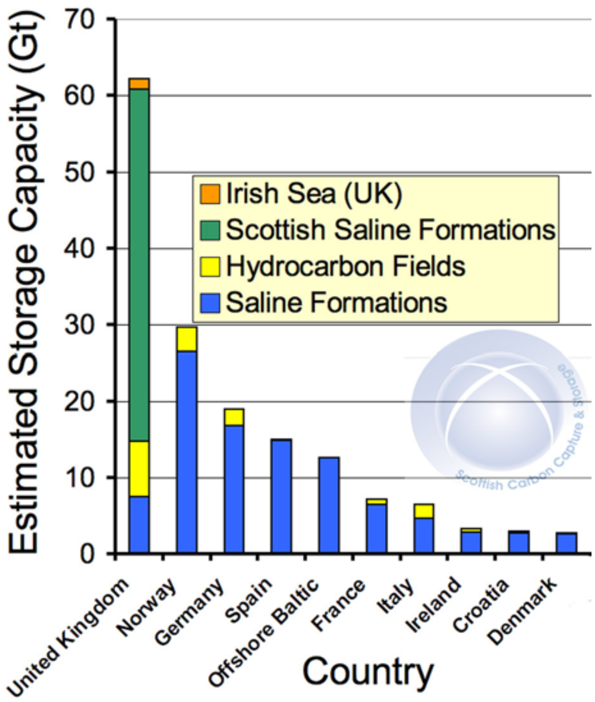
Storage capacity: There have been numerous surveys made of CO_2 storage on the UK continental shelf beneath the North Sea. Each survey provides a different assessment. Currently underway is the first comprehensive assessment of UK storage, funded by the Energy Technologies Institute (ETI) and due to report in September 2011.

The Poyry (2009) study for the CCC provides what is still a reasonable summary statement: “The storage capacity of deep saline aquifers needs to be assessed sooner, rather than later. There is likely to be insufficient suitable storage capacity in depleted UK oil and gas fields to support more than 10GW of power generation with CCS”

This should certainly not be understood as stating that the UK has limited capacity for CO_2 storage. Studies by the SCCS (2009), and underway by ETI have already shown that there is very large potential for CO_2 storage offshore of the UK. To prove this storage to the commercial satisfaction of power plant and pipeline investors is more difficult, but is advancing well in some North Sea regions (SCCS 2011).

It is clear that a very large potential resource of storage exists, with the UK holding about half the offshore storage available to the EU. Most of this is in salt water formations (saline aquifers). However it is also clear that very little of this storage has been validated by experiments injecting CO_2. The design and construction of experiments and the injection of commercial sized volumes of CO_2 are both required to validate this storage. The current rates of progress to assess commercially reliable capacity at an individual site show that saline formations require at least five, and usually 10, years to evaluate.

High quality validation of storage potential is barely available at this time and needs to be greatly accelerated.



Estimated storage potential in EU. The UK holds most potential, and this is in offshore areas which are technically capable of being developed, and have minimal public objection

If the UK wishes to accelerate the take-up and development of its exceptionally large geological storage potential, then promoting and undertaking validation injection experiments using the CO_2 provided from the DECC-1 and other CCS projects becomes a priority.

Cross-border transport

The UK and all EU Member States can undertake the first validation projects using existing laws and regulations. However it is apparent that 1) Onshore storage of CO_2 has been blocked by public opinion in crucial states of Germany, Netherlands and Denmark, and storage onshore has not been accepted in Poland, Spain or Italy. For CCS to have significant impact in the EU, it will be essential to transport CO_2 across Member State borders. Although now legal under the OSPAR Convention, this CO_2 transport is not yet legal under the London Convention main text – and only about three of the required 23 nations have ratified.

These are legal and political, rather than scientific or technical issues, but they will need solution before 2020 if the potentials discussed in this note are to be realised.

Capturing the CCS market

An important premise for short-term UK support of CCS investment now, is the possibility of creating skilled jobs in construction, design, and consultancy. For the FEED studies around Europe for NER 300, it is not at all clear that UK companies and businesses have gained significant contracts to work in other states. In the research sector, the UK has only a weak representation into future European funding via EERA.   In the research consultancy sector the recently formed TRI4CCS alliance between Norway, France and Netherlands <www.sintef.no/ccs-alliance> co-ordinates 450 experienced scientists onto CCS in a way that the UK cannot currently match.

The UK needs to consider whether, and if so how, the expertise of UK universities and especially of publicly funded research organisations can be focused to compete for global business at the scale of billion Euro projects, and then provide the necessary structures and incentives.

Global Activity in CCS

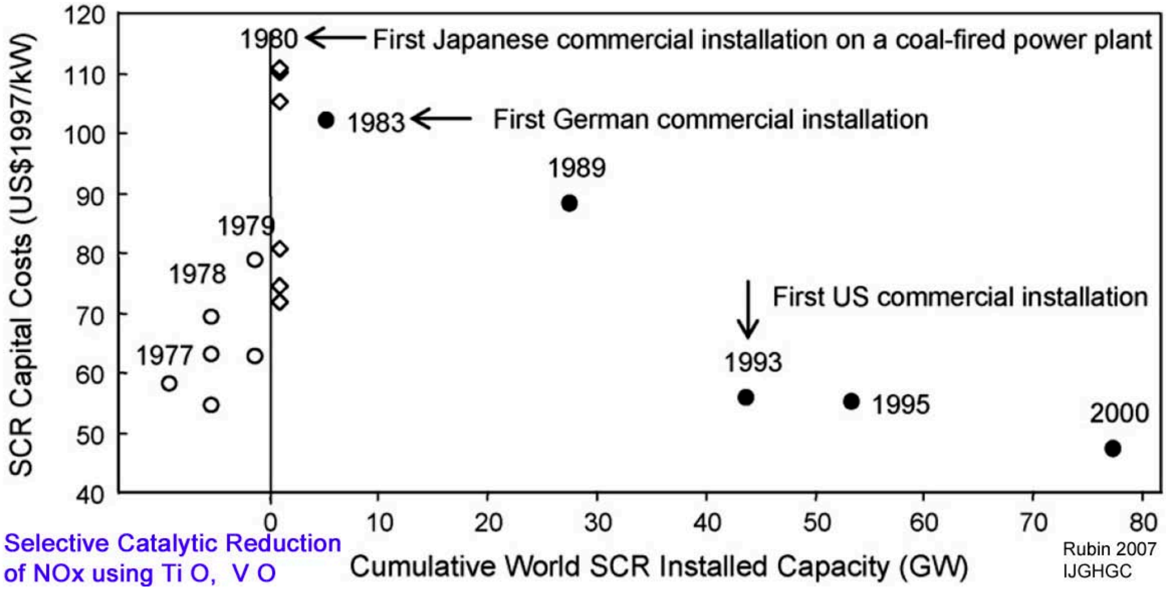
During the past five years, the EU, USA, Canada, and Australia have demonstrated interest in CCS projects Following the recent elections in Australia, the new government has maintained some support for research, but appears much less enthusiastic to fund real projects. Both the USA and Canada have received one-off stimulus money to support initial CCS projects, but only one small power plant CCS project (Boundary Dam, Saskatchewan) has so far reached a final investment decision. However neither country has yet created a method to support CCS on power plant after these initial projects. Consequently, it is likely that CO_2 - EOR (Enhanced Oil Recovery) projects will become the established route, due to the additional income from improved oil recovery. CCS is also likely to be applied to fossil fuel production (coal to liquids, oil sands, gas sweetening) rather than making low-carbon vectors (electricity, hydrogen, heat) if left to purely market forces.

Depending on the degree to which hydrocarbon substitution from different or more expensive sources occurs, a consequence of CCS being deployed largely in fossil fuel production and EOR may be that immediate full life cycle reductions in carbon emissions using CCS on a global level will be much less than present calculations predict.

Current UK Activity in CCS

It appears that several issues are conspiring which contribute to a slowing down of CCS activity in the UK.

Costs: Two comments can be made. Firstly it is to be expected that costing for a first of a kind (FoK) project will be conservative and exceed expectations, as engineers design additionally robust equipment, additional redundancy, to cover uncertainty in achieving reliability of operation. This means that cost reductions commence from a higher cost position than the initial generic estimates made beforehand on efficient routine plant designs. This is well illustrated from the compilation by Rubin (2007) on historical data for NOx scrubbing costs in the USA. By analogy, in 2009 the UK was at the lower left point (1977) on the curve, in June 2011, the UK is arguably at the highest point (1980) on the curve



Rubin, International Journal of Greenhouse Gas Control, 2007, 188-197

Secondly, anecdotal experience from the innovation, design and operation of complex industrial equipment suggests that if an over-budget (and over-designed) version of FoK plant is built, then after a time span of several years learning, this plant may function at better than its design capacity.

Work Teams: UK business activity on practical CCS projects has greatly reduced. Several large teams were created during the DECC bidding process, however some of these have already started to dissolve, and others are in the process of dissolution. Several companies in the UK which have not managed to gain involvement in the DECC competition have reduced, or even cancelled, CCS activity to await the outcome of DECC-1, and the outcome of the protracted NER-300 process and EMR. The only thriving CCS markets are in consultancy, reviews and desk studies, and research.

If the UK wishes to create a CCS industry, this is an already clear message that continuity of build-rate is essential to keep skilled teams together.

Jobs: The number of jobs of highly skilled staff in CCS has now become a significant point of interest for public, business, and especially media. Data now exist to historically measure the number of staff employed during FEED for both Longannet and Kingsnorth projects; these are thought to peak at about 400 per year. Two development agency studies of potential employment have concluded that three projects, on post-combustion coal and gas, would employ 5,000 people during construction and 400 during operation (Scottish Enterprise 2011); secondly the anticipated UK employment during construction of 10% of global objects would be 20,000 (SCCS 2011). It is apparent that most CCS jobs are related to construction of the capture plant and transportation system. Also, that CCS is anticipated to employ many fewer people than onshore or offshore wind power projects. The historical data suggest that these may be maximum estimates.

Investors: On the positive side, the UK has seven of 15 projects entered into the EU NER-300 competition for funding support. This demonstrates confidence that project scoping and outlining stages are supported by UK statements on funding plans and especially by the ability of the UK to license projects with viable storage options.

Country	Project	Key partners	EU public funding		Other public funding	Legislation in place?	Fuel type	Capture type	Storage type
			EEPR	NER300/1					
France	Grandranges	Arcelor Mittal	×	Applied			Industry (steel)		Gas reservoir?
Germany ●	Jaenschvalde	Vattenfall	€180m	Applied		Problematic (Länder opt-out clause)	Lignite	250MW oxyfuel and 50MW post-combustion	Onshore aquifer/gas reservoir (tbc) 1.7 MtCO2/yr
Italy ●	Porto Tolle	Enel-Endesa	€100m	Applied			Coal	264MW post-combustion	Offshore aquifer 1~MtCO2/yr
Netherlands	Green Hydrogen / Botlek	Air Liquide, Maersk	×	Applied for €211m	NL govt €60-90m		Industry	Crogenic	Offshore (trans-national shipping to EOR/gas reservoir in Denmark waters)
●	ROAD	EON Benelux, GDF Suez	€180m	×	NL govt €150m		Coal	Post-combustion	Offshore gas reservoir
Poland ●	Belchatow	PGE, Alstom, Dow Chemical, PIG, Gazoprojekt, Schlumberger	€180m	Applied			Lignite	260MW post-combustion	Onshore aquifer
Romania	Getica	Alstom	×	Applied			Coal	Post-combustion (Ammonia tbc)	Onshore aquifer
Spain ●	Compostilla	Enel-Endesa, CIUDEN, Foster Wheeler	€180m	×	×	Yes	Coal	330MW oxyfuel	Onshore aquifer
UK ▲	Longannet	ScottishPower	×	Applied	UK govt £1bn?		Coal	Post-combustion amine	Offshore gas reservoir
▲	Peterhead	SSE	×	Applied			Gas	Post-combustion CCGT	Offshore reservoir
●	Don Valley (Hatfield)	2CO	€180m	Applied			Coal	Pre-combustion IGCC	Offshore EOR + aquifer
	Drax	Alstom		Applied			Coal	Oxyfuel	Offshore
▲	Hunterston	Peel Energy, Doosan Babcock		Applied			Coal	Post-combustion amine	Offshore
	(Killingholme)	CGEN		Applied			Coal	Pre-combustion IGCC	Offshore
	(Teesside)	Progressive Energy		Applied			Coal	Pre-combustion	Offshore

7 from UK, ▲ 3 Scotland ● 6 EEPR projects part-supported by EU

On the other hand, it is apparent that CCS is already a global market, and the UK has to compete against other EU Member States, and other global CCS nations, to obtain investment. It is also clear that the incentives are not enough to attract investment from major oil and gas operators, who are accustomed to profit margins of 20%. Because of the protracted nature of the UK competition, and the EU competition for NER, the small teams within large transnational companies are very vulnerable to dissolution, and these companies are ranking CCS projects in comparison to established money making ventures within, and especially outwith the UK and the EU. The possibility of "investor fatigue" at senior management and CEO level is very real, and could lead to sentiment that the opportunity cost of CCS development within the complex UK regulation and funding landscape, is not worth the potential small profit.

If the UK wishes to capture business investment for CCS in DECC-1, and to maintain CEO interest levels, then it will be necessary to create systems which can

> ***1) make rapid decisions on public support,***
> ***2) provide guarantees of medium and long-term stability of regulation,***
> ***3) make the system simpler.***

Of particular concern is the persistent lack of interest from established hydrocarbon companies. This means that

> ***4) pricing for increased profitability is essential if storage investigations and operatorships are to be undertaken.***

Summary of action points to deliver CCS in the UK

1) Electricity market reform and complementary mechanisms for early projects must deliver CCS pricing attractive to industry, or no projects will be built. Current pricing proposals provide inadequate rewards, especially for subsurface storage operators.

2) To maintain investor confidence, DECC projects 2-4 need to become more explicitly funded, with defined timelines.

3) To ensure the UK can reach the electricity decarbonization targets for 2030 requires 5GW of CCS to be operating by 2020.

4) Liability for stored CO_2 must be considered, and will probably have to be taken by the UK government soon after site closure.

5) Monitoring technologies are inadequate to detect stored CO_2 with the accuracy implied by the EU CCS Directive. Equipment development and testing is needed.

6) The UK has half the CO_2 storage potential in Europe. This needs assessment and 5-10yr proving by test injections to convert into an extremely valuable resource.

7) The London, Convention needs to be ratified to legalise international cross-border transport of CO_2 to enable use of UK storage.

8) Enhanced Oil Recovery needs legislative and tax regime clarity on changes of use from oil to EOR to CO_2 storage.

9) UK services for CCS in the global market need enhanced co-ordination to counter the well-planned delivery from EU consultancy consortia of national laboratories.

10) CCS should be priced in £ per MWhr of low carbon electricity, not £ per tonne CO_2. Pricing of low carbon electricity demonstrates relative competitiveness against other sources (e.g. offshore renewables).

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