The UKERC / UKCCSC CARBON CAPTURE AND STORAGE ROADMAP

Workshop Report, 1-2nd May 2007

Prepared and organised by:

Clair Gough
Sarah Mander sarah.mander@manchester.ac.uk
UKCCSC / Tyndall Centre for Climate Change Research, University of Manchester

Stuart Haszeldine s.haszeldine@ed.ac.uk
UK Energy Research Centre

Jane Palmer
UKERC Meeting Place, University of Oxford

www.ukerc.ac.uk
www.co2storage.org.uk
www.tyndall.manchester.ac.uk/

Carbon Capture & Storage Road-Mapping Workshop

1st-2nd May 2007, Salisbury Green Hotel, Edinburgh

Report contact: Sarah Mander – s.mander@manchester.ac.uk

The UKERC/UKCCSC Roadmap

1. Introduction

With the publication of the fourth assessment report from the Intergovernmental Panel on Climate Change, it is now clear that carbon emissions from fossil fuel combustion, industrial processes and from land use change are forcing an increase in atmospheric CO_2 concentrations (IPCC, 2007), and consequent acidification of world oceans (Royal Society, 2005). The highly influential Stern report made initial projections of future economic costs of mitigation and adaptation, and clearly showed the cost effectiveness of early action to reduce CO_2 emissions, hence atmospheric CO_2 (Stern, 2006). The UK Government has persistently stated that the UK wishes to take and keep a leadership position in EU and world efforts to mitigate climate change (Blair, 2004), as demonstrated by the world's first domestic legislation to make CO_2 reduction targets legally bindings on successive governments (DEFRA, 2007). The current UK goals are a 60% reduction in emissions by 2050, an interim target of 26%-32% reduction by 2020 and five yearly 'carbon budgets'. Achieving these milestones will require fundamental changes in how energy demand is conceived, coupled with low carbon fuels and alternative forms of supply. This is a global challenge; the Stern report (Stern, 2006) states that CO_2 levels of 450ppm will be reached by 2035, with a 77-99% chance of exceeding 2°C warming and hence the commonly-adopted definition of a dangerous level of climate change. The challenge could be even more severe than Stern predicts with recently published research highlighting that the rate of growth in CO_2 emissions between 2000 and 2005 exceeds the worst case IPCC 2001 scenario (Raupach et al, 2007).

This roadmap addresses a technology which decarbonises emissions from large point sources, with a focus upon electricity supply: Carbon dioxide Capture and Storage (CCS). CCS reduces CO_2 emissions through the "chemical capture" of CO_2 at central electricity plant (powered by coal or gas) with subsequent transport of CO_2 to a geological storage site. The technology is endorsed by the IPCC and UK government as a key mitigation option (IPCC, 2007; POST, 2005). UK support for CCS was announced in the 2007 Budget through "a competition to develop the UK's first full-scale demonstration of carbon capture and storage" (HM Treasury, 2007), which will operate from November 2007. There are currently more than nine proposals in the UK for full-scale CCS power plant proposing diverse capture options and storage sites[1].

Increasingly, 'Technology Roadmaps' are being developed for emerging technologies. These are intended to inform R&D planning and identify research, business, government or other strategic goals, supporting the future development of a particular technology; they typically include a graphical presentation of pathways for achieving these goals (Placet and Clarke, 1999). Several roadmaps have been developed for CCS by Australia (CO2CRC, 2004), Canada (CETC, 2006), USA (NETL, 2006) and the Carbon Sequestration Leadership Forum (CSLF). The roadmap process presented here, however, is the first of its kind specifically for the UK[2].

---

[1] Since the workshop, BP have pulled out of the most advanced UK based CCS project, the DF1 Hydrogen plant at Peterhead.
[2] The DBERR (formally the DTI) is currently developing a coal abatement technology roadmap that will include CCS; this is due to be published in the first quarter of 2008.

The aim of this UK roadmap is to 'join up' knowledge and understanding across the entire CCS chain. It has been developed following a workshop that brought together a diverse group of stakeholders and experts active in the UK CCS debate, from academic, industry, NGO and policy communities. It adopts a whole system (rather than solely technology based) approach and is intended to serve an integration and communication function, placing CCS within the context of relevant externalities, legislation and technical requirements. By its very nature, this CCS roadmap should be seen as dynamic – its content inevitably subject to revision and updating as both the technology itself and the broader landscape evolve. It provides an overview of the current system and indicates one view of possible trajectories towards the realisation of CCS as a significant component in the portfolio of climate change mitigation options for the UK.

This report describes the output of a two day workshop held in Edinburgh in May 2007, which followed an online technical survey of stakeholders and experts conducted during 2006 (Gough, 2007). Whilst it is intended to provide a comprehensive overview of the discussions that took place, participants also reached consensus over five key conclusions; these are presented in Section 2. Three graphics have been developed to synthesise the workshop discussions, representing the externalities relevant to the development of CCS in the UK, and goals relevant to the short- and long-term application of CCS in the UK respectively. This distinction between short- and long-term broadly reflects the transition from the pre-commercial application to full scale commercialisation of CCS, although frequently actions in the short-term are necessary to achieve the goals identified for the longer-term. The graphics are presented at the end of Section 2. To ensure that the full spectrum of the workshop discussions is captured in the report, the workshop conveners reflect on the overall outcomes in Section 3. A summary of the workshop process, including presentations from the UKCCSC/UKERC team is to be found in Section 4. An overview of each of the break-out group topics is contained in Section 5, with comprehensive notes of all the discussion within the Appendices, along with a list of workshop participants.

2. Key Conclusions

CO_2 value and the financing of carbon capture and storage schemes

The carbon savings resulting from CCS need to have a value, and workshop discussions focused on the EU Emissions Trading Scheme (ETS) as the primary mechanism to support wide-scale deployment. There are, however, other financing mechanisms, e.g. electricity price, and R&D into alternatives is required. Demonstration plants, operating by 2012, **will** need additional support over and above the EU ETS, which will have a greater role to play beyond 2012. To attain full-scale commercialisation of CCS in the UK, longer term mechanisms operating within the market system may be necessary. The overall purpose of such mechanisms should, however, be to provide viable market conditions for a low carbon energy system as a whole, reflecting climate change imperatives, and not be driven by the needs of one particular technology. The scale of a carbon market is important, and carbon pricing at the EU, rather than global scale, may impact on the economic position of the UK by favouring businesses in other countries.

Lack of technical barriers to the deployment of demonstration scale CCS plant

From a technology perspective, the UK is ready to demonstrate certain types of CCS plant, although issues related to the scaling up of the process and the continuously available operation of variable-load electricity generation combined with continuously available capture still need to be overcome. That said non-technical challenges remain in the short-term. These include: clearer definition of regulations and liability; better understanding of how a successful business model can be developed across the entire CCS supply chain; representation from developing countries during the demonstration phase to facilitate genuine collaboration; and the development of a framework for information sharing on demonstration projects in recognition of Intellectual Property issues (which in turn will depend on the level of public funding for a project).

Regulation and liability

Demonstration projects will be highly visible and, given that public perceptions of CCS will be formed on the basis of their performance, it is essential that these achieve the highest possible standards. Whilst a robust regulatory framework is required early on, different regimes could be adopted for demonstration projects and commercial scale deployment. Of key importance is determining liability, to cover potential leakage both during the active project and in the longer term. Demonstration projects have a crucial role to play in improving understanding of leakage and hence the extent of long-term liability. The DBERR will announce a regulatory consultation process in June/July 2007; this will be completed by the end of 2007.

Storage

The 'base-case' should be seen as straightforward storage of CO_2; whilst there may be additional opportunistic benefits to be gained from Enhanced Oil Recovery (EOR), there should not be a presumption towards it for the demonstration projects. Key storage issues are focused around leakage and developing techniques to monitor dissolved CO_2. Monitoring will need to be affordable, routine and of high enough resolution to contain leakage to within 'acceptable' limits as defined by resulting environmental impacts. The demonstration phase will inform the development of monitoring techniques, the specification of which will be aligned with environmental impacts (i.e. 'acceptable' leakage will both determine and be determined by monitoring technology). While there is considerable expertise in modelling storage processes there remain limits to modelling techniques. Leakage is an issue across the entire CCS system, though different standards and approaches will be appropriate for onshore and offshore situations.

A long term vision is required

The viability of CCS requires a long-term vision supported by an R&D programme. This should address both technical (for example capture costs, energy penalties etc.) and non-technical issues (such as regulatory framework, financing & carbon price, engaging developing countries etc.).

Three graphics have been developed to synthesise the workshop discussions, representing the externalities relevant to the development of CCS in the UK, and goals relevant to the short- and long-term application of CCS in the UK respectively. This distinction between short- and long-term broadly reflects the transition from the pre-commercial application to full scale commercialisation of CCS, although frequently actions in the short-term are necessary to achieve the longer term goals identified.

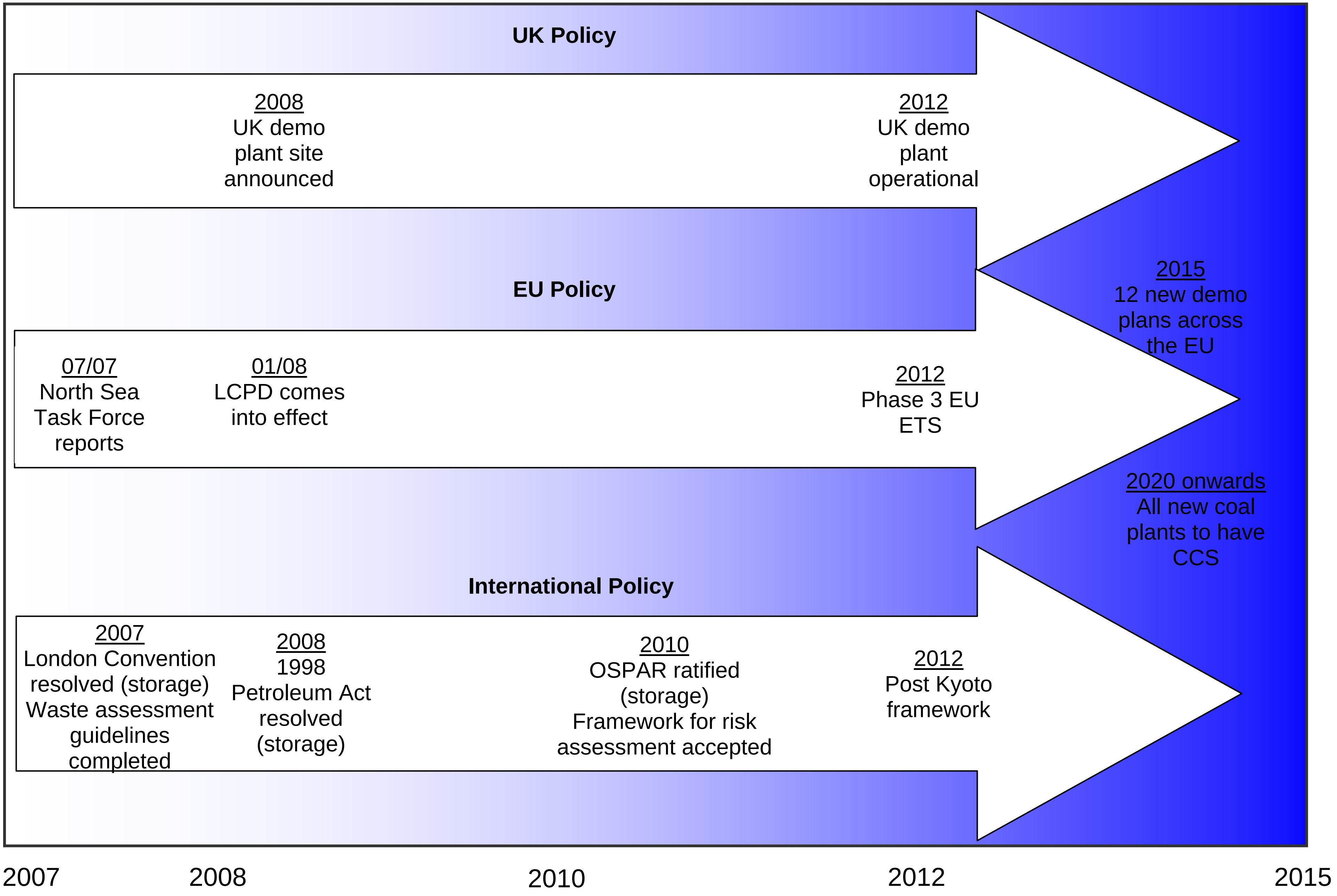


Figure 1. Externalities affecting the implementation of CCS

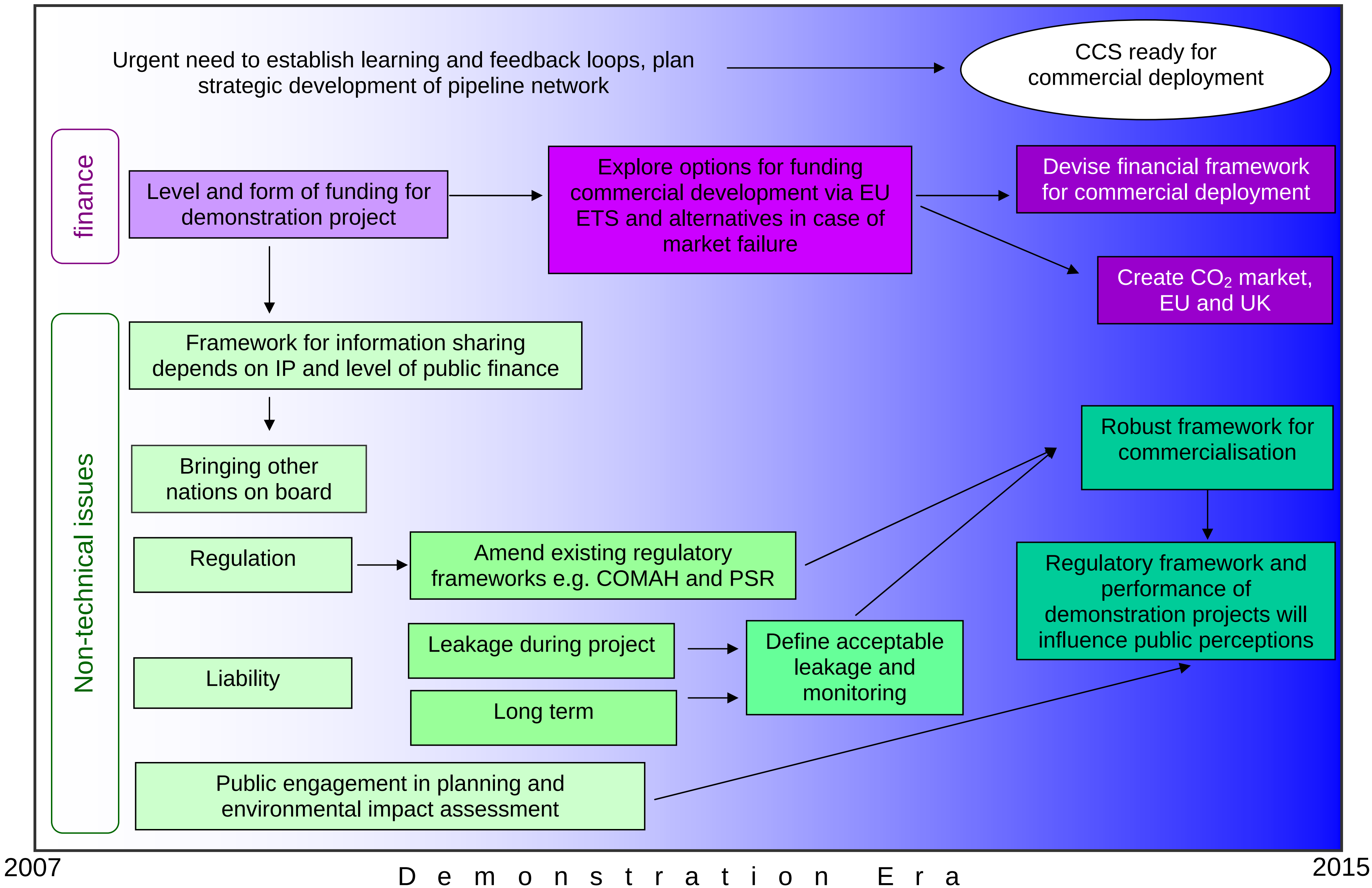


Figure 2. Short-term CCS road map

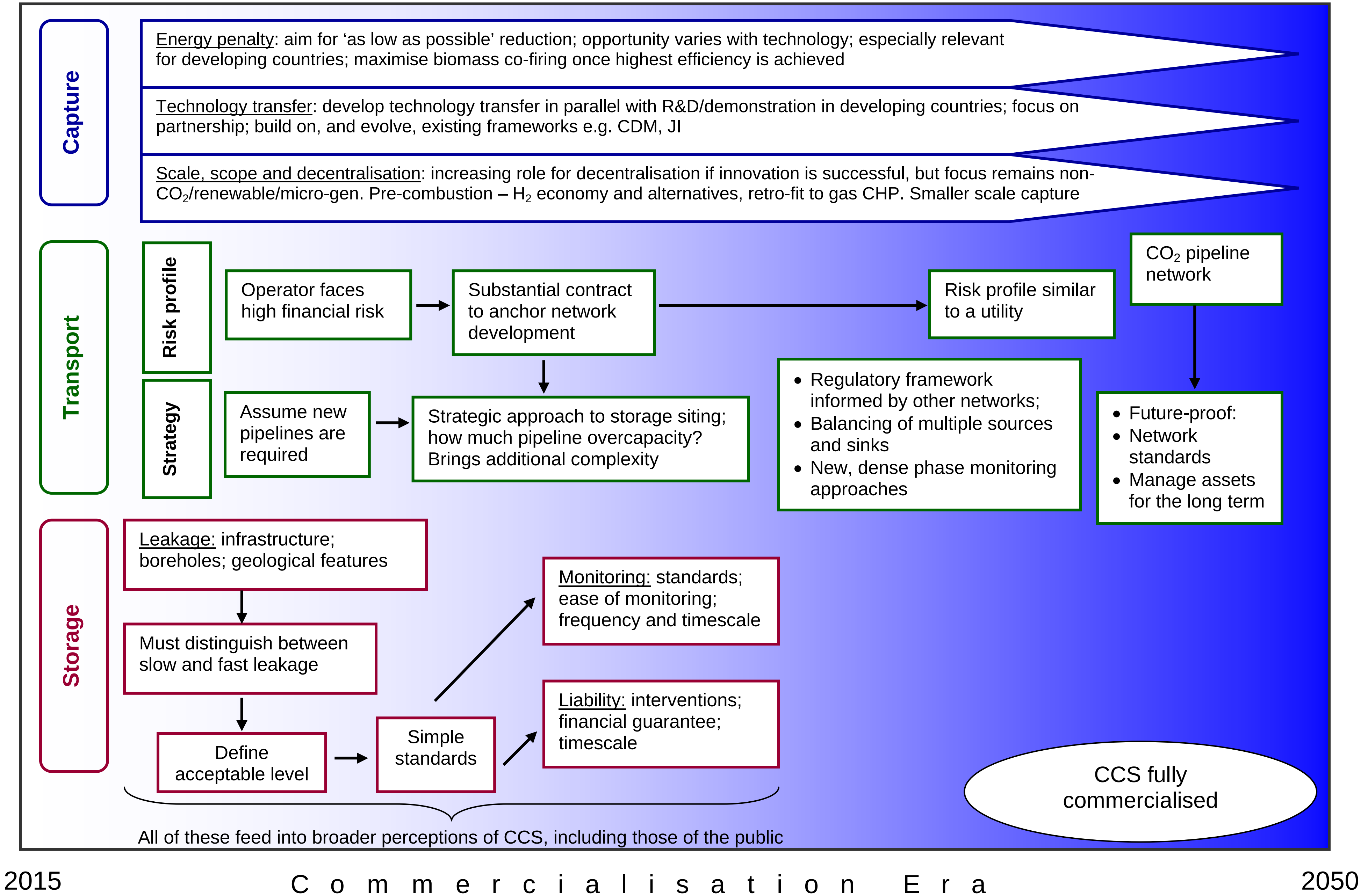


Figure 3. Long-term CCS road map

3. Convenors Comments

The main conclusions of this roadmap represent the consensus view of all of the workshop participants. This, inevitably, does not reflect the full range of opinions expressed, therefore the workshop convenors would like to make the following concluding comments.

Several industry representatives expressed concern that the UK Government is currently failing to provide the leadership that the CCS industry is waiting for, and is indeed essential, if the UK is to progress with demonstration scale projects. Industry participants were clearly of the view that CCS will not emerge without a significant enabling "push" from government across the entire CCS chain. Issues that will need to be clarified range from regulation and licensing, to a business model for transport of CO2, to site performance requirements and agreements over long term CO2 ownership. At the time of writing, there is an emerging tacit agreement that government will, eventually, take ownership of stored CO2 – but the timescale and conditions of transfer are obscure.

An additional problem, relevant to the very first pre-commercial demonstrations, is the transport network. Does the UK have a vision of a connected CO2 on-shore pipe network, and if so, who will operate and build it? Alternatively, regional networks could emerge from individual initial CCS developments, if these first initial developments were designed at the outset with additional future capacity. Offshore, similar problems of ownership and network capacity are compounded by the additional costs of laying hundreds of km of pipes to storage sites located either in aquifers or in depleted oil or gas fields. Experience of enhanced oil recovery (EOR) in the US, points to the importance of large-scale operations with a pipeline network as one means of reducing costs. Given the potential for adding 1,500 million barrels to UK total production over the next 20 years through EOR, is this a further driver for a pipeline network, and would such a network improve the economics of CCS through EOR? Finally, are transboundary links required to take CO2 from, or send CO2 to, Norway, Denmark, Poland and Germany?

CCS actors are waiting for clarity over financial incentives from DBERR (former DTI) for short term demonstration projects, and for medium term commercial deployment of CCS technology. At the time of the workshop the imminent publication of the 2007 White Paper, and the details of the DBERR funding competition for the first CCS UK-based demonstration project that it was assumed to contain, was eagerly anticipated by participants. Indeed for some, the timing of the workshop was seen as unfortunate, given the policy clarity expected in the near future. Unfortunately, announcement of the details of the competition have been postponed until November, with the winner to be decided around April 2008, which will have a knock-on effect in terms of the timescale for the commencement of CCS in the UK and the confidence expressed within this workshop report that a UK plant could be operational in 2012

The industry is divided over the DERR competition, with views ranging from enthusiasm to scepticism that it is an expensive and over-regulated delay. Although the UK is committed to this method of discovering "best value", given the potential for several different capture technologies, with diverse storage sites, will a competition with a single winner create the conditions for the range of CCS possibilities to be explored? Is price the most important criteria, or will the benefits of learning by doing, and the prospects for rapid deployment of successful plant at reduced cost be considered? Given that new fossil fuel plant will be built prior to 2015, and the importance of deployment of CCS in China, is a more strategic approach to the demonstration projects required? Thus would it be better, to invest in pre-combustion coal (as potentially most efficient in the medium term), post-combustion coal (for the Chinese markets) and in gas plant (which could supply over 40% of UK electricity)? With at least ten possible projects under discussion; selecting just one winner means nine losers. Overall, is this the best approach to support a diverse mix of UK developments at the early stages of a new technology supply chain, or can we conclude that several demonstrators are more sensible?

Moving beyond a successful demonstration project, CO_2 does not have a large monetary value hence there is no market pull to develop CCS. Most of the industrial players are placing their faith in the third phase of EU-ETS, post 2012, but this relies on the market delivering an adequate carbon price. If the price remains too low to cover the costs of capture, transport and storage, any CCS demonstration plants that have been built may remain an interesting experiment that becomes too expensive to operate. The UK would be wise to explore alternative approaches for financing CCS such as feed-in obligations, guaranteeing a higher price for low-carbon fossil-generated electricity, or by-passing domestic State Aid regulations.

The combination of climate change imperatives, energy futures, security of supply and CCS is a potent legislative opportunity. Even so the details of CCS requirements and licenses are still poorly understood. There is a risk of overly-specific regulation and space must be left for it to evolve on the basis of the knowledge gained from demonstration projects within the UK, EU Australia, Canada and USA. For early developments, guidance on the shape and direction of regulation and licensing is certainly essential, but it must also be clear that these are not the final answers which apply to subsequent plant or storage sites.

Liability remains a crucial issue. It seems inevitable that either the State or the Crown have to take ultimate ownership of stored CO_2 but there is a risk that public perception of industry handing over its problems to the UK public sector could stifle CCS. Thus, handover can only take place following adequate prediction and validation of storage performance to ensure that the risk of public liability is extremely low; this could be up to 30 years after storage site closure. Ideally site performance during this interim period would be well-enough understood to be insurable, though lack of insurance will exclude smaller companies from becoming CCS operators. Lessons from oil and gas exploration and production show that small and independent operators can develop opportunities inventively, at lower costs, and with consequent benefits to the UK. Opening the CCS transport and storage system to a diversity of players could enable the UK to go further and faster with deep CO_2 cuts, not just in centralised fossil fuel power plants.

The term 'demonstration project' encompasses different meanings for different stakeholders, and in some cases the issues pertinent to those with one area of expertise were new to those with a different area of expertise. Thus, the workshop was useful to bring diverse participants together and increase understanding between those working on different parts of the CCS chain. Indeed one participant commented "…I have changed my mind about the four key issues for CCS, because of what I have heard here."

At present there is little explicit link between energy and climate change policy and the continually evolving science of climate change. The latest IPCC report (2007) cautions that current world emissions are at the upper end of IPCC emission scenarios, implying global mean temperature rises are inevitable in the region of 4oC, as opposed to the 2oC cited in EU and UK climate policy. UK Government has recently accepted the importance of cumulative emissions, rather than end-point targets, to reaching climate change objectives. UK carbon emissions are currently rising and if Kyoto targets are achieved, this has not been as a result of climate change policy but rather due structural changes to the economy and a changing profile of electricity generation as a consequence of the dash for gas. Overall all these factors demonstrate that the urgency of the need to move towards a low carbon energy system cannot be overstated. CCS is an important technology in this context, and this roadmap charts the pertinent issues for CCS in the UK. Without adequate Government "push", CCS will not fulfil its potential as an alternative to established rapid and cheap-to-build natural gas combined cycle plant, to low carbon new nuclear.

4. Roadmapping workshop process

This report is the product of a two day workshop held in Edinburgh in May 2007, (which followed an online technical survey of stakeholders and experts conducted during 2006 (Gough, 2007)). The roadmapping approach was broadly informed by, and adapted from, that described in Placet and Clarke (1999), adopting a 'goals, pathways, gaps' approach. Throughout the workshop, participants were encouraged to consider the timescale for all proposals with the broad distinction between the short-term demonstration phase (here defined as up to 2015[3]) and the longer-term, during which CCS may achieve full commercialisation (beyond 2015), with a clear goal of producing a roadmap for each of the two timeframes. This section outlines the workshop process, which began with three introductory presentations.

4.1 Introduction - Stuart Haszeldine (University of Edinburgh)

The opening presentation set the scene for the workshop with an overview of the international and UK context for CCS. The IPCC has indicated that CCS has the potential to contribute to atmospheric CO_2 reductions on a large-scale worldwide although is not economic at present. However, there is a danger that the capacity to reduce emissions will be missed if the focus is solely on costs – the economics are highly dependent on the assumed price of carbon. Within the UK, the Treasury and DTI (now DBERR) have announced a competition for demonstration plant funding, although it is unclear whether this is for one or more projects. It is important, however, that progress continues beyond the first project – there are a number of projects under development in the UK and the outcome of the Treasury/DBERR funding will not preclude these other projects from proceeding.

The aim of the workshop was outlined; namely to produce a road-map for the deployment of CCS in the UK, which includes potential difficulties as well as opportunities. The need for a roadmap stems from the fact that the sector is not currently as joined-up as would be ideal, and there is a need to establish the challenges which exist. Over the two days, the intention was to look at the whole system, not just the technology aspects, and to establish a framework for CCS, with timelines to identify the various deadlines and externalities.

4.2 Technical survey: Clair Gough (Tyndall Centre, The University of Manchester)

This presentation provided an overview of the online technical survey for CCS in the UK on which the workshop was based, with a brief summary snapshot of some of the key results relevant to the workshop programme. The key conclusions included the identification of potential 'showstoppers' and the requirement to reduce costs.

The on-line survey itself consisted of ten broad sections on different aspects of CCS; the questions were initially drafted by researchers at the Tyndall Centre and piloted amongst the UK CCS

[3] 2015 was used to limit the short-term with reference to various political externalities that would impact on CCS development. These include the EU Large Combustion Directive, the end of EU ETS Phase 2 and the EU target for demonstration plants. It was felt by the organisers that going beyond this, say to 2020, would introduce factors more relevant to the longer-term.

consortium before the survey was launched. A total of 88 responses represented a wide range of backgrounds. The lowest representation was from the cost & economics sector, and is perhaps a reflection of the level of uncertainties that exist in this area. The survey did not investigate the level of support for CCS in detail – the aim was to elicit a feel for the areas of consensus/uncertainty from a technical perspective and to prompt discussion and debate. However, the majority of respondents were in favour of CCS (a reflection of the population consulted).

Selected results from the survey are as follows:

- Environmental concerns (including climate change mitigation) were the most commonly identified drivers of energy technology deployment in the UK, followed by energy security and costs/economics.
- The two most cited challenges to the implementation of CCS ('showstoppers') were a lack of long term UK policy and costs.
- There was less confidence about the potential for CCS with gas than with coal.
- In relation to pipeline construction, the majority of respondents thought the costs should be shared between the Government, site storage operators and CO_2 providers.
- A progression in the use of different reservoirs for large-scale storage was revealed over time
- Few respondents could make confident estimates of total UK storage capacity; in particular there is great uncertainty about the upper capacity limits in saline aquifers[4]. One of the workshop participants noted that the word 'storage' was not defined explicitly in the survey and the use of the word 'disposal' instead could have yielded different responses.
- Monitoring and remediation of leakage was thought to be relatively easy during capture and transport of CO_2 but more difficult when leakage occurred from geological faults. The perceived probability of a leak was not investigated.
- Costs are a crucial issue and currently highly uncertain. The survey looked at what would result in the greatest reduction in costs: technology breakthrough and experience from demonstration plants emerged as the top two issues for capture (which represents the greatest proportion of costs).
- There was also uncertainty over the cost incentive provided by enhanced oil recovery (EOR).
- In general, UK capabilities were rated as average within the international context, with greatest optimism in the area of storage.
- Well integrity and the fate of stored CO_2 were highlighted as key technical uncertainties for storage
- In relation to transport (capture was not covered), most respondents considered there to be no technical uncertainties, although corrosion and impurities emerged as important.

4.3 Road-mapping process: Sarah Mander (Tyndall Centre, The University of Manchester)

The final presentation outlined the workshop process beginning with an introduction to the principles behind the Batelle road-mapping approach (Placet and Clarke, 1999). Road-maps are a visual communication tool with an underlying process which is structured and transparent. Their purpose is to identify the potential pitfalls of deploying a technology and develop strategies to address them. The aim of this workshop, and road-map, was to initiate a communication process, integrating knowledge and experience from a variety of different areas. The road-map would take

[4] The British Geological Survey has, however, recently produced more up to date estimates of capacity

a 'whole system' approach, including planning, policy etc., rather than focus specifically on technology. It is intended to be complementary to, and feed into, the proposed DBERR road-map, which initial discussions with the DBERR had suggested would concentrate on technology and R&D[5]. The roadmap took as a given that CCS is an important technology for climate change mitigation and therefore must be deployed.

The workshop process was designed to work towards two levels, each with different foci and timeframes; level 1 considered demonstration projects to 2015 (based on EU targets for demonstration plant) though this date should not be deemed an end-point, but rather a milestone in preparing for 2020 and beyond; level 2 focused upon wide-scale deployment to 2040.

The 2015 timeframe was explored within the first two workshop sessions and addressed the showstoppers that were identified in the survey, namely the lack of long term policy and costs. The first session focused on policy, with separate break-out groups considering: UK climate policy; planning and consents; and EU and international climate policy. Given the diversity of participants, the groups were structured to ensure that each participant considered each of the policy streams. The second set of workshop sessions focused on the potential for cost reductions, with deployment of CCS in the UK (or learning by doing) emerging from the survey as the key to reducing costs. Separate break-out groups therefore focused on the challenges that needed to be overcome during deployment, namely: technology development; scale and integration; financing and economics.

The third session explored the technical uncertainties relating to wide-scale deployment to 2040.

The break-out group structure was based on the Batelle approach, with group exploring a specific issue. The first stage of the process was to un-pack the issue into distinct elements, or goals, that would have to be achieved for the issue under consideration to be addressed. In the second stage, pathways through which the goal could be achieved were defined. The final stage looked at the pathway and highlighted any barriers which could prevent the goal from being achieved in the future.

The workshop was organised around a combination of breakout sessions and plenary discussions, all moderated by members of the organising team. Each session was designed to deliver specific outputs, with the flexibility for particular groups to adapt the process if necessary; in practise the workshop format was modified in response to participants' suggestions. Table 1 describes the sessions, as they were implemented in each group. The composition of breakout groups was different in each session and determined in advance by the organisers to ensure a mix of expertise and institutional background in each group.

[5] Work on the DBERR roadmap is in the early stages, and it is likely that the scope will change.

Table 1. Organisation and activities of breakout and interactive plenary sessions

	Topic	Process	Summary Output
Session 1			
Session 1 – Policy ***3-way carousel:*** three groups moved between Stations A-C, so that each group visited each station.	Station A – What climate change framework is required to support CCS deployment?	Group 1: Brainstormed goals; in pairs, each pair selected a goal, identified pathways & gaps / challenges to achieving goal; pairs placed results on timeline and presented to group. Groups 2 & 3: Group identified any additional goals; pairs selected a new goal from the list, identified pathways and gaps / challenges to achieving goal or added to entries previously placed on timeline.	Roadmap template with colour-coded post-its describing goals, pathways and gaps placed on time scale. Appendix B
	Station B – What regulatory consents will be required?	As station A	As station A; Appendix C
	Station C– What are the international and EU policy requirements for establishing commercial scale CCS?	As station A	As station A; Appendix D
Plenary 1 – Facilitators reported back and brief plenary discussion.			
Session 2			
Session 2- Ensuring cost reductions through deployment ***2-way carousel[6]:*** Two groups attend 1 Station each: each visiting two stations (D, E, F).	Station D – What are the urgent technical/ hardware requirements?	Groups preferred to work as a group throughout and work up a list of issues to be discussed within the group	List of key technical issues; Appendix E
	Station E – What are the challenges resulting from the integration of separate elements of the CCS process into a demonstration scale plant?	Group 1: identified critical issues as whole group then consider issues of timing and scale for integration Group 2: working together, the group developed a timeline for large-scale UK demonstration project	Matrices: issues and timing associated with particular technologies; timeline for large scale demonstration by 2015; Appendix F
	Station F – What needs to be done in the short-term (2015) to reduce the costs/increase revenues of CCS and make it economically viable?	Each group: brainstormed goals, worked in groups of three to identify pathways and gaps, to be placed on timeline	Appendix G
Plenary 2 – Facilitators reported back and brief plenary discussion.			
Session 3			
Single dedicated group at each station.	Station G – What are the long term challenges for CO_2 storage?	Individuals identified three key issues relevant to storage over the longer-term. These were clustered and clusters further explored during group discussion.	List of broad issues, each with specific related points; Appendix H
	Station H – What are the long-term technical uncertainties related to CO_2	Group identified key issues relevant to transport over the longer-term and selected key issues for further discussion	List of four key issues, each with specific related points; Appendix I

[6] It was agreed during Plenary 1 that each group would attend two stations instead of three during Session 2, to increase the time available at each station.

	Topic	Process	Summary Output
	transport?		
	Station I – What are the long term challenges for CO_2 capture?	Individuals identified three key issues relevant to capture over the longer-term. Following brief discussion of these, group selected three from longer list for expansion	List of three key challenges, each with specific related points; Appendix J
Plenary 3 Rapporteur from each group reported back to plenary. Participants sat around three large tables. Each table was supplied with large printed notes from breakout sessions 1 & 2 to discuss and annotate contents.			Notes taken from discussion Annotated comments on outputs from carousel sessions
Plenary 4 Participants sat around three large tables. Each participant identified the four key issues to have emerged from the workshop as a whole, these were then discussed around the three tables and each table presented four consensus issues to plenary. In plenary, the results from the three tables were clustered and four key messages as consensus conclusions from the workshop were agreed.			Key summary conclusions agreed by all workshop participants

5. Break-out group summaries

5.1. Summary of Station A: What climate change framework is required to support CCS deployment?

Each group brainstormed a list of UK policy-related issues and selected goals from this list to review. Of these the goals, identified in italics, were further explored and placed on the roadmap template, identifying pathways and gaps:

2007

It is important to ensure that the UK maintains a diverse electricity supply system with a balanced mix of technologies. Steps to ensure this balance may include: communication of its importance; education of power engineers to avoid skills shortages; incentives to ensure long-term investment.

2008

Grants and certainty over the long-term future of the EU ETS required for *early support of demonstration plant*. *Long term liabilities* should be determined for the *UK demo project* once Government decision has been taken on the project.

Government must provide a *subsidy mechanism* for early adopters of CCS technology – either technology neutral or CCS-specific. *Incentives* would: provide a continuous financial framework, optimise cost/benefit to Government and promote early take-up. This will require upfront costs for extra capital for capture plant and guaranteed minimum C price over the long-term in the ETS. Enforcement of tighter National Allocation Plans (NAPs) is essential. Incentives should be established for all sources of CO_2 and underpinned by Government, e.g. via tax breaks.

Sufficient and robust regulation (for licensing, operation and abandonment) should be agreed in 2008 and in force by 2010, supported by minimum international guidelines, a permitting authority (for capture, transport and storage) and the resolution of transboundary procedures (pipelines and reservoirs). This is hindered by Government lethargy and uncertainty within OSPAR and LCPD.

Gap analysis and regulatory consultation required to *fit CCS into existing petroleum licensing regime*.

Establishing monitoring requirements will require EU/UK consultations to agree necessary timeframe, risk base and stakeholder acceptability and should be informed by IEA GHG best practice guidelines.

2009

An obligation for minimum % of CCS should be imposed on all plants commissioned by 2015 and emitting above a level consistent with the Climate Change Bill. This will require primary legislation and, although it should extend to imports entailing large embedded value of CO_2, it is not clear how this would be handled, and there may be potential conflict with EU competition regulations. There was also some discussion that carbon intensity/KWh would provide a better focus.

2012

Fairness of incentives could be achieved by decoupling carbon and energy prices and addressing perceived unfairness between sources and sectors; also applicable is the post-Kyoto process with respect to targets in developing countries and the CDM.

Long-term liabilities in relation to risk (allocation and mitigation) associated with commercial CCS projects are currently unclear, particularly with respect to probability, impacts, public acceptability and insurance of leaks, and must be resolved.

A *long-term licensing authority* must be established by 2012.

2015

By 2015, *CCS must be viable* between 40 -60 *Euro/ton CO_2*.

The potential role of (2nd generation) CCS in a more decentralised energy system will require clarification - 2nd generation capture may be suitable for decentralised application (conventional or biomass) or as centralised capture with decentralised generation (e.g. CHP), though remains politically and technically uncertain.

General comments from the plenary session relating to this Station identified that more discussion was required on the following points: public perceptions; requirement for Strategic Environmental Assessment offshore; the different roles and responsibilities of Government, industry and academia; future value chain for CCS; the need to distinguish between EOR and storage (which will have different business models).

5.2. Summary of Station B: What regulatory consents will be required?

The first group brainstormed an extensive list of the regulatory consents that would be required by a CCS plant that linked CO_2 capture within a generating plant to long term storage via a suitable transport mode. A second list of 'goals' was then defined i.e. regulations that would require amending to enable a CCS demonstration project to proceed. The two subsequent groups commented on these lists, and added some additional goals; all this information is contained in Appendix C. Working in smaller groups, those goals deemed most important were unpacked, and pathways outlined for how they may be achieved; this information was placed on the roadmap template and potential showstoppers identified (gaps). All the goals identified upon the roadmap need to be resolved prior to 2010.

2007

To avoid different regulatory agencies re-inventing the wheel in terms of their approach to CCS, they need to work together to develop a common approach. The long term risk profile of CCS is similar to that of a utility; hence a service model should be developed, identifying missing elements.

2008

Health and safety consent will be required for onshore pipelines. Currently, supercritical (dense) CO_2 is not categorised in design codes, therefore before pipeline design can begin a consensus needs to be established on which level of hazardous fluid is to be used, such that design codes can be incorporated into British Standards. Appropriate pipeline regulations will be required from HSE, though existing COMAH and PSR may be amended, based on studies of dispersion characteristics, and including definition of inspections procedures to provide sufficient risk protection and minimise public perceptions of that risk.

Change of use of oil and gas platforms for high pressure CO_2 injection will have health and safety implications. A gap analysis would identify how oil and gas regulations should be amended, and a standard must be established following appropriate research. The cost of compliance and efficacy of leak detection monitoring were identified as potential barriers. Furthermore, for both these goals, lack of experience of supercritical CO_2 within regulatory bodies was identified as a potential showstopper.

2009

A CO_2 quality specification is required to limit pipeline damage and potential impacts on storage. In the absence of inadequately defined purity standards, specification may be set by default. Overall, knowledge will need to be shared between each party in the CCS process chain.

Issues of long term liability for stored CO_2 will need to be resolved. 6 storage phases were identified: Exploration of sites; assigning rights to a storage operator; full site characterisation; injection; closure/decommissioning and monitoring; handover to the Crown. The need to identify crown ownership rights (2008); the issue of who decides the scale of payment from site operator to crown (2009) and the division of responsibility between oil field operator and storage operator (2009) were identified as potential barriers.

A regulatory structure for decommissioning is required that includes procedures and timelines for decommissioning; performance standards for equipment leaks; a financial bond to cover future costs liabilities and procedures for monitoring the reservoir for any deviation from predicted performance.

2010

Resolve OSPAR framework and translate into UK legislation – This goal highlighted a limitation with the workshop approach, namely that there were gaps in participant's expertise. Thus, whilst a pathway via which *OSPAR* could be resolved was defined this has not been included within this summary since this work is ongoing at the DBERR, with ratification likely to be achieved in 2008.

For several goals, the need for CCS regulations to be integrated with oil and gas regulation was identified, specifically in terms of injection of supercritical CO_2, and in devising a regulatory procedure for decommissioning. Risks should be comparable to the oil and gas industry. Concerns were also expressed that the regulatory structure may make CCS in general too expensive, with the economics of storage in saline aquifers also likely to be impacted by over-regulation.

5.3. Summary of Station C: What are the international and EU policy requirements for establishing commercial scale CCS?

The first group brainstormed an extensive list of international and EU policy-related goals, to which only one or two additional goals were added by subsequent groups – there appeared to be broad acceptance of these goals as the consecutive groups selected goals from this list to review. Of these the following were further explored and placed on the roadmap template, identifying pathways and gaps:

2008

Minimise risk in RDD for UK by sharing risk through international collaboration under UK leadership. However, unlike UK investment overseas, there is currently no clear mechanism through which other nations would be encouraged to invest in UK demonstration projects.

EU Energy Policy to promote security of supply and price may help avoid *the effects of volatile coal and natural gas market*, though given that energy supply comes from unstable areas, such effects may not be avoidable. A comment in plenary suggested that the real issue is achieving a stable long term carbon price (for example through a long term CO_2 contract).

CCS must be defined as pre-competitive to *comply with competition law* – this may require new rules of engagement for demonstration projects (that may benefit industry consortia), transparent reporting of their process and further support mechanisms for future projects.

2010

The UK must input to CO_2 target-setting in the EU – the strength of the target e.g. 20% or 30% and timescale will impact on deployment of CCS, and may influence targets outside the EU. The success of CCS demonstration projects could also influence the target adopted, as could the response from the US and developing countries, and improved understanding of climate system.

Post 2012 negotiations (Kyoto) will provide a basis for inter-governmental trading to meet caps or reduce CO_2 emissions. Whilst negotiations are political, they should be based on understanding of climate science, and their implementation will depend on industry. Potential problems include: artificial benchmarks, the problem of allocation of non-market goods and, for CCS, understanding is required of comparison between CO_2 avoided and captured.

2012

CCS must be within EU ETS by 2012 – lower allocations are required to increase carbon price, which requires willingness across member states, and further technical regulation & clarity for industry. Alternative incentives should also be investigated as a back-up either at UK, EU or international level though will entail a new process of negotiation. Intentions for phases 4 & 5 also must be outlined now. The EU ETS needs to provide certainty in regulation for around 15 years in order to establish an efficient trading scheme, and deliver an adequate carbon price. This is hindered by the rules changing every few years.

2015

Other EU policy may need resolving, e.g. does the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal apply to CCS? This may require modification (in defining waste and CO_2) which in turn may present technical, economic and political barriers; a comment to this was added during plenary that modification of EU directive (phase 3) is being discussed in DEFRA / ETG with view to including CCS.

The following brainstormed issues were not expanded by any of the groups: State aid rules/world trade rules; transition from EU demo aspiration leading to policy; UK participation in EU demo process; Exported emissions, EU/UK CO_2: how to cut 30% by 2020; the need for a long term vision on Strategic Environmental Assessment.

5.4. Summary of Station D. What are the urgent technical/hardware requirements?

Neither of the two groups was comfortable setting out timescales for short term technical developments and neither group considered that any breakthrough in technology would be required to establish demonstration scale CCS, since the process of full scale demonstration would resolve particular technicalities. The two groups also independently described the demonstration phase of CCS as a first step towards realising the bigger picture of commercial scale deployment by the 3rd or 4th plant constructed. The second group noted that any technical risks faced by a company in the demonstration phase would be outweighed by subsequent 1st user benefits. The summary below presents issues that were raised in each group specifically; the discussions in each group involved all participants throughout the session.

Group D1 identified the following technical issues for the demonstration phase:

Integrating a full scale plant (also identified in Group D2):

Post combustion - volumes of CO_2; *pre-combustion* – whether IGCC is currently fully commercial even without capture (i.e. achieving 85% load factor and 45% efficiency associated with the technology).

Oxyfuel is less well developed than pre- or post-combustion capture (e.g. new alloys)

Novelty of burning H_2 in gas turbine (e.g. DF1)

Uncertainty over the *behaviour* of CO_2 when released (source term[7] for CO_2 unknown)

Storage:

How CO_2 behaves when stored: demonstrations are needed to validate computer simulations

CO_2 EOR offshore: will require re-engineering of rigs etc to deal with CO_2 (DF1 does not have these issues to same extent as the field already CO_2 contaminated, so infrastructure etc. is already handling CO_2). This re-engineering also requires extending the life of existing infrastructure. Technical challenge is regenerating CO_2 from the oil that is recovered.

Characterisation of aquifers

Choice of demonstration type in UK:

Should we aim for a *diversity of demonstrations* in UK to spread the (economic) risk, or is it enough to partly rely on demonstrations elsewhere?

Part of the discomfort in engaging in these discussions derived from a preference to await the *forthcoming DBERR decision on the first UK demonstration project*. Until this is made it was felt that it would be premature to develop a technical roadmap.

The decision over what technology to pursue is a choice between prioritizing the *lowest (economic) risk option versus the option with the greatest potential* (for CO_2 reduction).

The session concluded with a short exercise in which each participant named what they thought represented the lowest risk demonstration option; this exercise highlights the diversity of views across CCS experts with the following six options selected: IGCC[8]; H_2 reforming from methane – burn in gas turbine, store in depleted gas field already contaminated with CO_2; post-combustion (with greatest potential including EOR); technology appropriate to China/India and decentralization; retro-fit, post combustion; onshore pipeline, new infrastructure (least technically risky due to experience of CO_2 transport in the US).

Group D2 also discussed the issue of definition of demonstration plant and expressed the choice in terms of pursuing a low risk of proven technology (which was considered to be the Government's aim of the demonstration plant; the BP DF1 project given as an example) or whether it should entail higher risk innovative new technology (such as the Futuregen programme in the US, to be

[7] The source term is the mathematical equation that describes the flow rate of an accidentally released pollutant.
[8] Integrated gasification combined cycle

realised post-2015). This group went on to identify the following additional issues relating to technical requirements:

Scaling up issues: integration; operator experience; demonstration of containment (no leakage)

None of the low carbon technologies are good for the grid; they either operate at base load or are intermittent. CCS exacerbates an existing problem by introducing more plant competing for base load.

At the end of their session, Group 2 reviewed points from Group 1 and broadly agreed with main points made.

5.5. Summary of Station E: What are the challenges resulting from the integration of separate elements of the CCS process into a demonstration scale plant?

Both groups focused on the critical issues related to CCS plant integration as highlighted below. Group 1 developed a matrix outlining issues of timing and scale, whereas Group 2 developed a timeline for a large scale (800MW) demonstration plant. Following announcement on government policy, the Miller plant could be operational within 5 years, once issues such as an incentive package and long term liability are resolved. The timeline for the 800MW plant, however, demonstrates that there is a longer lead in time for projects involving new pipelines. Deployment will not proceed without clarity from government.

What is meant by integration?

Integration means different things, depending on your ‘place’ within the CCS supply chain:

- For a generating plant operator, capture plant must be integrated within a plant whose primary purpose is to supply electricity. An operator may require in-built flexibility to enable them to shut off the capture plant when price of electricity is high to make extra money by avoiding the energy penalty.
- Design of capture plant must consider the location and size of compression equipment, solvent disposal, size of scrubbers, need for flue gas desulphurisation etc.
- Storage strategy: does the demonstration project initiate a strategic storage plan? This determines whether the demonstration pipeline is the first element of a network linking storage sites or a one off point to point pipeline.
- High pressure injection will require balancing of CO_2 supply from a potentially variable source
- The quality and state of CO_2 required for transportation and storage needs to be clarified. This can impact upon the capture/generation process costs and specifics.

Scalability

- Different capture technologies will be ready for demonstration at different times, and will require ‘demonstrating’ at different scales. All parts of the ‘process’ need to be sized so they can be integrated. These two issues have a knock-on effect in terms of the transport system required, and the type of storage site that could be used.

- Timing impacts on: depletion curves for oil and gas field, there may be conflict of uses and potentially the need to identify areas which should be prioritised for CO_2 storage and for gas extraction
- In terms of 'readiness' for deployment, Miller is the closest, followed by IGCC, post combustion gas, post combustion coal and oxy fuel.

Aim of the demonstration plant

There was no consensus between participants as to the ultimate aim of the demonstration plant:

- Should capture be proved first and with other parts of the process later proved separately e.g. use an existing CO_2 stream to prove transport and storage?
- Is the intention to couple parts of the system together to test performance and explore impact of CCS on value chain components such as the sale of electricity?
- The offshore challenges of EOR are huge, does this confuse the objectives and are the additional challenges worthwhile?
- Is the purpose of the demo part of a strategy to start large scale deployment, facilitate deployment overseas or to be seen to be doing something? The policy is not clear.
- The 'simplest' project would: not include EOR; offer large amounts of CO_2; have existing landfall permits and follow the route of existing pipelines; be close to shore; use a simple storage site

Intermediate storage within a CO_2 network

There was disagreement over the need for intermediate storage

- Oversized pipelines would provide buffer capacity
- Venting is an alternative to storing CO_2

5.6. Summary of Station F: What needs to be done in the short-term (2015) to reduce the costs/increase revenues of CCS and make it economically viable?

The first group brainstormed a list of goals, to which additional goals were added by subsequent groups. Of these, the following were further explored and placed on the roadmap template, identifying pathways and gaps:

2007

Develop cheaper materials (for all stages) e.g. new coatings / surface finishes, linings (near the point of injection). However, this will require new sources of NACE (National Association of Corrosion Engineers) compliant stainless steel. This may entail global working parties to share development costs and depends on availability of materials at global scale.

Reduce energy penalty of capture (by 2015) via technology R&D (membranes and coatings), exploring capture from other processes (chemicals, cement), enhanced solvent efficiency (post-combustion capture), more efficient O_2 separation (membranes vs. cryogenic), upgrading demo plants. This is currently hindered by lack of commercial investment and a knowledge gap (e.g. does EOR reduce energy penalty?).

2009-12

Infrastructure re-use: retrofitting capture to existing power plant, although this further reduces efficiency and post-combustion capture is not technically proven; location of platforms close to storage reservoirs and identifying suitably located pipelines. However, there is currently a gap between short-term decommissioning of existing vs. new investment in plant over longer-term, infrastructure may be used for other purposes and may be old with poor integrity and inappropriate metallurgy for CO_2 use (re-lining required but costs need reducing), there may be limited opportunity for pipeline reuse and there may be complex commercial and ownership arrangements.

Build (and define) capture-ready with space for retrofit. Will need to address local regulations, match sources to sinks, define timeframe and emission limits, account for loss of revenue during downtime and prepare a design template. The disadvantages of capture-ready include: risk of diverting focus away from retrofit R&D; it may be perceived as 'stalling'; limit plant flexibility (fuels); render operator vulnerable (to be forced into installing capture); increase cost in the short-term (although presumed to reduced long-term costs); fall short of future capture technology requirements; there may also be a shortfall in current capabilities of the Regulatory Authorities.

There may be multiple *users of source/sink* with joint/single ownership, multiple wells and provision for future use. This may raise monitoring and liability issues, represents a technical rather than political solution and raises questions of cost-bearing.

Reduced operator risk may be achieved by higher CO_2 value, improved reliability of demo plant, maintaining merit order, improving understanding of optimal 'operating point' (balancing operating cost and capture rate). The key challenges are that capture reduces plant reliability and flexibility and current lack of incentives.

2015

Plans in place for *commercial scale by 3rd iteration* achieved by a stepped deployment of options and ensuring support for development ('market pull'); this will require parallel mechanism alongside the market.

RD&D of *Monitoring electronics* (micro-engineering)

Remaining brainstormed goals: relationship between contract cost and risk (aim to reduce risk); 'Brown Book' equivalent on CO_2 containment and release; proving technology; power plant close to sinks; not over-burden with regulation; government-lead facility sharing between industries; explore new paradigms e.g. Australia hub approach; learning from other countries; skills/retraining; high price CO_2; partial capture sufficient?; who pays?; sharing costs/risks/value; not picking winners.

5.7. Summary of Station G: What are the long term challenges for CO_2 storage?

Discussions in this group started around a quick brainstorming session in which each participant wrote on to Post-it notes three key challenges for storage. These were then clustered and from the clusters the following broad topics were identified and discussed (No timescales were specified).

Design

- This will be much tighter on first sites: tailored to individual sites, especially monitoring
- A generic framework should be developed with regulation in place as the process moves from a "testing" phase to a business / commercial phase at subsequent sites

Leakage

Three leakage routes were identified, each with different conditions

- Infrastructure – i.e. pipelines etc.
- Boreholes - primarily a concern in existing hydrocarbon fields, where wells are not designed for with subsequent storage in mind
- Cap rock, other geological features, faults etc. – these are less well understood for aquifers than hydrocarbon fields (although here integrity may be changed by storage). Gas fields are the best understood although these may not be available as first storage sites.
- Perception of leakage is important
- Need to distinguish between fast or slow leakage with different implications for regulation and monitoring
- Regulatory aspiration is for zero leakage but in practice there will be some kind of acceptable level (which cannot simply be a percentage) in order to evolve a simple standard. Zero leakage is impossible over geological timescales (e.g. oil and gas fields are not zero leakage although perceived as such).

Monitoring

- Frequency of monitoring will vary e.g. at pilot sites, during operational phase during closure and after handover. The government may have different notions of ideal monitoring rates (and longer timescales for monitoring by the State)
- Standards will need agreeing for quality of monitoring (i.e. detection limit)
- Once CO_2 has dissolved it becomes difficult to monitor (especially in aquifers); also issue over other elements (e.g. H_2S, Mercury…) which cannot easily be monitored in the subsurface (suggested standard not exceeding pre-storage background levels)
- Practical issue – what can be measured, over what timescale? Long term liability – implicit assumption is for transfer to State but details not debated. Regulations required to protect against operator insolvency (without loopholes)

Liability

- Intervention required if monitoring reveals a problem but there are complexities of who should intervene (and securing insurance may be an issue)
- (im)-purity – impacts of a leak to surface dependent on composition of leaked material
- Timescale

Perception

- All of the above points feed into broader (incl. public) perception of CCS
- Standards will evolve (becoming more stringent over time)
- Future-proof

Baseline and character

- 'Reasonable'
- Site specific

5.8. Summary of Station H: What are the long-term technical uncertainties related to CO_2 transport?

The group began by brainstorming a list of the key issues related to the transport of CO_2; these formed the basis of subsequent discussions. Several findings from the initial research questionnaire were also highlighted by the facilitator and discussed by the group. Overall, it was concluded that technical uncertainties would need to be resolved in the short term, so that CO_2 could be transported from source to storage site within full scale demonstration plants. In the long term, there are no technical barriers to a pipeline network; the challenges lie with the business model for commercial development, and the design, procurement and management of a transport infrastructure. Overall, human factors are crucial, and the industry must have appropriate procedures and mind set to manage an asset for the long term.

Short term issues

Technical issues relate to the *interface of transport and capture system*. Water within the CO_2 stream would cause pipeline corrosion, but, given that pipelines made from corrosion resistant materials are prohibitively expensive, the CO_2 will have to be dried prior to transport. More broadly, *a specification for CO_2 purity* will have to be agreed. *Pipeline routing*, particularly within urban areas, and the related issue of accidental damage to pipes and the *risk of crack propagation*, will need to be addressed in the short term. HSE are aiming to resolve regulation within 2 years and pipeline design codes will either specify crack arrestors or tough materials.

These short term issues must be resolved for demonstration projects to be deployed.

Long term issues – how may a CO_2 transport network by developed?

Risk profile

In the short term a CO_2 pipeline operator faces a high financial risk due to high cost of their asset and low returns. The level of financial risk is equivalent to that associated with the oil and gas industry.

In the long run the risk profile for investment in CO_2 transportation is different to the oil and gas industry, and potentially less risky than other parts of the CCS system; similar to a utility?

Pipeline operators are reliant on other parties to supply CO_2 and provide the sink; using the LNG industry as an example, a substantial contract would be required to provide the initial anchoring for network development.

Over- capacity

The cost difference for CO_2 transport within a network and without could be as much as Euro 5 per tonne depending on the commercial system. Initiating development of a network, whilst involving a higher element of financial risk, is a more sensible long term strategy, than filling a pipeline from A to B to the maximum, with no option for expansion. Moreover, a big pipeline provides a storage buffer. Development of a network implies a strategic approach to storage siting. A pipeline network will bring non-trivial additional complexity.

Network management

CO_2 network management will depend on the balancing of multiple sources and sinks, as well as correctly metering, charging and so on. There is a considerable amount that can be learnt in this area from the experience of operating other networks, e.g. gas, CO_2 in the US and the national grid. Regulatory issues can therefore be easily resolved, but in the longer term new metering approaches will be required to allow for monitoring the quality of dense phase CO_2. A network would require 'future-proofing' to enable imports of CO_2, this would involve a network specification for input gas to a particular network and thought given to how the gas would be 'landed'.

Re-use of existing pipelines

No strategy for CO_2 transport should rely on re-use of existing pipelines, but instead assume that new pipelines will be built. Existing pipelines are reaching the end of their natural life and have been designed for operation under different operating conditions.

5.9. Summary of Station I: What are the long term challenges for CO_2 capture?

Discussions in this group started around a quick brainstorming session in which each participant wrote their three key challenges for capture onto Post-it notes. These were then clustered into six challenges by the group: *Power generation flexibility*, *environmental impact*, *cost reduction*, *scale*, *international issues*, *and energy penalty*. The group then split into three and each subgroup selected one out of the six topics to focus on.

Energy penalty and plant efficiency (including role of biomass co-firing)

- Rather than target setting, we should be aiming for an energy penalty which is as low as possible; this could be a reduction of 8-14 percentage points below current penalty (which is approximately 30%).
- The opportunity for improvement varies with technology: fairly limited from post-combustion, oxyfuel limited by air separation process, pre-combustion greatest opportunity.
- Reducing the energy penalty is especially relevant for developing countries.

- Once the highest possible efficiency has been achieved, the system can move towards maximising biomass co-firing (aiming for near zero emission CCS).

Technology transfer / development

- A parallel development of technology transfer should begin with R&D and demonstration in developing countries supporting dynamic growth and application in developing economies. There should be an emphasis on the shift from technology transfer towards true collaboration and partnership between all countries.
- This should build on existing frameworks and can be facilitated by evolution of trading schemes (e.g. CDM, JI). There may also be policy requirements such as local / regulatory support and on-going intellectual property issues.

Scale, scope and decentralisation

Parallel R&D is required to develop solutions over the longer-term; over the next 40 years, decentralisation will have an increasing role but the balance will be decided by pace and success of technology/innovation. Specifically:

- Pre-combustion*:* technical challenges for hydrogen distribution, retrofitting CCS to gas CHP, alternatives to hydrogen economy
- Smaller scale capture: at large industrial clusters, cost reductions across whole system will be critical, mobile and dispersed applications [needs clarifying]
- Focus for *decentralised power* remains on non-CO_2/renewable/micro-generation (micro-CHP, Stirling engine etc.)

Issues identified for the remaining three challenges not explored further include:

Power generation flexibility (understanding the generation mix will drive understanding of flexibility, IGCC with CCS flexibility: 100% hydrogen, 100% electricity, CCS is required for all fossil fuel generation – centralised and decentralised).

Environmental impact (aim for zero/negative impact from capture technology, other environmental / sustainability implications of capture (e.g. other pollutants and materials needs).

Cost reduction (Cost/capture penalty, cut cost by 50-75% by 2040).

Note that: for all issues, cost of carbon abatement is critical (system cost, not just plant cost)

6. References

Blair, T., 2004. PM Speech on Climate Change.

CETC, 2006. Canada's CO2 Capture & Storage Technology Roadmap, Canmet Energy Technology Centre.

CO2CRC, 2004. Carbon dioxide Capture and Storage Research Development & Demonstration in Australia - a Technology Roadmap. 2004/01, Cooperative Research Centre for Greenhouse Gas Technologies, Canberra.

CSLF, CSLF Technology Roadmap, Carbon Sequestration Leadership Forum.

DEFRA, 2007. Draft Climate Change Bill, HM Government, London.

Gough, C., 2007. State of the Art in Carbon Dioxide Capture and Storage in the UK: an experts' review. International Journal of Greenhouse Gas Control, forthcoming.

HM Treasury, 2007. Budget 2007: Building Britain's long-term future: prosperity and fairness for families. HM Treasury, London.

IPCC, 2005. IPCC Special Report on Carbon Dioxide Capture and Storage, in: B. Metz, O. Davidson, H.C.d. Coninck, M. Loos and L.A. Meyer (Eds.). Cambridge University Press, Cambridge.

IPCC, 2007. Fourth Assessment Report, Working Group 1: The Physical Basis of Climate Change, Intergovernmental Panel on Climate Change.

NETL, 2006. Carbon Sequestration Technology Roadmap and Program Plan, US Department of Energy, National Energy Technology Laboratory.

Placet, M. and Clarke, J.F., 1999. Emerging Technology Road Maps: the Batelle Approach.

POST, 2005. Carbon Capture and Storage (CCS). 238, Parliamentary Office of Science and Technology, London.

Raupach, M. R., Marland, G., Ciais, P., Le Quere, C., Canadell, J. G., Klepper, G. And Field, C. B. (2007) Global and regional drivers of accelerating CO_2 emissions. PNAS 104, 10.1073/pnas.0700609104, 10288-10293.

Royal Society, 2005, Ocean acidification due to increasing atmospheric carbon dioxide, Royal Society Policy Document 12/05, June 2005

Stern, N., 2006. The economics of climate change: the Stern Review, HM Treasury & the Cabinet Office.

Appendix A: Workshop participants

Participant		Email	Organisation
Eugene	Balbinski	BalbinskiE@rpsgroup.com	RPS Energy
Brendan	Beck	Brendan@ieaghg.org	IEA GHG
Adina	Bosoaga	a.bosoaga@cranfield.ac.uk	CRANFIELD UNIVERSITY
Tim	Cockerill	t.t.cockerill@reading.ac.uk	University of Reading
Stephen	Connolly	Stephen.Connolly@hse.gsi.gov.uk	Health & Safety Executive (Offshore Division)
Mike	Cowling	mike.cowling@thecrownestate.co.uk	The Crown Estate
Clair	Gough	clair.gough@manchester.ac.uk	Tyndall Centre for Climate Change Research and UKCCSC
Fatosh	Gozalpour	F.Gozalpour@hw.ac.uk	Heriot-Watt University
Ian	Graves	ian.graves@dti.gov.uk	DTI
Stuart	Haszeldine	s.haszeldine@ed.ac.uk	University of Edinburgh (UKERC and UKCCSC)
Ian	Havercroft	uctlich@ucl.ac.uk	UCL
Tim	Hill	tim.hill@eon-uk.com	E.ON UK
David	Jones	david.jones@bg-group.com	BG Group
Alex	Kemp	a.g.kemp@abdn.ac.uk	University of Aberdeen
Judith	Königshofer	judith@ccsassociation.org	Carbon Capture and Storage Association
Peter	Loftus	ploftus@renewteesvalley.co.uk	Renew Tees Valley
Sarah	Mander	s.mander@manchester.ac.uk	Tyndall Centre for Climate Change Research and UKCCSC
Duncan	Mclaren	dmclaren@foe-scotland.org.uk	Friends of the Earth Scotland
John	Mitchell	john.mitchell@scottish-southern.co.uk	Scottish and Southern Energy plc
Stuart	Mitchell	SMitchell@doosanbabcock.com	Doosan Babcock Energy Limited
Judith	Packer	packerj@pbworld.com	PB Power
Jane	Palmer	jane.palmer@ouce.ox.ac.uk	UKERC Meeting Place
Julia	Race	j.m.race@ncl.ac.uk	Newcastle University
Alastair	Rennie	alastair.rennie@amec.com	AMEC
Nick	Riley	njr@bgs.ac.uk	British Geological Survey
David	Santillo	d.santillo@ex.ac.uk	Greenpeace international
Philip	Sharman	philip.sharman@pera.com	DTI Global Watch Service
Nina	Skorupska	nina.skorupska@rwenpower.com	RWEnpower
Malcolm	Stephenson	malcolm.stephenson@shell.com	Shell UK Exploration and Production Ltd.
Jim	Watson	w.j.watson@sussex.ac.uk	SPRU, University of Sussex
Iain	Wright	wrightiw@bp.com	BP

Appendix B: Output of Station A – Regulation to support deployment

What regulatory framework is required to support CCS deployment?

Brainstorming

- Incentives
- Allowances
- Obligations
- Prohibitions/caps
- Timescales
- Controls: Legal (i.e. not prosecuted for using CCS) & Trans-boundary licensing – pipelines and reservoirs
- Continuity
- Consistency in policy at UK level and fit with EU/International
- Recognition of UNFCC
- Degree of trading – efficiency of incentive
- High liquidity
- Base/underpinning carbon price
- Equity between schemes – transparency – life cycle analysis
- Long-term liabilities
- Carbon authority
- Ownership
- Licensing procedure
- Clarity over responsibility of regulators
- Recognition of value chain – requires different regulations
- Operating procedure

- Licensing procedure: monitoring, verification, how obtain and how surrender – links with liabilities and remediation
- Technology and policy transfer
- Level of CO_2 – what amount of impurity is allowable?

- Position of CCS in UK energy supply mix – opportunity costs, competition – what is the balance between maintaining existing supply technologies, developing renewables and developing new technologies (e.g. CCS)
- Can CCS fit with a more decentralised system?

Regulatory roadmap - What regulatory framework is required to support CCS deployment?

- Public perceptions
- Need local infrastructure
- Strategic Environmental Assessment needs doing offshore regions (2 years to do see entry on table)
- Will / how will this routemap enable big multiplaction (?) ready after 2020, x20, x100 scale up? => needs political will
- Focus on competition not helpful – too narrow
- Need to focus on multiple subsidised "demonstrators" which are commercial "MK I --> MK II"
- All have negative NPV at present and need to fund the higher priced electricity by some method e.g. different support for value chains for different CCS types of demonstrator

General comments from Table 2 (day 2 plenary)
No REAL discussion of addressing public perception /education
Roles and responsibilities of government Industry and Academia?

Need to separate EOR using CO_2 from storage of CO_2. EOR might provide a cash-flow benefit in some isolated cases. Storage will have a different business model to EOR so financing and executing storage will be different to financing and executing EOR

No real consideration or discussion of future value chain / business model for CCS Industry. How will these discussions / issues influence the flow of cash / profit throughout the system?

	GRP	GOAL	PATHWAY	GAPS	COMMENTS
2007	A3	Ensuring balance between energy technologies: existing (security of supply/renewables/CCS)	• Consistent communication of importance of balance • White Paper to provide revised incentives • (Power) engineers go to university for free OR get bursary	• Market doesn't drive long term investment when major change required • World shortage of materials and skills for new build	
2008	A1	Early support for demos	• Grants: - demos - commercial	• Certainty of ETS - will it be there post 2012? - underpinning	
2008	A1	To have in place a sufficient and robust set of controls (licensing, and operation and abandonment) to enable early project	• Completion of, and influence over, minimum international guidelines (OSPAR, LC/LP) • Permitting authority for storage, transport, capture (2008)	• Government lethargy • OSPAR and/or LC/CP not resolved in harmony	

		development/ implementation. Requirements agreed end of 2008, in force end of 2010	• Resolution of trans-boundary procedures (?2010) • Resolve OSPAR (end 2008)		
2008	A1	Long-term liabilities – UK Demo project (link to 2012)	• Government decision for demo project	•	
2008	A2	Fit CCS into existing petroleum licensing regime	• Gap analysis – use regulatory consultation – fill gaps	•	
2008	A2	Establish monitoring requirements	• EU/UK consultations • IEA GHG best practice guidelines • Agree what is needed: - timeframe - risk base (not one size fits all) - minimum acceptable for stakeholders	•	
2008	A2	Clarify incentives for early adopters	• Mechanism to allocate subsidy – technology neutral*	• Government subsidy	
Add	A3		• CCS-specific mechanism to incentivise CO_2 saving	• Change government approach/ sympathy to specific incentives	
2008	A3	Incentives – objective 1. Provide definite continuous financial framework 2. Optimise cost/benefit for Government 3. Promote early start	• Extra capital allowance for capture plants for specified period only (large upfront cost) – compare with R&D • ETS: floor on price of CO_2*– guaranteed continuity of scheme for long term		
2009	A1	To have an obligation to establish x (small) amount of CCS	• Consistency with the Climate Change Bill • Primary legislation to	• How to handle consideration of imported carbon	• Good for short term • Potential conflict with EU competition

		commissioned by 2015. Obligatory on sites emitting more than y tonnes COs per year [compare with Renewables Obligation	impose additional cost on emitters • Obligation extends to imports with large embedded value of CO_2	through imported goods	regulations
Add	A2	Comment that incentive proposed is too high level – better to focus on carbon intensity per kWh	•	•	
2010	A1	Effective incentives	• National Allocation Plans (NAPs): - tightening - agreement between countries - enforcement • All sources of CO_2: - sectors: power, industrial, domestic - balance/equity - allocation • Tax breaks - capital - petroleum revenue • Government underpinning of carbon price – 'contract for difference'	• Low carbon price (due to soft NAPs) • NAPs - no consensus between countries - non-compliance	Need to sort out incentives - but not covered within the DTI 'competition'
2012	A1	Fairness of incentives	• Decoupling carbon price and hydrocarbon price (energy price) • Post-Kyoto	• Developing countries (post-Kyoto) if do not have reduction targets • CDM • Perceived unfairness between sources/sectors • Carbon price interaction with hydrocarbon price – decoupling needed	

2012	A1	Long-term liabilities – to support commercial projects in longer term	• Risk allocation – consultation, clarification of risks, consensus • Capture • Transport • Storage – ongoing & post-storage operations • Mitigation of risk	• Insurability of risk? • Clarification of risks • Likelihood of leaks • Impact of leaks • Public acceptability – onshore/offshore	
2012	A2	Establish licensing authority (long term)	•	•	
2015	A1	Viability – about 40 euro per tonne co2 via range of incentives. Supersede obligations to CCS with allowances by 2015 (2020)	•	• Remains unviable	
Add	A3	Viability is at 60 euros per tonne (BP Peterhead figure)	•	•	
2015	A3	Clarify whether, and if so how, CCS has a role in a more decentralised energy system (2nd generation of CCS assuming politicians driving 1st generation)	• ?'Second generation' capture technologies likely to be appropriate for decentralised use (learning from 1st generation and following proving of transport and storage elements • Explore scope for centralised 'capture' (fuel processing) and decentralised generation (with CHP) [pre-combustion capture] • Explore scope for capture technologies associated with decentralised biomass (UK woody) use (for heat and/or power) [pre- or post-combustion capture?]	• In decentralised system, will CCS win enough policy attention? • Knowledge over compatibility of CCS and CHP on the same plant • Clarity of proportions • Political will • Technical transition from centralised to decentralised	Can we design CCS centralised to be compatible with decentralised CHP (50 kton CO_2 / yr) needs a pipe one way or another implies conceptual long term > 2025 More experience / knowledge needed

Appendix C: Output of Station B – Regulation and consents

1. The three group sessions each opened by considering the following question: Which regulations and consents will be required for deployment of CCS? Each group added to the list generated by the previous groups.

Capture

- Pollution control – IPCC
- Section 36 of Electricity Act – required for retro-fit and new plant from Secretary of State or devolved administrations
- Local authority planning consent – will require HSE (Health and Safety Executive) analysis, an EIA (environmental impact assessment) and stakeholder consultation.
- Grid connection – generic for all power stations; capacity constraints may be an issue given ideal potential location for CCS on East of UK

Transport

Ship

- May be used for small scale demonstration projects or transport over distances offshore greater than 500 km
- Maritime regulations – not thought by group to be an issue

Pipelines

- PSR – pipeline safety regulations for onshore and offshore, and including the use of existing pipelines
- Consent for pipeline on seabed – to be secured from DTI and Crown Estates. Will require consultation with other marine users, and local stakeholders
- Re-consenting required for re-use of existing pipeline – not required for EOR
- EIA
- Planning permission for onshore pipelines – requirements for permission from all local authorities along pipeline route likely to be amalgamated and consent sought from Secretary of State
- Section 30 for pipelines

Storage – assuming that this means disposal

- There was discussion as to the definition of the term storage, and whether this meant permanent disposal or EOR. In the future, CO_2 may become a valuable commodity for EOR and there may be benefits in removing CO_2 from storage in one site for EOR in another.
- OSPAR – this is not an issue for EOR
- License for site operator including provision for ongoing monitoring
- Long term liability – this is assumed to be handed back to the Crown; quality standards required for seal;

2. The following GOALS were identified, focusing on the question of which consents would need amending to allow for CCs deployment (*items underlined were worked up within the roadmap)*

- National planning framework for CO_2 pipelines
- <u>Resolve issues of long term liability (crucial issue)</u>
- National planning framework for CCS plant – streamlining existing process (disagreement over this goal)
- <u>OSPAR – essential for getting CO_2 off the ground</u>
- <u>Monitoring standards</u>
- <u>Decommissioning – risks and liability</u>
- <u>Health and safety consent for long pipelines</u>
- <u>Health and safety consent for high pressure CO_2 injection offshore</u>
- IPCC regulations for use of chemical in capture plant
- COMAH – control of major accident hazards
- <u>Quality of CO_2 and impurities e.g. H_2S – risk assessment for pipeline planning</u>
- Re-using hydrocarbon reservoirs - whilst a lot is known about depleted oil and gas fields, their properties change from baseline characterisation .e.g. cap rock, therefore they could not be pressurised with CO_2 to original pressure.
- Is infrastructure left to the free market, or is a more strategic approach required given the number of key players?
- Regulation to reduce impact of storage on fisheries and other marine uses
- Safety case of manned platform with CO_2 coming in – need to regulate for large leakage of dense case and how the platform would be evacuated.
- Storage onshore

The following additional issues were highlighted:

Inheriting abandoned wells, which could be leakage paths.

Areas of non-consensus

- Streamlining of planning framework – some saw this as essential, others questioned whether it was desirable
- Whilst regulations for hydrocarbon fields could be adapted for aquifers, these were deemed to present different challenges, but disagreement over what these were e.g. reactiveness around the borehole

Parked issue

- Need to cross check elements of roadmap with appropriate experts whose area of expertise may not have been included amongst workshop participants.

Consents and regulation – Roadmap

Comments from Table 1 (day 2 plenary) marked on matrix

Comments from Table 2 (day 2 plenary) marked on matrix

	2007	2008	2009	2010	Comments
Goal				Resolve OSPAR framework and translate into UK regulation	▪ See DTI timeline ▪ Need to clarify meaning of London Protocol words and ensure harmony
Pathway	▪ Contingency route – intensify research on on-shore options e.g. saline aquifers ▪ Bonus – China likely to need saline aquifer technology rather than oil/gas reservoirs	▪ Defining CO_2 gas an exception ▪ Using EOR as a worked example to demonstrate effective CO_2 management	▪ Clarifying and resolving differences under OSPAR ▪ Establishing appropriate monitoring arrangements/protocols		▪ Not much oil in China ▪ Aquifers longer term
Gap	International opposition to undersea storage				
DTI timeline	Technology guidance Legal amendment June	Ratification by 7 countries			
Goal			Balanced standard; min burden; sufficient risk protection		
Pathway		▪ Learn from existing regulations – COMAH/PSR and amend as			

	2007	2008	2009	2010	Comments
		necessary to minimise burden ▪ Evaluate risk			
Gap			▪ Evaluating comparative risk ▪ Understanding public perception		
Goal				Resolve issue of long-term liability	
Pathway			▪ Establish 5 storage phases: ▪ Exploration of site ▪ Assigning rights to a storage operator ▪ Need extra phase of full site characterisation ▪ Injection ▪ Closure/decommissioning and monitoring ▪ Handover and Crown		Exploration of site will not be optimal if rights have not been assigned.
Gap		Clarify crown ownership rights	▪ Who decides payment from site operator to crown? ▪ For oil/gas fields, division of responsibility between oil field operator and storage operator		▪ UK only has rights to 'exploit'; technically UK doesn't own oil either. ▪ UK needs to claim pore space > 12 mile limit
Goal		Window of opportunity to devise regulatory structure for decommissioning – risks should be comparable to oil and gas			
Pathway	▪ Procedure and timelines for decommissioning	▪ Performance standards for equipment leaks ▪ How and who pays for financial decommissioning – financial bond	▪ Monitor reservoir – departure from predicted performance		

	2007	2008	2009	2010	Comments
Gap				Too expensive	
Goal				Integration with oil/gas regulation	
Pathway			▪ Testing difference between sc-CO_2 injection and present water and gas injection ▪ Design and certification of CO_2 recompression equipment ▪ Specialisation of well completion for CO_2 injection		
Gap				Risk of making saline aquifer injection uneconomic through over-regulation	

Year	Goal	Pathway	Gap	Comments
2007	Models development for UK Agencies (DTI, EA etc)	UNIV, C of E developing the models	▪ Acceptance of service models (water industry, telephones) ▪ Missing elements	
2008	Health and safety consent for onshore pipelines	▪ Operator protocols –prove you are a competent operator ▪ Devise pipeline inspection procedures and incorporate in pipeline regulations – HSE ▪ Design codes for pipes and associated equipment for dense phase CO_2 – incorporation into British Standards ▪ Studies of dispersion characteristics- kill zone – may be more correct to talk about impact radii or circles, or Building Proximity distances	▪ HSE – lack of experience of CO_2 pipeline ▪ Design of pipelines limited by supercritical CO_2 not being defined as hazardous in the UK	One of the gaps is that supercritical (dense) CO_2 is not categorised in the current design codes, therefore before pipeline design can begin a consensus needs to be established on which level of hazardous fluid is to be used

2008	Fluid displacement (injecting CO_2 in aquifer) or pressure build up	Boundary of aquifer, seal pressure fracture	More research on seal integrity	
2008	Health and safety requirements for change of use of platforms (pipelines) for CO_2	▪ Health and safety gap analysis, oil and gas safety regulations – CO_2 safety ▪ Research required to close gaps ▪ Establish standard	▪ Cost of compliance impacts on economics ▪ Leak detection monitoring ▪ Public debate/enquiry - delays/blocks	
2008/2009	▪ CO_2 specification ▪ Impurities ▪ Pipeline damage ▪ Impact on storage	▪ Purity requirements ▪ Limitations ▪ Identify boundaries	▪ Danger - CO_2 spec set by default ▪ Sharing of knowledge ▪ Split of standard between owners	

Appendix D: Station C – EU and international policy

What are the international and EU policy requirements for establishing commercial scale CCS?

Brainstorming

- Existing EU Directives (water, landfill etc. liability) impact on storage
- Should UK buy into other overseas projects rather than bear entire risk?
- Trans-boundary shipment of waste
- State aid rules/world trade rules
- Slow rate of CCS feeding into EU ETS
- Weakness of EU ETS
- Uncertainty of EU ETS
- Clarity of including CCS in JI
- Post 2012 negotiations (Kyoto)
- CDM as enabler
- OSPAR not yet aligned with London
- Price of fuels (and rise of LNG) impinge on use of coal (or gas)
- Aspiration (EU demo) leading to policy
- UK participation in EU demo process
- Competition law may prevent consortia/industry benefits
- Exporting emissions, EU/UK CO_2: how to cut 30% by 2020

Regulatory roadmap - What are the international and EU policy requirements for establishing commercial scale CCS?

- Strategic Environmental Assessment (SEA)
- UK needs to decide long term vision and initiate strategic environmental assessment for most likely geographic areas
- SEA 1-8 for all oil and gas and renewables. Show the mechanism can be DBERR or DEFRA – this requires stakeholders engaged (including public) + flush (??) not generic environmental + socio economic issues.
- Includes impact on coast and coastal facilities

Comments from Table 2 (day 2 plenary) marked on matrix

	GRP	GOAL	PATHWAY	GAPS	COMMENTS
2007					
2008	C1	How to minimise risk in RDD for UK out to 2015	• UK demos (UK lead) – shared risk with international collaboration (2010)	• No clear process to invite other nations to collaborate at significant level ie buy into UK demo projects	
2008	C1	Correct functioning for coal and natural gas market	• EU energy policy - security of supply - price	• Dysfunctional gas market • Energy supply from unstable countries • Adoption of UK extension in China/India	~~Not~~ a good description better is 'volatile' especially on minor spot trade volumes. Real issue is CO_2 price and need to stabilise long term CO_2 mean price e.g. by long term CO_2 contract
2008	C2	Clarification of CCS as pre-competitive	• EU/UK writing rules of engagement/communication of competition for demonstration project • Transparency of technology development, risks (etc) of selected demonstration	• Problem of competition law in some EU countries • Unknown issue of competition law across EU	

			projects • Mechanisms for further support for other projects (and future under-developed projects)		
2008	C3	UK in EU demo process	• Define demo objective • UK influence definition • Fit of UK demo into EU demo process	• Willingness to co-operate (IPR) - company - national - governments • Lack of definition	
2010 (for 2020)	C3	UK inputs to EU CO_2 reduction targets	• Reductions of 20% or 30% or ??? - impact of CCS • Decision point on 20%/30%/??? - when - how • International persuasion re higher targets (EU 30% commitment on others) • UK to define our reduction 'mix' – interacts with policy • CCS demos – leads to assurance of realistic targets	• Factors underlying the 'mix' ie EE, RE, FF, nuclear - analysis - transparency • 550ppm – enough reduction? Or 450ppm or less? Interacts with science • (Non) participation of USA and developing countries	
2012	C1	CCS in EU ETS Sub-goal: - CO_2 price - Alternative incentive	• Investigate alternatives • Member buy-in agreement • EU ETS Directive negotiation • Technical regulation clarity • Lower allocations • Member commitment	• Member willingness • Whole new negotiations	
Added	C2	Outline intentions for phases 4&5			
Post 2012	C3	Government have a basis for inter-governmental trading to meet caps or less CO_2 emissions. CO_2 value based on fundamental totals of carbon mined and carbon	• Politics first to decreasing targets and shares and then action by industry • Create value by limiting carbon minimum plus CCS • Explore fundamental drivers and resources	• Artificial benchmarks • Easy to cheat (?) • Fraud • Problem of the commons • Avoided vs. captured not worked	

		sequestered	• Dig carbon loosely compare with looking for gold (limited supply) ?	out – what reference?	
Post 2012	C3	EU ETS: certainty in regulation for around 15 years	• Fully efficient trading scheme • Delivers right CO_2 price •	• ETS rules change every few years	
2015	C2	EU policy: does Basel apply [trans-boundary shipment CO_2]	• EU Directive modification	• Technical • Economic • Political	Modification of EU directive (phase 3) is being discussed in DEFRA / ETG with view to including CCS

Appendix E: Station D – Urgent technology breakthrough

What are the urgent technical/hardware requirements?

Includes comments from Table 3 (plenary, day 2)

Neither groups felt comfortable setting out goals etc on a time line for short term technical developments

Integrating a full scale plant

- Post combustion - volumes of CO_2
- Pre-combustion – is IGCC fully commercial without capture (= 85% load factor, 45% efficiency)

Community (industry) recognise that starting demo phase is crucial step in ironing out technicalities – not a case of big picture, by version 3 or 4 will achieve commercial

Diversity of demonstrations in UK to spread risk, or is it enough to demonstrate partly elsewhere?

Oxyfuel less well developed than pre or post combustion (e.g. new alloys)

Burning hydrogen in gas turbine (DFI) – group 2 disagreed with how novel this is

Behaviour of CO_2 when released (source term)

Storage:

- How CO_2 behaves when stored (validating computer simulations)
- CO_2 EOR offshore: re-engineering of rigs etc to deal with CO_2 (Miller does not have these issues to same extent as field already CO_2 contaminated), life extension
- Regenerating CO_2 from the oil that is recovered
- Characterisation of aquifers

Premature exercise – depends on DBERR decision on demonstration (Road map – technical)
Risk versus potential

Least risk – quick run round each person to pick their favoured option for least risk demonstration:

- IGCC
- Hydrogen reforming from methane – burn in gas turbine, store in depleted gas field already confirmed with CO_2
- Post combustion (with greatest potential including EOR)
- Technology appropriate to China/India and decentralisation
- Retro-fit (post combustion) but pre has none at all (x 3)
- Post combustion – which solvent
- Onshore pipeline, new infrastructure

Should highlight that this is least technically risky as all of the experience e.g. in the States is onshore. Only one offshore pipeline has been built by Statoil and it is not yet operational.

Group 2

- No technical barriers to CCS
- Demonstration plant, commercial scale in short time, 1st generation
- Issue with definition of demonstration plant
- Government aim of demonstration plant – low risk of proven technology (e.g. DF1 --- 2012) or innovative new technology (Futuregen 2015 +) which is high risk
- Technical risks outweighed by 1st user benefits
- Scale up; integration; operator experience; containment (preventing leakage) demonstrated
- All low carbon technologies are not good for grid – base load or intermittent
- CCS exacerbates existing problem: more plant competing for base load

Terminology
- technicalities versus technology breakthrough
- demonstration versus R&D
- gap between industry and academic
- criteria for selecting demonstration plant

Appendix F: Station E – Integration

- Different levels of integration required:
  - Within source
  - Pipeline – need for temporary storage for balancing flows
  - Injection
- Supply of fuel and the technology used will have issues for capture and transport
- Location and size of compression equipment, though large scale compression is carried out in other processes e.g. acid gas injection
- Scalability - important that all parts of the process are sized so they can be integrated and this has implications for the scale of demo
  - For example, two 800 MW will produce 8.5 Mt CO_2 – this will need a pipeline to transport CO_2 to a site
  - Thus different capture processes will be appropriate for demonstration at different scales
- Integration of capture plant with the need of a generator to supply electricity
  - Flexibility to shut off plant when price of electricity is high and make extra money by avoiding energy penalty of CCS
- There was no consensus as to the ultimate aim of the demonstration plant – either:
  - Prove capture first and then prove other parts of the process later, or use an existing CO_2 stream to prove transport and capture (add contaminants for realism?)
  - Coupling parts together to test performance and explore impact of CCS on value chain components such as the sale of electricity

- Is a demonstration pipeline part of a network or a one-one to point to point? E.g. can Miller grow or is it too isolated from other point sources?
- Solvent disposal, size of scrubbers
- Flue gas desulphurisation
- Nearness to deployment: Miller, IGCC first, post combustion gas, post combustion coal, oxy fuel later
- The quality and state of CO_2 required post the capture process and needed for transportation and appropriate storage needs to be clarified. This can impact upon the capture/generation process costs and specifics.

Disagreement over the need for intermediate storage:
Oversize pipelines to provide buffer capacity or vent CO_2

EOR

- Does it complicate demonstration project – add additional challenges?
- Method of EOR – WAG or gravity feed has an impact on integration with the CCS process

Group 2 addressed the following questions to decide upon goal of demonstration project

1. Is purpose of demo part of strategy to start large scale deployment, facilitate deployment overseas or to feel good? This is not clear from a policy perspective
2. EOR or simply storage – offshore challenges of EOR are huge which confuses the objectives
3. For offshore storage alone – choose the shortest route as this will cost less, fewer issues for recompression offshore. Good sites would be Southern North Sea or Irish Sea

4. An ideal site would meet the following criteria: large amounts of CO_2; existing landfall permits and follow route of existing pipelines; close to shore; simple storage site
5. Timing – depletion curves, conflict of uses and potential need to identify areas which should be prioritised for CO_2 storage and those prioritised for gas extraction
6. Goal for timeline (Figure 2) – demo to facilitate wide scale deployment to address climate change (800 MW plant)

Figure 1 Issues of timing and scale for integration (Group 1)

				Storage			
	Demo	Commercialisation	Transport	Aquifer	EOR - WAG	EOR - gravity	Depleted gas field
IGCC		2012-2014 450MW-1GW	Pipeline Onshore 5-7 yrs Offshore 3-5 yrs	No timing issues	Storage starts a few years before production ceases Would need buffer as IGCC continuous feed of CO_2	Storage starts when production ceases	When exhausted – fields available now
Post combustion	1MW		Vent				
	2013 30 MW		Mineralisation Ship				
		2017 800 MW	Pipeline				
Gas - Miller		2010/11/12 350 MW – though classed as demo for funding	Pipeline				

Figure 2 Time line for deployment of large scale (800 MW demo project) by 2015

2007	2008		2009	2010	Comments
Clarity of purpose of demo plant from government			Full feed package	Order with contractor	
Ring fenced incentive package			Fully costed project		
Agreement on liability – model from elsewhere					
Criteria for choosing capture plant concept – IGCC/PC etc	Capture concept				
	Scale of capture impacts on pipeline	Pipeline decision – size, first part of network			
Storage concept	Storage strategy – one off site or strategic development of area				

Appendix G: Station F – Cost reduction

What needs to be done in the short-term (2015) to reduce the costs/increase revenues of CCS and make it economically viable?

Brainstorm

- Relationship between contract cost and risk – aim to reduce risk
- ‘Brown Book’ equivalent on CO_2 containment and release
- Reducing operator risk
- Lower cost capture technology (capture is 65-85% of total costs)
- Proving a technology
- Building power plant close to the sink
- Multiple users of same source/sink
- Not over-burden with regulation
- Infrastructure re-use
- Build capture-ready
- Shared facilities between different industries – lead by Government
- Look at new paradigms e.g. Australia hub approach
- Learning from other countries – not reinvent what has already been done
- Develop technologies
- Develop cheaper materials
- Skills issue – retraining

- Amazingly high price of CO_2
- Don’t try to capture all CO_2 – partial capture sufficient?
- Who pays? Important in gaining political support

- Working together – sharing costs/risks/value
- Balancing system
- Not picking winners

Cost reduction Roadmap

What needs to be done in the short-term (2015) to reduce the costs/increase revenues of CCS and make it economically viable?

Comments from Table 1 and Table 3 (day 2 plenary) marked on matrix

	GRP	GOAL	PATHWAY	GAPS	COMMENTS
2007	F1	Develop cheaper materials (pipeline and process)	• Develop (R&D) new coatings/surface finishes, linings (near point of injection)	• New sources of cheaper stainless NACE (National Association of Corrosion Engineers) compliant	Capture/transport/storage
Add	F2		• Global working parties to share development costs	• Global availability of the materials necessary	
2009-2012	F1	Reduce costs by re-use of infrastructure [gap exists between short-term decommissioning of existing vs new investment in plant in longer term]	• Retrofit capture to existing power generation	• Make low efficiency power stations less efficient • Post-combustion capture not technically proven yet	Transport & storage
2009-2012	F1	Reduce costs by re-use of infrastructure [gap exists between short-term decommissioning	• Location of platforms close to storage reservoirs • Pipelines in the right place (identify them!)	• Infrastructure is decommissioned before CCS starts • Infrastructure used for other purposes • Ownership and commercial	

		of existing vs new investment in plant in longer term]		complexity • Asset trading • Infrastructure is old – integrity is poor • Metallurgy for CO_2 use	"re-lining" required to update old existing assets – lower costs of this. Monitoring Gap – no single ownership of infrastructure
Add	F2		• Norwegian/UK study on North Sea infrastructure – report due out in July 07 – deals with pipeline issues • Timing of cessation of production vs injection of CO_2 needs clarification	• Limited availability in short to medium term to re-use pipes • No one has job of integrating North Sea infrastructure	
2010	F1	Build capture-ready to reduce cost (possible?)	• Defining 'capture-ready'!! • Space for retrofit • Capture process • Address local regulations • Timeframe • Source/sink match • Route to storage • Minimum emission limit post-capture • Economic analysis (of time to absorb additional cost) – downtime=loss of revenue • Regulate 'capture-ready' as part of permitting • 'Template' for design (and economic?) studies • Process to mitigate risk of operator	• May divert focus from retrofit R&D • Public acceptance – are utilities stalling? ('window dressing') • Does 'capture-ready' limit plant flexibility (fuel) • Does being 'capture-ready' make operator vulnerable (ie easy 1st target to force into capture) • What if 'capture-ready' today doesn't address capture technology of tomorrow? • Regulatory Authorities don't	Cost-risk trade-off of waiting for innovation to retrofit. What carbon price Waiting fore innovation (policy, economic, tech etc.)

		"storage ready" – e.g. do not cap depleted oil and gas fields		have understanding/ capability • <u>Increases</u> cost in short-term. Reduces in long-term? Presume yes	
2010	F1	Multiple use of same source/sink	• Same as hydrocarbon route • Possibility of single/joint ownership with multiple wells and provision for future use	• Monitoring and liability issues • More political than technical • Who bears the costs?	
2012	F2	Reduce operator risk Replace: 'increase CO_2 value'	• Satisfy internal hurdle rates over project life • Improve reliability of demo plant • Reduce some operator risks • Merit order neutral therefore plant will 'run' • Understand costs of flexibility of plant • Understand optimal 'operating point' for margin operating expense vs. capture rate	• CCS reduces reliability and flexibility of plant/system • Incentives not in place e.g. EU ETS	
2015 (results but start 2007)	F2	Cutting the energy penalty of capture (currently 30%)	• Technology R&D e.g. membranes/coatings (not currently a UK speciality – choice for UK as to whether to pursue) • Explore other processes (e.g. chemicals, cement, which may have lower	• Knowledge gap: can EOR be seen as reducing energy penalty of system (CCS)? If so, why? If not… • Lack of targeted commercial	

			energy costs in capture) • Enhance solvent efficiency for post-combustion capture • Energy-efficient separation for O_2 (?membranes vs. cryogenic) • Provisions for upgrading demo plants (into experimental facilities) – technically feasible? Commercial cost?	investment	
2015	F2	Successful commercial operation after 3rd iteration [demo is not the end of the process] Getting the policies and thinking / plans in place by 2015, but the 3rd iteration won't be operational by 2015 Slim line drilling technology	• Allow demonstration projects to demonstrate (bridge gap to commercial viability) • Stepped deployment options proving technical and commercial effectiveness • Ensure support for development – 'market pull' R&D micro engineering new materials	• Needs parallel mechanism alongside market Create market opportunity	
		Evolution of monitoring electronics	• R&D micro engineering new materials	• Specialised electronics / environment	

Appendix H: Station G – Storage

Feedback to plenary

Perception
- Public
- Standards
- Future-proof

Leakage
- Infrastructure
- Boreholes in the hydrocarbon fields
- Cap rock, faults….
- Perception
- Fast or slow

Liability
- (im)-purity – leak to surface
- Who?
- Timescale
- Intervention

Monitoring
- Frequency
- Quality (detection limit)
- Aquifer dissolved CO_2: fate not exceed 'natural' aquifer pollution

Design
- First sites: individual especially monitoring
- Later sites: generic rules
- Regulation clear to fir with economics date

Baseline and character
- 'Reasonable'
- Site specific

Appendix I: Station H – Transport

Discussion of points raised in CCS Survey

Technical uncertainties related to transport:

- Perception that there are no technical uncertainties
- Capacity requirements – how much capacity is there in existing pipelines, and how much new capacity would be required?
- Impurities and the boundary between capture and transport
- Corrosion – is this a perceived problem only?
- Routing of pipelines particularly within urban areas – regulations will be resolved by HSE within 2 years
- A related issue is the risk of crack propagation, particularly due to accidental damage of pipes. Crack arrestors or specification of tough materials will be required to address this issue.
- Dispersion of dense gaseous CO_2 and urban risk pattern.
- Availability of existing pipelines – in Northern North Sea, pipelines are still in use, though this is less of an issue for the Southern Basin. Existing pipelines are deemed hard to re-use for technical reasons (pressure requirements for CO_2 transport), and integrity is compromised as they are reaching the end of their life. There is therefore tension between re-use and thinning pipes.
- Pipelines – who should own pipeline network? The Teeside model is that it will be developed by a Transco-like company.
- Is regulation of the pipeline network by an OFGEM like body desirable? Offshore pipelines are unregulated, this requires negotiation between parties, getting OFGEM to agree to changes is a time consuming process.
- Pipelines are expensive. There are technical reasons for the cost of offshore pipelines, whereas onshore pipelines are expensive for routing reasons. The costs are fundamental and will not be decreased through new technology – new materials may drive the costs up.
- Ships may be used for transport of CO_2 over distances greater than 500 km, or for small amounts of CO_2. Vessels will be purpose built, as opposed to dual (CO_2 and LNG) purpose. How easy is it to convert LNG carriers?
- Metering and balancing – working and managing a network such that charges are correctly levied. How do you meter? Learn from other networks e.g. Transco, and from US CO_2 transport networks. Resolve regulatory issues within 2 years.
- Balancing pressure between source and field, and in keeping with required pressure for transport (you will not get a steady pressure output from a power station given variable load, whereas injection wells require a steady flow of CO_2).
- A big pipeline would provide buffer capacity.
- Look for other point sources of CO_2 to use in a network – Teeside.

Long term issue (2040) – How do you design transport infrastructure for the long term?

- Balancing multiple sources and sinks is the key issue
- Non trivial piece of pipe required for demo stage (30km and 36″ onshore) to resolve issues highlighted earlier – Government to meet additional costs to facilitate long term vision of CO_2 network.

- A specific source would always be there as an end of life power station is replaced since there is already a grid connection and fuel supply infrastructure.
- Finance over 15 years, but design for operating life of 50 years – could be an infinite life
- Operators will maintain a pipeline better if it is planned to have a long life time – asset integrity will be preserved. There is an issue of whether an operator will accept responsibility of long life times – Forth Bridge cited as an example of where this is accepted. Human factors are crucial.
- Is there reservoir capacity for a 50 year pipeline? Such a pipeline would only be built for targeted reservoirs.
- Developing a network would reduce transport costs in the long term, by spreading the load. Is this cost reduction worth the additional risk due to increased complexity?
- How would it be paid for?
- North Sea pipelines that have worked have been backed by big contracts therefore a CO_2 network would start with an oversized spine, anchored by a large project, and then build up incrementally.
- Aiming for a situation where there is low risk/low return, like a utility business e.g. water
- Quality of input CO_2 is governed by pipeline requirements. In 50 years, CO_2 may be a valuable commodity. A network would require future proofing e.g. harbours for delivery of CO_2 from overseas by ship. 'Network' standard for specification of input CO_2 from capture plant. Different networks would have different entry conditions, due to, for example, the length of the pipeline.
- Can quality of input CO_2 be measured? Measurement problems associated with attempting to measure in the dense phase, this could be due to the residence time within current meter designs.
- Human issues as important as technology

Appendix J: Station I – Capture

List of issues

Power generation/flexibility

- Understand what plant will play 'peaking' role for power market – understanding of the generation mix will drive understanding of flexibility
- IGCC with CCS flexibility: 100% hydrogen, 100% electricity
- Plant flexibility/reliability
- CCS <u>is</u> required for <u>all</u> fossil fuel generation – centralised and decentralised

Total environmental impact

- Reduce environmental impact of capture technology to zero (or negative??)
- Addressing other environmental/sustainability implications of capture (eg other pollutants and materials needs)

Costs

- Cost/capture penalty
- Cut cost by 50-75% by 2040
- Reducing costs

Energy penalty

- Significant reduction in energy penalty (<10%?)
- Reduce energy penalty
- Reduce energy penalty by 50%+ by 2040
- Increasing plant efficiency
- Lifecycle of CO_2 emissions of CCS/capture (=improving overall efficiency towards 90%)
- Reducing energy penalty of capture processes
- Continues drive to increase the basic efficiency of the generation technology to minimise the amount of CO_2 to be captured?

International/technology transfer/development

- Technology transfer and deployment in developing countries
- Widespread use of capture in China/India – leads to development of 'local' variants of capture technology
- Post-combustion retrofit of non-capture ready plant
- Reduce size/footprint of capture technology to allow retrofitting to 'non-capture-ready' plant
- Establishing capture manufacturing facilities in developing economies

Scale, scope, decentralisation

- Do capture processes meet requirements of a 'hydrogen' economy (if one is developing)
- Capture for mobile and dispersed applications
- Commercial availability of CO_2 capture in decentralised CHP/district heat plants
- Capture for non-power sector: chemicals, cement, etc
- Extrapolation down to smaller scales

NOTE: For all issues, cost of carbon abatement is critical (system cost, not just plant cost)

Technology transfer/development

[listed in sequence with some parallel aspects]

- R&D transfer (from now onwards) – build upon current framework eg UK to China, EU to China, Defra working with India
- Policy transfer (local)/regulatory support (need an institution?)/intellectual property (from now onwards)
- Future evolution of trading schemes to encourage development in emerging economies (2012 onwards)
- Culture aware mechanisms to deliver – active working on CDM (CCS part of it)/JI
- EU/UK commercial technology available (circa 2025)
- Involving developing economies in EU development of CCS commercial technology (starting capacity building)
- Retrofit technology evolves from EU/UK demo and commercial deployment

Other points

- Partnership – joint problem solving (conflict for UK plc – intellectual property and profits)
- Cutting energy penalty is especially relevant for developing economies

Summary

A parallel development of technology transfer beginning with R&D and demonstration in developed countries supporting dynamic growth and application in developing economies. There is high value in involving developing countries throughout this process. Emphasis on the shift from technology transfer towards collaboration and partnership.

Scale, scope and decentralisation

- Assumed
- Parallel R&D for decentralised users
- ?Sub-set of pre-combustion research stream = technical challenge for fuel distribution (hydrogen?). Retro-fitting CCS to gas turbine CHP plants
- What, if any, alternatives to the hydrogen economy might emerge from innovation? Link to 'poly-generated' from IGCC/pre-combustion plants
- Explore potential for capture at smaller scales with large industrial clusters (in China!)
- Cost reductions critical to extrapolation to smaller scales (system costs, not just capture costs)
- Focus for decentralised power remains non-CO_2/renewable/micro-geneartion (micro-CHP, Stirling engine etc.)

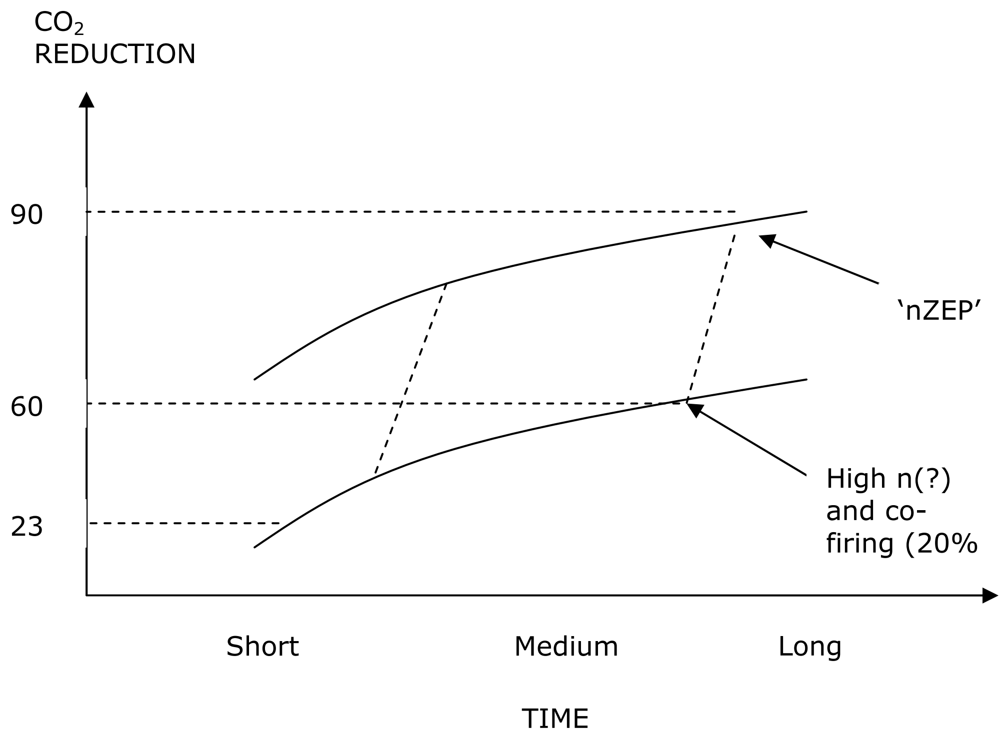
Timeline

➔ 2015 demo plants -> 2020/2025 scaling up and deployment -> 2040+ scaling down? & decentralisation

|-→ now onwards R&D for scaling down -> 2015 start for R&D scale down -> smaller scale demos -> feeds into scaling down in 2040

Summary
Parallel R&D to develop solutions over the longer-term – over the next 40 years, decentralisation will have an increasing role but balance will be decided by pace and success of technology/innovation

Energy penalty and plant efficiency (& role of biomass co-firing)



Energy penalty <u>now</u> 8-12 percentage points ie around 30%

[Is there an efficiency/lost trade off? Will society accept the cost?]

By 2040:

Post-combustion [this is today's technology R&D for 2040 technology – post-oxy pre]

- reduce solvent loss – increase life
- easier regeneration
- steam usage
- 'pre-combustion' capture cleaning
- <8 percentage points
- 'AD700'

Oxy-fuel firing [2020 demo (full scale)]

- << 8 percentage points
- pressures
- ASU – membranes, efficiency
- Reduce CO_2 recycle – materials

Biomass co-firing [why co-fire? What type of biomass? Food vs biomass challenge]

- Reduces amount of CO_2 capture required [why not aim for negative CO_2?]
- Higher mix (5-20%, 40%?)

Pre-combustion

- Poly-generation
  - mixed feeds including biomass
  - mixed (flexible) outputs ~ H_2, heat, FT fuels
- Full energy balance capability
- Latest/next generation GTs
- High-H_2 turbines
- Integration
- <6 percentage points energy penalty
- reliability issues

Summary

A matter of dealing with moving towards the highest possible efficiency plant then towards co-firing biomass and greatest extent feasible whilst moving towards near zero emissions for CCS. Over the next 30 years, reduce energy penalty. Integration with renewables to cover penalty.