International Journal of Greenhouse Gas Control 4 (2010) 1–12

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

# A roadmap for carbon capture and storage in the UK

Clair Gough [a,*], Sarah Mander [a], Stuart Haszeldine [b]

[a] Tyndall Centre for Climate Change Research, Pariser Building, University of Manchester, PO Box 88, Manchester, M60 1QD, UK
[b] School of GeoSciences, Edinburgh University, EH9 3JW, Scotland, UK

ARTICLE INFO

*Article history:*
Received 11 December 2008
Received in revised form 9 October 2009
Accepted 12 October 2009
Available online 29 November 2009

*Keywords:*
Stakeholder engagement
Climate change mitigation
Energy technology

ABSTRACT

Carbon capture and storage (CCS) technology has been endorsed by the IPCC and the UK government as a key mitigation option but remains on the cusp of wide-scale commercial deployment. Here we present a technology roadmap for CCS, depicted in terms of external factors and short- and long-term pathways for its development, moving from a demonstration to commercialisation era. The roadmap was been developed through a two-phase process of stakeholder engagement; the second phase of this, a high level stakeholder workshop, is documented here. This approach has provided a unique overview of the current status, potential and barriers to CCS deployment in the UK. In addition to the roadmap graphics and more detailed review, five consensus conclusions emerging from the workshop are presented. These describe the need for a monetary $CO_2$ value and the financing of carbon capture and storage schemes; the lack of technical barriers to the deployment of demonstration scale CCS plant; the role of demonstration projects in developing a robust regulatory framework; key storage issues; the need for a long-term vision in furthering both the technical and non-technical development of CCS.



## 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 and 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 binding on successive governments (DEFRA, 2007). The current UK goals are a 60% reduction in $CO_2$ emissions by 2050 (with recent recommendations from the Climate Change Committee for an 80% reduction in greenhouse gases 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 450 ppm 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).

Carbon capture and storage (CCS) technology is endorsed by the IPCC and UK government as a key mitigation option for reducing the emissions from stationary sources such as fossil fuelled power stations (IPCC, 2005; 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 was launched in November 2007 and, at the time of writing, is reviewing four short-listed proposals to the competition.

Most new technologies face barriers to their deployment and technology roadmaps are becoming more commonly used for identifying obstacles and opportunities facing the development of new energy technologies. This paper presents a technology roadmap for the deployment of CCS in the UK, developed through a stakeholder engagement process. Following a brief introduction to the concept of technology roadmaps, we describe the aims and process underpinning a roadmapping workshop held in 2007. The results of the workshop are summarised in three graphics, in the form of CCS roadmaps, representing the externalities relevant to the development of CCS in the UK, and goals relevant to the short-

* Corresponding author. Tel.: +44 0161 306 3447; fax: +44 0161 3273.
*E-mail address:* Clair.gough@manchester.ac.uk (C. Gough).

1750-5836/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijggc.2009.10.014

and long-term application of CCS in the UK, respectively. A discussion of issues raised during the workshop follows each roadmap. The paper concludes with five key conclusions devised as a workshop consensus.

## 2. The roadmap approach

Technology roadmaps are intended to inform R&D planning and identify research, business, government or other strategic goals, supporting the future development of a particular technology (Placet and Clarke, 1999). They are a visual communication tool devised through a structured and transparent process. Their purpose is to identify the potential pitfalls of deploying a technology and develop strategies to address them. The Carbon Sequestration Leadership Forum (CSLF, 2006), the European Technology Platform for Zero Emission Fossil Fuel Plant (ZEP, 2006) and the IEA (IEA, 2008) have developed roadmaps focusing on international activities to accelerate deployment of CCS. CCS has also been the subject of several national scale roadmaps intended to facilitate deployment of the technology in Australia ($CO_2$CRC, 2004), Canada (CETC, 2006) and the USA (NETL, 2006). The UK roadmap developed for CCS in the UK is intended to complement these other activities, whilst considering CCS in a UK context and enabling country specific issues which will impact on its deployment, such as national energy and climate change legislation, land-use planning and the liberalised electricity markets to be considered.[1]

The aim of this UK roadmap, and the workshop that informed it, was to initiate a communication process, integrating knowledge and experience across the entire CCS chain, (i.e. capture, transport and storage). This was achieved by bringing 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' approach, including planning, policy, legislation, etc., and placing CCS within the context of relevant externalities, legislation and technical requirements, rather than focusing solely on technology. This roadmap is intended to be complementary to, and feed into, the proposed Department for Business, Enterprise and Regulatory Reform (DBERR) roadmap, which, initial discussions with the DBERR had suggested, would concentrate on technology and R&D.[2] 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.

The process through which the CCS roadmap was devised took as a starting point an extensive on-line survey of more than 80 'expert' stakeholders. Initially conceived as a Delphi study, this detailed survey collected both responses to technical questions and respondents' opinions on specific issues relating to the deployment of CCS in the UK (Gough et al., 2007; Gough, 2008). Questions were organised into 8 topics: UK energy landscape, capture and engineering, storage, risks and leakage, costs and economics; incentives; regulation; international context. A traditional Delphi adopts an iterative approach to developing a consensus view on a set of questions or statements, presenting results of previous rounds to a single group of experts (Linstone and Turoff, 1975); Delphi studies have in the past involved either individual (Woudenberg, 1991) or group participation (Webler et al., 1991) in the process. The process presented here differed from a traditional Delphi study, in that it was designed to operate in two distinct phases with the survey results informing the follow-up group roadmapping workshop. The approach enabled us to build greater complexity and scope into the original survey.

The roadmapping process was broadly informed by and adapted from that described in (Placet and Clarke, 1999), adopting a 'goals, pathways, gaps' approach, taking as a given that CCS is an important technology for climate change mitigation and that its deployment would be required. Specifically the aims of the workshop were to:

(i) Provide a distillation of the UKCCSC expert survey results as a 'helicopter view' of CCS, rather than presenting fine detail.
(ii) Communicate the state of CCS technology and its prospects.
(iii) Facilitate knowledge integration on CCS.
(iv) Produce a roadmap to sit alongside other UK CCS roadmaps, e.g. DBERR.

## 3. The workshop process

This section outlines the workshop process that took place over 2 days in May 2007. Participants to the workshop were carefully selected to ensure a high level of expertise across the whole CCS chain (including industry and trade representatives, academics, NGOs, government departments, *inter alia*). 31 participants attended the workshop; priority was given to those who had completed the initial survey, with additional participants invited to ensure a balance of views and expertise. Following the workshop, a report documenting the outcomes of the workshop, including the three graphics presented here, was circulated to all participants and revised on the basis of the feedback received.

Proceedings began with three brief presentations introducing the aims and background to the workshop, presenting an overview of the survey results, outlining the principles behind the Batelle roadmapping approach and the processes to be adopted during the workshop. The workshop process was designed to map out the context for the development of CCS across two levels, each with different foci and timeframes, with a clear goal of producing a roadmap for each of the two timeframes. Level 1 considered the short-term demonstration phase to 2015 (based on EU targets for demonstration plant); this date should not be seen as an end-point but rather a milestone in preparing for 2020 and beyond. Level 2 then focused the longer term to 2040, during which CCS may achieve full commercialisation.

The workshop was organised around a combination of breakout sessions and plenary discussions, all moderated by members of the organising team. Table 1 describes the organisation and outputs of the workshop sessions. Each session was designed to deliver specific outputs as outlined in Table 1, with the flexibility for particular groups to adapt the process if necessary. 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. On the final day, participants agreed a set of key conclusions informed by discussions during the workshop and arrived at through a consensus building process.

Based on the Batelle approach, each breakout group explored a specific topic; listed in Table 1. The first stage of the breakout process was to unpack the topic into distinct elements, or goals, which would have to be achieved for the topic 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.

Sessions 1 and 2 focused on the 2015 timeframe and the addressed the two key showstoppers identified in the stakeholder

[1] The DBERR (formally the DTI) is currently developing a coal abatement technology roadmap that will include CCS; this was due to be published during 2008.

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

**Table 1**
The workshop process.

| | Topic | Process | Output |
|---|---|---|---|
| Session 1 | | | |
| *Session 1—policy. 3-Way carousel*: three groups, each group visited three stations | What climate change framework is required to support CCS deployment? | Group 1: brainstormed goals; in pairs, selected a goal, identified pathways and gaps/challenges to achieving goal, placed on timeline and presented to group. | Roadmap template with colour-coded post-its describing goals, pathways and gaps placed on time scale. |
| | What regulatory consents will be required? | | |
| | What are the international and EU policy requirements for establishing commercial scale CCS? | Groups 2 and 3: group identified any additional goals; pairs selected a new goal from the list, identified pathways and gaps/challenges or added to previous entries on timeline. | |
| *Plenary 1*—facilitators reported back and brief plenary discussion. | | | |
| Session 2 | | | |
| *Session 2—costs. 2-Way carousel*[a]: two groups, each visited two stations | What are the urgent technical/ hardware requirements? | Groups preferred to work as a whole and work up a list of issues to be discussed. | List of key technical issues. |
| | What are the challenges resulting from the integration of separate elements of the CCS process into a demonstration plant? | Group 1: identified critical issues as whole group then considered 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 for particular technologies; timeline for large-scale demonstration by 2015. |
| | 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. | Roadmap template with colour-coded post-its for goals, pathways and gaps. |
| *Plenary 2*—facilitators reported back and brief plenary discussion. | | | |
| Session 3 | | | |
| *Session 3—long-term challenges.* Single dedicated group per station | 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 for further exploration in group discussion. | List of broad issues, each with specific related points. |
| | What are the long-term technical uncertainties related to $CO_2$ transport? | Group identified key issues relevant to transport over the longer term and selected four issues for further discussion. | List of four key issues, each with specific related points. |
| | What are the long-term challenges for $CO_2$ capture? | Individuals identified key issues relevant to capture over the longer term. Group selected three from longer list for further discussion. | List of three key issues, each with specific related points. |
| *Plenary 3*: Rapporteur from each group reported back to plenary. Participants sat at three large tables, each table supplied with large printed notes from breakout sessions 1 and 2 to discuss and annotate contents. | | | Notes taken from discussion; Annotated outputs from carousels. |
| *Plenary 4*: Participants sat at three large tables, each participant identified the four key issues from the workshop as a whole, these then discussed around the three tables, each table presented four consensus issues to plenary. In plenary, the results from the tables were clustered and four key messages as consensus conclusions from the workshop were agreed. | | | Key summary conclusions agreed by all workshop participants. |

[a] 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.

survey (Gough et al., 2007), namely the lack of long-term policy and costs. The third set of breakout sessions explored the technical uncertainties relating to wide-scale deployment in the longer term to 2040.

All material generated during the workshop was documented in a final report (Gough et al., 2007) which includes detailed outputs from the breakout discussions. Three graphics have been developed by the authors, 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. The 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.

## 4. Three roadmap graphics

The following section presents the three roadmap graphics, and discusses their underlying context. The material presented is intended to summarise points made by participants during the workshop sessions, capturing the richness and detail of the discussions as far as possible, with additional material from other referenced sources. With the exception of the five key conclusions presented towards the end of the paper, it does not represent a consensus view from the workshop as a whole.

### *4.1. Externalities affecting the deployment of CCS*

Fig. 1 presents externalities at the UK, European and wider international policy levels that may affect the implementation of CCS in the UK. The discussion considers how each of the factors highlighted will be resolved, and their impact on the deployment of CCS.

In the UK, DBERR launched a competition in November 2007 for the construction of a CCS demonstration plant, specifying that it would use post-combustion capture in a coal-fired power station and offshore storage. Four pre-qualifying bidders were announced in June 2008 from the nine entries made to this competition.[3] The next phase of the competition will consider the 'technical,

[3] BP Alternative Energy International Limited, EON UK Plc., Peel Power Limited and Scottish Power Generation Limited.

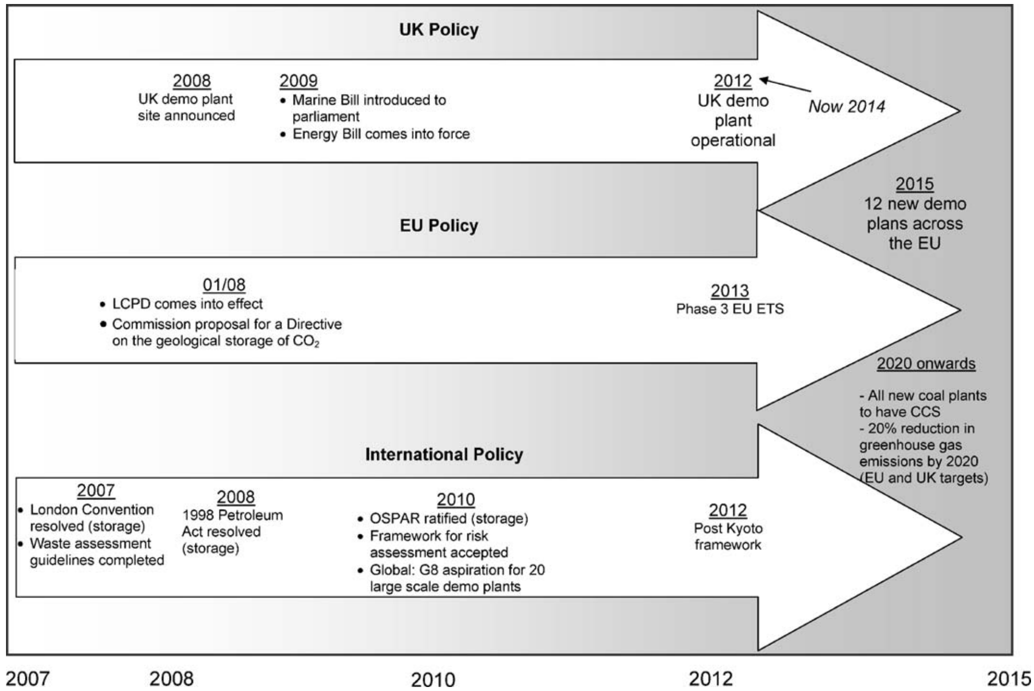


**Fig. 1.** Externalities affecting the implementation of CCS.

**Table 2**
Key European policy initiatives.

| Name | Type of initiative | Notes | Timescale |
|---|---|---|---|
| North Sea Basin Task Force | Bilateral agreement between UK and Norway | Establishes guidelines for CCS | Est. 2005<br><br>1st report (2007)<br>Infrastructure report (2007)<br>Phase II report (due 2008) |
| European Union Emissions Trading Scheme (EU ETS) | Cap and trade system across European countries and sectors | UK DEFRA Consultation on EU ETS (closed summer 2008) | Phase 2: 2008–2012<br>Phase 3: 2012 onwards |
| Directive of the European Parliament on the Geological Storage of $CO_2$ | Proposed EU Law | Regulation of $CO_2$ storage, removes barriers to storage in existing legislation<br>UK DBERR consultation on Directive (closed September 2008) | Likely to be adopted in 2009 |
| European Parliament proposed emission limit on new plant (500 g $CO_2$ per KW h) | Proposed EU Law | Requires approval by European Council and European Commission | Announced 2008, if realised would apply to new plant from 2015 |
| EC Large Combustion Plant Directive | EU Law | Limits emissions of air pollutants from plants | Came into force January 2008, 'opt-out' plants will close by 2015 |

commercial, contractual and financial issues' associated with the proposed project, aiming for the successful project to be operational by 2014[4] (DBERR, 2008a). The Energy Bill (House of Lords, 2008), which sets out the legislation required to implement the 2006 Energy Review and the 2007 Energy White Paper (including a regulatory framework for CCS projects), received its third reading in the House of Lords in November 2008. In April 2008 a draft Marine Bill was published for consultation (now complete) and is currently being amended prior to introduction to Parliament (DEFRA, 2008b). The main implications for CCS of this Bill will be to the use of offshore pipelines with the establishment of Marine Conservation Zones.

The main policy initiatives that apply at a European level are summarised in Table 2. The North Sea Basin Task Force was established in 2005 by the Norwegian and UK governments in order to establish a set of common principles for "managing and regulating the transport, injection and permanent storage of $CO_2$ in the North Sea sub-bed" (NSBTF, 2007). The first report of the Task Force, published in June 2007 (after the workshop), concluded that deployment of CCS in the North Sea would deliver direct and indirect benefits to both Norway and the UK, although barriers still remain in the form of "institutional uncertainties and associated risks" which echo those identified in the roadmap work presented here. The report identifies a brief window of opportunity of about 5 years after which infrastructure which could be re-used for CCS will be removed. A traffic light system is adopted to identify issues that, without action from the Task Force, will not be solved within the time period (red 'barriers'), are likely to be solved (amber 'follow-up') and have been solved (green 'enablers'). The red light barriers identified are: long-term liability and responsibility whilst amber lights requiring follow-up include risk acceptance and site approval criteria, economics and monitoring and verification. A

[4] The original date for this was 2012, subsequently revised by DBERR to 2014.

risk management approach is proposed covering site selection, operation, closure and post-closure phases to stimulate a Best Available Technology (BAT) approach. A set of common principles for a North Sea Regulatory Framework for geological $CO_2$ storage is set out. Phase II of the Task Force, due to report towards the end of 2008, will follow up both the issues identified in its first Phase and the results of the UK–Norway infrastructure study (DBERR, 2007) carried out on behalf of the Task Force.

The European Union Greenhouse Gas Emission Trading Scheme (EU ETS) commenced operation in January 2005 and is a 'cap and trade' system for trading emissions in $CO_2$ across countries and economic sectors. The current, second, trading period ends in 2012 after which the scheme will be extended to include further industrial sectors and aviation. It will include new emission targets, to be reduced each year and national allocation plans will be replaced by auctioning under single EU-wide rules with the power sector subject to full auctioning (EC, 2008a). CCS is included within the EU ETS current phase only via an 'opt-in' but in January 2008 the EU Climate and Energy package proposed amendments to the EU ETS to fully include CCS (proposing that $CO_2$ captured and stored would count as not having been emitted and thus not requiring permits to be purchased) and a proposal for a Directive and Communication aimed at the regulation of $CO_2$ storage and removing barriers to $CO_2$ storage in existing legislation[5] (EC, 2008b). A UK consultation on behalf of the UK Department of Environment Food and Rural Affairs (DEFRA, 2008a)[6] on the proposals to amend the EU ETS beyond 2012 has been conducted during summer 2008 and a parallel consultation on behalf of DBERR inviting responses on 'the principle of carbon capture-readiness and the regulation of $CO_2$ storage' with reference to the proposed EU CCS Directive, to be completed at the end of September 2008 (DBERR, 2008b).

On 7 October 2008, the European Parliament voted to set an emission limit of 500 g $CO_2$ per KWh on new plant from 2015, essentially mandating the use of CCS on any new coal-fired power station. This proposed amendment to the CCS Directive requires further approval from both the European Council and European Commission before becoming binding (Jowit, 2008). In addition the European Parliament also voted to establish a €10 billion fund to support CCS projects, funded from the EU ETS. This supports the European Council recommendation that the Commission enable the construction of up to 12 demonstration plant across Europe by 2015[7] and that beyond 2020 all new fossil fuel power generation plant is equipped with CCS (subject to technical and economic feasibility). The commercial use of CCS is one of seven key energy technology challenges highlighted by the European Commission in its Strategic Energy Technology Plan (EC, 2007).

The Large Combustion Plant (LCP) Directive came into force in January 2008, requiring all power plant larger than 50 MW to comply with strict limits on emissions of $NO_x$, $SO_2$ and particulate matter, plants may opt-out of the scheme for a 'limited life derogation' which severely restricts the operating time of those plants (EC, 2001). LCPs governed by the Directive may also participate in a scheme enabling transfer of annual limits between plants under the UK National Emission Reduction Plan (NERP). Since the CCS Directive will remove regulatory barriers from other Directives such as the LCPD, the main impact on CCS of the LCPD will be the closure of 'opt-out' plants by 2015.

The regulation of CCS is governed by various existing EU Directives including The EIA (Environmental Impact Assessment) Directive, the Waste Directive and Waste Shipment Regulation and the Water Framework Directive which is also currently being amended to enable geological storage of $CO_2$. The IPPC (Integrated Pollution Prevention and Control) Directive, currently being revised, will regulate the quality of $CO_2$ captured and stored using a Best Available Technique approach, for which no data is currently available for CCS (EEB, 2008).

In addition to EC Directives, offshore $CO_2$ storage comes under the jurisdiction of the London and OSPAR Marine Conventions. The London Convention[8] was amended to allow sub-seabed storage of $CO_2$ from February 2007 and its Waste Assessment Guidelines were completed in January 2007. In June 2007, the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic adopted amendments to the Annexes to the Convention to allow the storage of $CO_2$ in geological formations under the seabed within the OSPAR Guidelines for Risk Assessment and Management of Storage of $CO_2$ in Geological Formations. A recent review of the regulations governing CCS can be found in (Haszeldine et al., 2007).

The current emission reduction targets under the UN Framework Convention on Climate Change (UNFCCC) Kyoto Protocol are set for the period 2008–2012 and provision for CCS is not specified under the current agreement. After 2012 it is hoped that this will be extended and a new international agreement will be established within the UNFCCC; it is likely that $CO_2$ reductions made using CCS will be included within the post-2012 agreement.

During the roadmapping workshop described in the current paper, the EU policy breakout group considered that post-2012 negotiations (Kyoto) will provide a basis for intergovernmental trading to meet caps or reduce $CO_2$ emissions. Whilst negotiations are political, workshop participants expressed concern that they should be based on understanding of climate science and that their implementation will depend on industry. Potential problems were identified during the workshop and these include employing artificial benchmarks, the problem of allocation of non-market goods and, for CCS, a required understanding of the comparison between $CO_2$ avoided and captured.

### 4.2. Short-term: demonstration era

The near-term goals and pathways identified for the demonstration era during the workshop can be grouped into two broad areas: finance and non-technical issues (particularly in transport and storage). The specific tasks and areas requiring further clarification are summarised in Fig. 2; these are shown as pathways (rectangles) towards achieving the goals (ellipses) listed for the completion of the demonstration era. Addressing these key issues was considered to be necessary to carry CCS through its demonstration era towards the final overarching goal of bringing CCS to commercial deployment. Below we set the context for the demonstration projects in the UK, elaborating on the development of a financial framework for CCS, including cost reductions through R&D and the reduction of operator risk, and a strategic approach towards managing the non-technical aspects of transport and storage.

At the time of the workshop, no details concerning the proposed UK CCS demonstration plant were available; moreover, there was no consensus between participants over the ultimate aim of the demonstration and, for example, desirability of including EOR,

[5] Likely to be adopted in 2009.

[6] http://www.defra.gov.uk/corporate/consult/euets-2013amendments/letter.htm.

[7] Funding for CCE demonstrations in the EU will be supported through two mechanisms: firstly, the EU ETS via the allocation of 300 million allowances from the "new entrants reserve" to CCS and innovative renewable energy technologies demonstration projects (EUROPA, 2008) and secondly, under the European Economic Recovery Plan (EERP) Euro 1.05 billion has been made available towards CCS projects (of which it is envisaged that 180 million will support 4 projects in the UK (Longannet, Tilbury, Hatfield, Kingsnorth) (EC, 2009).

[8] Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 and the 1996 Protocol Thereto.

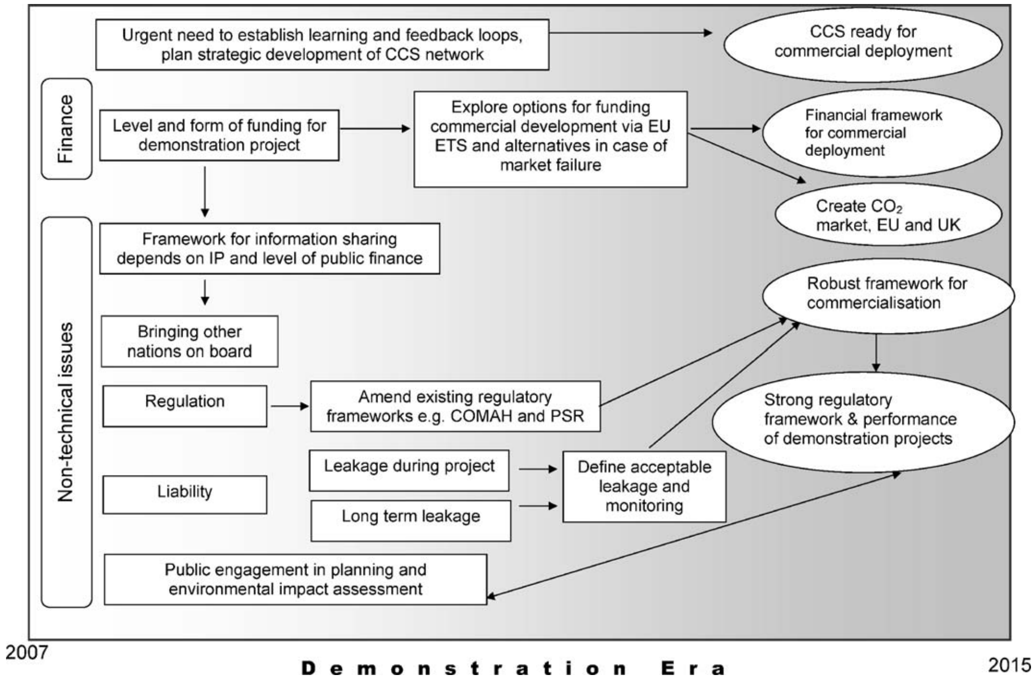


**Fig. 2.** Short-term CCS roadmap.

which capture technology should be deployed, the type of storage site and the relative importance of demonstrating the technology for the UK or for export. This uncertainty, and indeed the number of possible technology combinations, highlights the scale of the challenge in establishing a single demonstration for CCS.

The Energy White Paper (DTI, 2007), published shortly after the workshop took place states that: "*The demonstration of commercial scale CCS on power generation in the UK could enable the technology to be proven and facilitate a better understanding of the costs. In turn this could contribute to the deployment of CCS on a national and international basis*" and that the first demonstration plant "*when operational [. . .] will make the UK a world-leader in this globally important new technology*". Ultimately, the BERR competition has focused specifically on post-combustion in a coal-fired power plant with offshore storage, a scope which many would argue is too narrow, and a point that will be returned to later in this paper. Through the competitive process, DBERR will contribute "*. . .up to 100% of the additional construction and operating costs incurred by the developer*" (DBERR, 2008a), thus testing the performance of the whole system and exploring the impact of CCS on value chain components such as the sale of electricity. Given that different capture technologies will be ready for demonstration at different times, and will require 'demonstrating' at different scales, further into the future, it is hoped that additional funding will be secured from Europe for subsequent iterations (DBERR, 2008a).

This first UK CCS project is expected to begin operation during the third trading phase of the EU ETS and will provide a vital test ground for the economic sustainability of CCS. Subsequent plants will depend on the market delivering an adequate carbon price under EU ETS to support deployment of CCS, which in turn relies on the enforcement of tighter National Allocation Plans (or the emission targets that replace them) than during the current phase. 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*" (workshop participant).

To avoid demonstration plants becoming 'white elephants' further into the future, the roadmap identifies the need for the UK to explore alternative approaches for financing CCS such as feed-in obligations, a guaranteed price for low carbon fossil-generated electricity, or the by-passing of domestic State Aid regulations. Furthermore, Groenenberg and Coninck (2008) suggest that it is unlikely that the EU ETS alone will provide sufficient incentive to induce the necessary innovations and compensate for the high investment costs associated with the construction of the first CCS plants. They also present a review of alternative policies that may be used in conjunction with the EU ETS, noting that the use of a alternative market instruments may require a corresponding reduction in emission caps in order to avoid the effect of artificially reducing carbon prices (Groenenberg and Coninck, 2008).

The third phase of EU ETS will end in 2020; if the intentions for subsequent phases of the EU ETS were set out, the resultant 15 years of regulatory certainty would help to establish an efficient trading scheme which delivers an adequate carbon price.

Commercialisation of CCS can be seen as an iterative process, where 'learning by doing' ensures that successive schemes are more reliable than previous ones, reducing operator risk. Workshop participants raised concerns over the intellectual property rights associated with the operation of the first plant and consequently the level of broader information sharing from the project, which is partly dependent on the level of public funding for the project. However, the White Paper explicitly states that "*project developers will [. . .] be expected to include proposals for knowledge and know-how transfer to third parties*".

Returning to the issue of operator risk, risks have to be considered from the point of view of the operators of each element of the supply chain. For a generating plant operator capturing $CO_2$, the operation of the demonstration plant will improve understanding of optimal 'operating points', balancing operating cost and capture rate. As well as reducing reliability, $CO_2$ capture could impact on plant flexibility. Chalmers and Gibbins (2007) have explored the impact of $CO_2$ capture on plant flexibility; under certain conditions, for example when electricity prices are high, it may be cost-effective to shut down the capture plant, in order to sell the additional electricity that it would use. Under these conditions, the plant would be operating unabated (depending on the regulatory provision for unabated operation and unless facilities are developed for solvent storage, with solvent regeneration occurring when electricity prices are low) and the relative prices of electricity and carbon become crucial to the operation of the CCS process (Chalmers and Gibbins, 2007). Such interruptions to the capture process would also impact further down the CCS chain as storage site operators would have to balance $CO_2$ supply from a potentially variable source.

Crucial to the economic viability, and hence future deployment of CCS, is the reduction of costs and increase in revenue in the short-term. Key areas from an R&D perspective include materials and the need to reduce the energy penalty of capture. All stages of the CCS chain require cheaper materials, such as new coatings, surface finishes and linings (near the point of injection). Costs will also be affected by the global availability of materials. Reduction of the energy penalty of capture is currently hindered by a lack of commercial investment and knowledge gaps. Crucial areas for R&D include membranes, coatings, solvent efficiency for post-combustion capture and more efficient $O_2$ separation (membranes vs. cryogenic).

There are short-term technical issues relating to the interface between the transport and capture systems which must be resolved before full chain demonstration projects can be deployed. Water within the $CO_2$ stream causes pipeline corrosion, so, 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 also need to be addressed in the short-term. The Health and Safety Executive (HSE) are aiming to resolve regulation within 2 years and pipeline design codes will either specify crack arrestors or tough materials.

The demonstration project will include the first of many offshore $CO_2$ storage sites; initiating a strategic storage plan would identify whether the demonstration pipeline is the first element of a network linking storage sites or a one off point to point pipeline. Whilst the latter is cheaper in the short-term, in the long-term, a strategic approach to storage would reduce costs. There may be multiple users of a source/sink with joint or single ownership, multiple wells and provision for future use. This may entail monitoring and liability issues, requiring a technical rather than political solution and raising questions of cost-bearing. Timing of storage impacts on depletion curves for oil and gas fields, 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. The quality and state of $CO_2$ required for transportation and storage can also impact upon the capture/generation process costs and specifics. Given that a strategic approach to transport and storage is unlikely to be delivered by the private sector, and with the danger that a sub-optimal approach would result, government intervention is considered to be desirable.

For storage offshore, the roadmap presented in Fig. 2 highlights the need for a robust regulatory framework for the performance of the demonstration project and liability for leakage, both during injection and in the longer term. The North Sea Basin Task Force and the EU CCS Directive has begun to address these issues, as discussed in the previous section. Experience of other large infrastructure projects cautions that public perceptions of CCS will be formed around the performance of the early demonstration projects, emphasising the importance of a robust regulatory framework.

At both the EU and UK levels, the desirability of making new fossil fuel plant capture-ready is currently under debate, not least within the context of the outstanding planning decision for the proposed development of new coal capacity at Kingsnorth in the UK. The aim of requiring new plant to be capture-ready is to avoid future lock-in to carbon emissions from plant built before CCS becomes commercially available and the concept covers a range of options. However, due to the inherent uncertainties associated with how the CCS technology will develop and be deployed, it also brings with it risks of overprescribing and of building plant that could remain unabated should CCS technology fail to achieve commercial maturity (Markusson and Haszeldine, 2008). Various definitions for capture-ready have been proposed (for example, (Bohm et al., 2007), (Irons et al., 2007)). Markusson and Haszeldine (2008) present a detailed review of the capture-ready debate and the implications associated with varying degrees of capture-readiness. They propose that the capture-ready concept should extend to technical modifications to the power plant; additional space for equipment, pipes and expansion of support systems; assessment of methods and routes for the storage and transport of $CO_2$ captured; development of skills to operate the plant and coordinate the actors across the CCS chain; identification of the full CCS value chain and clear regulation to enforce the conversion to fully operational CCS (for example within three years of a full CCS chain becoming operational anywhere in the world). The recent DBERR consultation (DBERR, 2008b) on capture-readiness and the EU CCS Directive should add further clarity to the debate.

## 5. Long-term: commercialisation era

The long-term road map shown in Fig. 3 shows key challenges for each of the three main stages in the CCS chain: capture, transport and storage. It covers the longer term, following the demonstration era, mapping out requirements for CCS in its transition towards full commercialisation in the UK. These specific challenges, or pathways (represented on the diagram as rectangles), towards the long-term goals (represented on the diagram as ellipses) are elaborated in the following section.

### 5.1. Capture

The system cost of carbon abatement is critical when considering any improvements to the CCS process, with the potential for reducing costs by 50–75% by 2040 identified during the workshop. Cost reductions in the capture process underlie each of the three main challenges identified below for the longer term. These are: reducing the energy penalty, promoting technology transfer to developing countries and an increased role for CCS in decentralised applications.

Clearly, reducing the energy penalty and improving plant efficiency, including the role of biomass co-firing, are essential ongoing goals in the development of capture technology particularly for the use of CCS in developing countries. Aiming for an energy penalty which is as low as possible was considered preferable to setting a target; feasibly, this could yield a reduction of 8–14% below the current penalty (which is approximately 30%). The potential for improvement varies with technology; the greatest opportunity for improving energy efficiency is offered by pre-combustion capture, whilst it is relatively limited for post-combustion capture and the oxyfuel process, the latter being constrained by the air separation process. Noting that achieving the highest possible efficiency remains the top priority, the introduction of biomass co-firing could enable the system to aim for near zero emission CCS. In addition, taking into account other environmental and sustainability implications of capture (e.g. other pollutants and materials needs), the aim is for zero or even negative impact from capture technology.

A parallel development of technology transfer, beginning with R&D and demonstration in developing countries would support dynamic growth and application in developing economies. An emphasis on the shift from technology transfer towards true

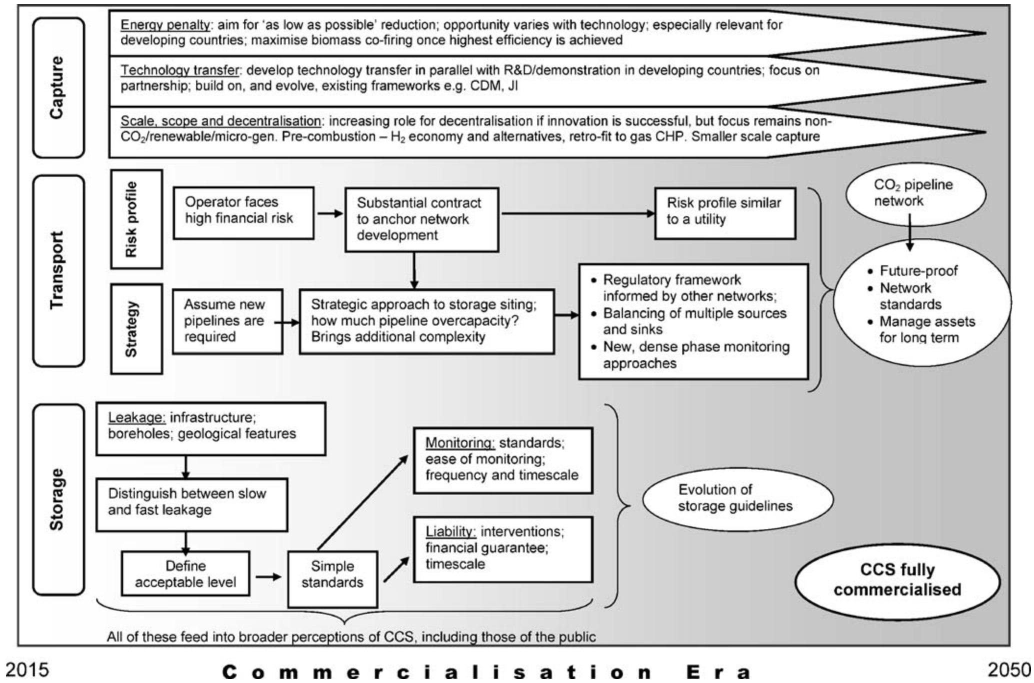


**Fig. 3.** Long-term CCS roadmap.

collaboration and partnership between all countries would build on existing frameworks and could be facilitated by the evolution of trading schemes (such as the Clean Development Mechanism, Joint Implementation). This will entail consideration of specific policy requirements such as local conditions, regulatory support and the resolution of potential on-going intellectual property issues.

In the longer term, a greater understanding of power generation flexibility may be required, for example IGCC with CCS could range from 100% hydrogen to 100% electricity. Over the next 40 years, decentralisation will have an increasing role in energy supply and CCS may be required for all fossil fuel generation, both centralised and decentralised. The focus for decentralised power currently remains on non-$CO_2$ producing renewables and micro-generation (such as micro-CHP, Stirling engines, etc.), the balance of technologies will be decided in part by the pace and success of technologies and innovation. Cost reductions across the whole system will be critical at large industrial clusters; R&D to address challenges associated with incorporating CCS at decentralised applications in the longer term is required in parallel to that directed at larger centralised applications of CCS. Specifically, pre-combustion capture brings technical challenges for hydrogen distribution and developing alternatives to a hydrogen economy, techniques are required for retrofitting CCS to gas CHP installations and clarification is needed on the potential for mobile and dispersed applications.

### 5.2. Transport

Challenges identified for the transport of $CO_2$ are expressed over the shorter and longer terms. It was concluded that technical uncertainties would have 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 longer 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. In general, human factors are crucial, and the industry must have the appropriate procedures and culture to manage an asset for the long-term.

The longer term issues relate to establishing a risk profile and strategy for the development of a $CO_2$ transport network. In the short-term, a $CO_2$ pipeline operator faces a high financial risk due to the high cost of the asset and low returns; the level of financial risk is equivalent to that associated with the oil and gas industry. In the long run however, the risk profile for investment in $CO_2$ transportation was considered to be different to the oil and gas industry and, potentially, less risky than other parts of the CCS system. Pipeline operators are reliant on other parties to supply $CO_2$ and provide the sink; taking the LNG (liquefied natural gas) industry as an example, a substantial contract would be required to provide the initial anchoring for network development.

The cost difference between $CO_2$ transport within a network and without could be as much as €5 per tonne, depending on the commercial system. Initiating development of a network, whilst involving a higher element of financial risk, was considered to be 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, although a pipeline network would introduce non-trivial additional complexity.

The management of a $CO_2$ network 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 potentially 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 would have to be given to how the gas would be 'landed'.

Existing pipelines are reaching the end of their natural life and have been designed for operation under operating conditions different from those that will be required for $CO_2$ transport. Although offering the potential for cost reductions, there may be limited opportunity for pipeline re-use as infrastructure may be old with poor integrity and inappropriate metallurgy for $CO_2$, as well as a gap between short-term decommissioning of existing installations vs. new investment in plant over the longer term. Moreover commercial and ownership arrangements could be complex. Hence the roadmap specifies the assumption that new pipelines will be built and that the re-use of existing pipelines should not be relied on for $CO_2$ transport.

### 5.3. Storage

Six broad long-term challenges for $CO_2$ storage are identified on the roadmap; these are design, quality of baseline, leakage, monitoring, liability and perceptions of CCS.

Storage design in general, and in particular the monitoring regime, is likely to be much tighter at the first storage sites and will need to be tailored to individual sites. The storage group concluded that 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. Baseline characterisation will require 'reasonable' guidelines which, again, are likely to evolve over time and be tailored to different types of storage site.

Clearly the issue of leakage is crucial in terms of both abatement efficacy and the broader perceptions and acceptability of CCS. The regulatory aspiration is for zero leakage but in practice it is more likely that there will be some kind of acceptable level (expressed in absolute rather than percentage terms) in order to evolve a simple standard. Zero leakage is impossible over geological timescales; for example, although they are frequently perceived as such, oil and gas fields are not zero leakage. It was also considered necessary to distinguish between fast or slow leakage with different implications for regulation and monitoring. Three leakage routes for stored $CO_2$ were identified, each associated with different conditions: from infrastructure such as pipelines, etc.; from boreholes; and via the cap rock or other geological faults. Boreholes were considered to be primarily a concern in existing hydrocarbon fields, where wells are not designed with subsequent storage in mind. The potential leakage through geological features is less well understood for aquifers than hydrocarbon fields (although the integrity of the latter may be changed by storage); gas fields are the most well understood of the storage options, although these may not be available as first storage sites.

Agreed standards for quality (i.e. detection limits) and frequency of monitoring will be required. Monitoring frequency will vary during the lifetime of a project for example, at pilot sites, during the operational phase, during closure and after handover. Specific monitoring challenges include difficulty in monitoring $CO_2$ once it has dissolved (especially in aquifers) and including other elements such as hydrogen sulphide ($H_2S$) and Mercury, *inter alia*, which cannot easily be monitored in the subsurface; a possible standard for the latter would be to not exceed pre-storage background levels. However, in practice it is likely that monitoring would be limited by technical constraints governing what can be measured and over what timescale. The impacts of a leak to the surface, and consequently the resulting implications and response, will be dependent on the composition of the leaked material and its level of purity or impurity.

If a problem with $CO_2$ storage is revealed by the monitoring process, intervention will be required—exposing complexities over who should intervene and the issue of ensuring adequate insurance. The implicit assumption for long-term liability of storage is for liability to transfer to the State ultimately; regulations would also be required to protect against operator insolvency (ensuring that there were no loopholes).

All of the issues identified for storage feed into the broader perception of CCS (including public perceptions). As standards evolve they are likely to become more stringent over time and an element of 'future-proofing' may serve to satisfy broader concerns.

## 6. Five key statements

In the light of the discussion throughout the workshop, participants were able to agree on five key points to present as consensus statements from the workshop; these are summarised below.

### 6.1. $CO_2$ 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 2014, 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.

### 6.2. 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).

### 6.3. 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. An overview of the key regulatory and liability issues associated with CCS can be found in (IRGC, 2008).

### 6.4. 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). Whilst 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.

### 6.5. 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 and carbon price, engaging developing countries, etc.).

## 7. Additional discussion

The main conclusions of this roadmap, presented above, represent the consensus view of all of the workshop participants. This, inevitably, does not reflect the full range of opinions expressed during the workshop; in the following section we present some additional concerns expressed during the workshop in relation to the perceived urgency in establishing a role for CCS technology in climate change mitigation.

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 $CO_2$, to site performance requirements and agreements over long-term $CO_2$ ownership. At the time of writing, there is an emerging tacit agreement that government will, eventually, take ownership of stored $CO_2$—but the timescale and conditions of transfer remain 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 $CO_2$ onshore 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 1500 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 $CO_2$ from, or send $CO_2$ to, Norway, Denmark, Poland and Germany?

CCS actors are waiting for clarity over financial incentives from DBERR 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 soon after. However, announcement of the details of the competition was postponed until November, with the pre-qualifying shortlist only announced in June 2008, having a knock-on effect on the timescale for the commencement of CCS in the UK. The timeline presented in the roadmaps showing that a UK plant could be operational in 2012 has already been put back to 2014.

The industry was 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 initially 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?[9]

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 essential, but these are not likely to be 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 has 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

[9] Plans for up to four UK demonstration plants were announced in the Budget of 2009 (HM Treasury, 2009).

one participant commented "...*I have changed my mind about the [...] key issues for CCS, because of what I have heard here*."

## 8. Conclusions

The roadmap presented in this paper has been developed through a combination of a two-phase process of stakeholder engagement and review of the CCS landscape by the authors. The extensive consultation and discussion that informs this research has provided a unique overview of the current status, potential and barriers to CCS deployment in the UK. It is clear from the above that we are at a critical stage in the evolution of CCS technologies, not least as far as the UK's potential to play a significant role in their contribution to climate change mitigation at a national and a global scale. Although remarkably little has changed to the roadmaps' content in the year since the original workshop, the concept of CCS is now more firmly part of the mainstream debate on energy and climate policy in the UK. This is highlighted by recent controversy associated with the potential construction of two new super-critical coal-fired units at Kingsnorth power station; central to this debate is the possible future requirement for CCS at the plant (Macalister and Topping, 2008). With electricity supply companies facing a reduction in coal capacity at the hands of the Large combustion Plant Directive in 2015 contributing to a potential electricity supply shortfall if ambitious renewable energy targets are not met by 2020, urgent decisions over the building of new coal plant are needed within the next 3 years (Lockwood, 2008). In the context of political uncertainty surrounding the post-2012 international agreement on climate change, the price of carbon within the EU ETS and the commercial availability of CCS within the next 10–15 years some clear regulatory signal is required. The recent European Parliament recommendation to set an Emission Performance Standard on new power plant amounts to the latter but applying to plant only from 2015 onwards, it does not simplify the current situation. In the longer term, however, the EU Directive on Geological Storage of $CO_2$ (EC, 2008b) and in the UK the two recent consultations on the EU ETS (DEFRA, 2008a) and on the EU Directive (DBERR, 2008b) will shape the future of CCS. In terms of technological and economic progress, any step changes appear to be dependent on a move to an established commercial scale demonstration of CCS.

At present, the link between energy and climate change policy and the continually evolving science of climate change is gradually being recognised. The latest IPCC report (IPCC, 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 4 °C, as opposed to the 2 °C 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 to structural changes to the economy and a changing profile of electricity generation, a consequence of the 'dash for gas'. Overall, all of these factors demonstrate that the urgency of moving 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.

The 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. Grubler et al. (1999) have developed a typology in which 6 stages in the life cycle of a technology are identified. Using this typology, the roadmap graphics can be seen as covering the transition of CCS from its current stage of innovation and demonstration, becoming an incremental technology within a 'niche market commercialisation' phase in the medium term to achieving 'pervasive diffusion' across the longer term. Grubler et al. note the investment necessary to bring a technology through its pre-competitive stage in to larger scale commercialisation is linked to the prospect for future returns; in the case of CCS it will thus depend on confidence in future carbon markets or strict limits on $CO_2$ emissions.

This paper has described the gathering momentum of CCS, with policy changes overtaking the academic publication process that this article is subject to. As the urgency and political action on climate change mitigation grow, so does the potential for CCS to become a key component in a secure and low carbon global energy supply system. As several countries vie for technological and economic leadership in CCS, the roadmaps presented here show that the UK is still well-placed to establish itself as a major player in bringing CCS to the mainstream.


## Acknowledgements

The authors would like to thank Jane Palmer (formerly of the UKERC Meeting Place) for her help in organising and running the Edinburgh roadmapping workshop. We are also indebted to all those who participated in the workshop and contributed to a rich and challenging process. The work was funded by NERC (Natural Environment Research Council) as part of the UK Consortium on CCS.


## References


Blair, T., 2004. PM Speech on Climate Change. www.number-10.gov.uk/output/page6333.asp, Accessed May 2007.

Bohm, M.C., Herzog, H.J., Parsons, J.E., Sekar, R.C., 2007. Capture-ready coal plants—options, technologies and economics. Int. J. Greenhouse Gas Control (1), 113–120.

CETC, 2006. Canada's $CO_2$ Capture & Storage Technology Roadmap. Canmet Energy Technology Centre.

Chalmers, H., Gibbins, J., 2007. Initial evaluation of the impact of post-combustion capture of carbon dioxide on supercritical pulverised coal power plant part load performance. Fuel 86, 2109–2123.

$CO_2$CRC, 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, 2006. CSLF Technology Roadmap. Carbon Sequestration Leadership Forum.

DBERR, 2007. Development of a $CO_2$ Transport and Storage Network in the North Sea; Report to the North Sea Basin Task Force. Department of Business Enterprise and Regulatory Reform, London.

DBERR, 2008a. Next Steps on Carbon Capture Readiness and UK Demonstration Competition. Department for Business Enterprise and Regulatory Reform, London.

DBERR, 2008b. Towards Carbon Capture and Storage. Department for Business Enterprise and Regulatory Reform, London.

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

DEFRA, 2008a. Consultation on Proposed EU Emissions Trading System from 2013. Department for Environment Food and Rural Affairs, London.

DEFRA, 2008b. Draft Marine Bill, Department for Environment Food and Rural Affairs. http://www.defra.gov.uk/marine/legislation/index.htm, Accessed 15 October 2008.

DTI, 2007. Meeting the Energy Challenge, a White Paper on Energy. Department of Trade and Industry, London.

EC, 2001. Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants. O.J. European Communities, 44 (L309).

EC, 2007. A European Strategic Energy Technology Plan (SET-PLAN): Towards a low carbon future'. Communication from the Commission to European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions, Commission of the European Communities, Brussels.

EC, 2008a. 20 20 by 2020: Europe's climate change opportunity. Communication from the Commission to European Parliament, The Council, The European Economic and Social Committee and the Committee of the Regions, Commission of the European Communities, Brussels.

EC, 2008b. Directive of the European Parliament and of the Council on the geological storage of carbon dioxide and amending Council Directives 85/337/EEC, 96/61/EC, Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and Regulation (EC) no 1013/2006, 23/01/2008.

EC, 2009. Proposal for a regulation of the European Parliament and of the Council establishing a programme to aid economic recovery by granting Community financial assistance to projects in the field of energy. 7848/1/09 REV 1. Brussels, 20/03/09.

EEB, 2008. EEB Position Paper and Amendments to Proposed Carbon Capture and Storage Directive. European Environment Bureau, Brussels.

EUROPA, 2008. Questions and Answers on the revised EU Emissions Trading System, MEMO/08/796, Brussels, 17/12/08.

Gough, C., 2008. State of the Art in Carbon Dioxide Capture and Storage in the UK: an experts' review. Int. J. Greenhouse Gas Control 2 (1), 155–168.

Gough, C., Mander, S., Haszeldine, S. and Palmer, J., 2007. The UKERC/UKCCSC Carbon Capture and Storage Roadmap, Workshop Report, 1–2nd May 2007 UKCCSC and UKERC.

Groenenberg, H., Coninck, H.d., 2008. Effective EU and Member State policies for stimulating CCS. Int. J. Greenhouse Gas Control 2, 653–664.

Grubler, A., Nakicenovic, N., Victor, D., 1999. Dynamics of energy technologies and global change. Energy Policy 27, 247–280.

Haszeldine, R.S., Reiner, D., Shackley, S., Kendall, M., 2007. Regulation for CCS Beneath the UK Offshore and Onshore: Deep Geological Storage and Sequestration of $CO_2$. International Risk Governance Council, WA, USA.

Treasury, H.M., 2007. Budget 2007; Building Britain's Long-term Future: Prosperity and Fairness for Families. HM Treasury, London.

HM Treasury, 2009. Budget 2009. Building a low carbon recovery http://www.hm-treasury.gov.uk/d/Budget2009/bud09_chapter7_193.pdf, accessed 17th September 2009.

House of Lords, 2008. Energy Bill 2007–2008. Houses of Parliament.

IEA, 2008. $CO_2$ Capture and Storage—a Key Carbon Abatement Option. International Energy Agency.

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

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

IRGC, 2008. Regulation of Carbon Capture and Storage. Policy Brief. International Risk Governance Council.

Irons, R., Sekkapan, G., Panesar, R., Gibbins, J., Lucquiard, M., 2007. $CO_2$ Capture Ready Plants. IEA Greenhouse Gas Programme.

Jowit, J., 2008. Dirty Coal Power Hit by Euro Vote. The Guardian, London, 7 October.

Linstone, H.A., Turoff, M., 1975. The Delphi Method Techniques and Applications. Addison-Wesley Publishing Company, MA.

Lockwood, M., 2008. After the Coal Rush: Assessing Policy Options for Coal-fired Electricity Generation. Institute for Public Policy Research, London.

Macalister, T., Topping, A., 2008. Plans for Kingsnorth Push Ahead Despite 'Clean Coal' Talks. The Guardian, London, 6 August.

Markusson, N. and Haszeldine, S., 2008. How ready is 'capture ready'?—Preparing the UK power sector for carbon capture and storage. Report written by the Scottish Centre for Carbon Storage for WWF-UK.

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

NSBTF, 2007. Storing $CO_2$ under the North Sea Basin: a Key Solution for Combating Climate Change. North Sea Basin Task Force, Norwegian Ministry of Petroleum and Energy, UK Department of Trade and Industry.

Placet, M., Clarke, J.F., 1999. Emerging Technology Road Maps: the Batelle Approach. The Joint Global Change Research Institute, MD, USA.

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

Raupach, M.R., Marland, G., Ciais, P., Le Quere, C., Canadell, J.G., Klepper, G., Field, C.B., 2007. Global and regional drivers of accelerating $CO_2$ emissions. Proc. Natl. Acad. Sci. U.S.A. 104 (24), 10288–10293.

Royal Society, 2005. Ocean Acidification due to Increasing Atmospheric Carbon Dioxide. Royal Society, London.

Stern, N., 2006. The Economics of Climate Change: the Stern Review. HM Treasury & the Cabinet Office.

Webler, T., Levine, D., Rakel, H., Renn, O., 1991. A novel approach to reducing uncertainty: the group Delphi. Technol. Forecast. Social Change 39, 253–263.

Woudenberg, F., 1991. An evaluation of Delphi. Technol. Forecast. Social Change 40, 131–150.

The European Technology Forum for Zero Emission Fossil Fuel Plants, 2006. Strategic Deployment Document, http://www.zero-emissionplatform.eu/website/docs/ETP%20ZEP/ZEP%20SDD%20-%20draft%2012.pdf (accessed 25th August 2009).