

# KEY MESSAGES FOR COMMUNICATION NEEDS FOR KEY STAKEHOLDERS

**Report: 2013/07**

**March 2013**

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The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° [265847].

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The report should be cited in literature as follows:

‘Key messages for Communication Needs for Key Stakeholders, 2013/07, March, 2013.’

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# **KEY MESSAGES FOR COMMUNICATION NEEDS FOR KEY STAKEHOLDERS**

## **Background to the Study**

CO<sub>2</sub> Capture and Storage (CCS) is becoming more visible to the general public and more stakeholders are taking an interest as the technology progresses from pilot scale to larger demonstration and commercial scale initiatives. Due to this increase in visibility and the increased focus of many groups of interested parties, it is important that there is a repository of information that is accessible for stakeholders to allow them to learn about the subject and its intricacies without having to try to comprehend verbose and lengthy reports and scientific papers.

IEAGHG are well placed to address this gap, as an unbiased and not-for-profit entity that is tasked with evaluating the technological options to mitigate the effects of greenhouse gases on climate change. IEAGHG's work programme evaluates and assesses technology options, while remaining impartial throughout the evaluation process. This is why IEAGHG can use its extensive range of technical studies to create a set of papers addressing key concerns over the relevant aspects of the CCS chain, and provide a thorough grounding in the different elements of the technologies.

IEAGHG invited tenders from key organisations and research bodies around the world who were felt to have the capability to extract this information and present it in plain language without reverting to excessive technical jargon. The successful tender was a consortium bid from the University of Edinburgh, Scottish Centre for CCS and CSIRO in Australia.

## **Scope of Study**

The main deliverables from the study will be a series of Briefing Notes (BNs) covering the key information needs of key stakeholders, and a series of shorter Information Sheets (ISs) which provide a more basic introduction to the same topics. Note: the BN's are the main deliverable of the study, and the ISs will be finalised and circulated after the technical report has been produced and disseminated.

The study will work from, but not exclusively from, IEAGHG's technical studies and reviews to identify the topics requiring BNs and the final BN's will be reviewed by members of the Social Research Network, among others, as part of the peer review.



## Results & Discussion

The study initially performed a literature review to extract the key themes from the technical reports, and determine the key messages that need to be communicated. Once these have been identified, a series of interviews and focus groups were conducted both in the UK and Australia, where the contractors operate, and these interviews and focus groups included audiences such as:

- science and technology journalists,
- science and technical writers,
- science communicators involved with public engagement,
- professionals involved in school curriculum development,
- local and regional council elected officials.

In total, 3 interviews, 4 focus groups and a presentation to a council meeting were held to gain an understanding of the information needs of key stakeholder groups.

Once this understanding was defined, the main outcome of the study was commenced upon, namely the determination of topics for and the authoring of some 13 Briefing Notes (BNs). These briefing notes typically lie between 1700 – 3200 words, and explain the concepts involved from an initial introduction to the key issues and challenges remaining. They attempt to acknowledge any issues that remain, while focussing on the knowledge base that has been created, and the progress that has been made.

The second phase of this process will follow the expert review and study publication, and will involve the services of a professional science communicator to create shorter, more concise introductory level Information Sheets using graphics and pictures where possible to inform less engaged stakeholders who may only commit a few minutes to the topic. The theory behind this two-stage approach was to ensure that the deliverables would be sufficiently informative for stakeholders at a level where decision makers and policy makers would use them as a basis and introduction to the topic, and also provide an introduction to those less engaged, minimising the risk of the audience being switched off by too much information, while leaving them free to engage further by reading the longer BNs.



## Perceptions

### *CO<sub>2</sub>*

In general perceptions of CO<sub>2</sub>, what it is, what are its effects, and other characteristics were limited among most respondents. There were some misconceptions that relate to CO, and this represents a potential issue – in many cases, asking local residents to accept CO<sub>2</sub> pipelines or capture and storage activities requires them to remember chemistry lessons that may have been a long time previously, and not required since. Very few respondents could list any commercial uses of CO<sub>2</sub>, and perceived it as having no commercial value.

### *CCS*

The perceptions of CCS show great variety, largely depending on the location of the sample group and the propensity of CCS projects proposed, accepted or rejected in the local vicinity. Among those who had heard of CCS, the major knowledge gaps tended to be in terms of the maturity of the technology, and that it was being proposed as an alternative to renewable energy, efficiency improvements etc, and this can easily be addressed by defining the scenarios described by the IEA Energy Technology Perspectives, and that in fact all options will be required in order to mitigate the effects of anthropogenic climate change.

### *Issues and Concerns*

Predictably, concerns around development of CCS centre around 3 basic premises; environmental impact, leakage & monitoring, and health and safety. There were other issues noted, but primarily these 3 were more frequently reported. The main report goes into a little more detail on the issues raised, varying by location.

## Briefing Notes

Following the interviews, meetings, and focus groups along with analysis of the IEAGHG technical report library, the topics determined to be requiring of a Briefing Note were as follows:

- **‘What is CO<sub>2</sub>?’** With so many perceptions about CO<sub>2</sub> being misconceptions, it was decided to start with a very short briefing note, describing the physical properties of CO<sub>2</sub>, clarifying the difference between CO<sub>2</sub> and CO. Due to the introductory nature of this BN, it is much shorter than the others, and will be a first stop in the public engagement process.
- **‘Setting the Scene for CCS: Human Caused Climate Change’.** This explains the need for CCS, briefly going into the basics of climate change science, and the effect greenhouse gasses (GHG) have on the earths’ climate. It also explains the carbon cycle and the dramatic increase in GHG emissions over recent decades and the reasons we need to act.



- **‘A Brief History of CCS Development and its Current Status’.** Explaining the different type of CCS project, this note goes back to the historical development of the CCS technology in general, as well as explaining the scale and number of projects required. Enhanced Oil Recovery is also contained within this note.
- **‘From Sources to Stores; Matching Sources of CO<sub>2</sub> with Potential Storage Sites’.** This note explains the need to match sources to sinks, taking into account transport and infrastructure elements, and addresses storage capacity as well.
- **‘How is CO<sub>2</sub> Captured?’** Now that the scene has been set, the history has been defined and the need explained, this briefing note explains the different options for CO<sub>2</sub> capture, and their relative merits and developmental progress. It also touches on the energy penalty and briefly mentions the costs of capture.
- **‘The Costs of CCS’.** Following on from the capture briefing note, this note goes into more detail on costs, explaining the uncertainties and expressing that costs will reduce over time, and compares these to other options for energy generation.
- **‘What Infrastructure is Needed for the Transport of CO<sub>2</sub>?’** This note explains the history and record of gas transport by pipeline, and also covers transport by ship, before explaining the possibility of reuse of existing infrastructure.
- **‘Carbon Dioxide Naturally Occurring Underground’** Addressing natural sources of CO<sub>2</sub>, both volcanic and sedimentary in origin, this note tackles the subject of leakage incidents from natural stores such as Lake Nyos. While this is an emotive and possibly controversial aspect, we felt that this couldn’t be ignored as there is a great deal of information available, and the focus groups concluded that clarity must be maintained.
- **‘Storage & Site Integrity’** This note explains that site selection is a very involved process, and all sites selected will be verified as suitable for storage, and explains the role of caprocks, and storage mechanisms.
- **‘Impacts of Leakage Onshore’** This note explains the likely effects of leakage from an onshore storage location, both on people and flora and fauna. It also explains that technologies exist to detect and mitigate leaks.
- **‘Impacts of Leakage Offshore’** Similar to the previous note, this note is focussed on the same topics for offshore storage, sub-seabed storage.
- **‘Monitoring: Safe Storage of CO<sub>2</sub>’** An important topic, this note explains that there are a multitude of technologies and tools available to monitor the CO<sub>2</sub> both during injection and after to ensure that the injected CO<sub>2</sub> remains where it is intended, and that methods are also available to fix and remediate leaks if they do occur.



- **‘Legal Issues of CCS’** The legal aspects were summarised in this BN, and it addresses the classification of CO<sub>2</sub>, the permanence of storage, ownership issues, and the different laws being established around the world.
- **‘What do the public think about CCS?’** This note examines the issues that have most frequently come up when dealing with the public and CCS projects, and looks at how we can learn from these interactions to improve the communication between operators and local residents.

These notes form the main element of this study, to be followed by the shorter information sheets that will be created following the study publication.

### **Expert Review Comments**

The study was sent out to Expert Review, and detailed comments were received from 3 reviewers. The reviewers were unanimously very complimentary of the study, with the range of comments relating only to grammatical discrepancies, additional references and ensuring that all elements were using the same style. These have all been accepted and addressed accordingly.

### **Conclusions**

The series of interviews and focus groups that were held covered a wide range of stakeholders, and allowed the contractor to determine the information needs for the set of Briefing Notes. The needs that were defined were all subjects that are covered within the IEAGHG technical study library, and this study has served to extract the key messages and communicate them in a non-technical manner that should prove accessible to interested parties and stakeholders alike.

The subsequent Information Sheets will also serve to provide an introductory level of information to equally interested, but less engaged stakeholders, and will direct them towards further reading if required.

### **Recommendations & Key Messages**

The very nature of this study meant that the feedback received through the interviews and focus groups gave a clear indication of what should form the basis of further work. Clear gaps were identified, and these can be summarised as follows:

#### *Link CCS and Day-to-Day Activities*

There is no link between the perception of a ‘new climate change mitigation option’ and peoples everyday lives. There will always be questions asked about what else money and funding could be diverted to, and so there needs to be a clear reasoning shown for the need for projects. A minority of the public are still sceptical that climate change is a direct result of human activity, and this needs to be continually explained.



### *Graphic Improvements*

The general feedback on graphics and illustrations is a lack of human elements, and a sense of everything occurring in one place. A sense of scale needs to be created, with reference to everyday objects, or distances.

### *Creative Public Engagement*

If developers use modern e-based communication methods, engagement is generally better from an early stage. Successful projects in terms of public engagement have utilised tools such as webcams and online Q&A forums, and these are recommended for CCS projects to instigate early involvement and engagement.

### *Acknowledge Counter Views*

Controversially, it could be seen as beneficial to give a voice to those who are not unequivocally supportive of projects, to promote a sense of openness, and to encourage any issues to be debated and dealt with. In this manner it could be possible to overcome potential showstoppers before they escalate into major concerns.

### *Further Work*

There is clearly a great deal of work to be continued into this area, and IEAGHG are reasonably well placed to take a leading role in this. Social science is a growing element of CCS, and involvement in the groups looking into this would be something to add value to the programme. The University of Nottingham has held a workshop addressing Public Engagement, and this is intended to continue into a series, which IEAGHG should continue to participate in.

**Final Report - Key Messages for Communication Needs for Stakeholders IEA/CON/11/194**

Prepared by Scottish Carbon Capture and Storage (SCCS) & Commonwealth Scientific and Industrial Research Organisation (CSIRO) for the IEAGHG

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## 1. Introduction

Scottish Carbon Capture and Storage (SCCS) at the University of Edinburgh (UEDIN) in the UK and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia, were commissioned in 2011-2012 to prepare a series of CCS Briefing Notes (BNs) (5 – 7 pages and 2k to 3.5K words) and an accompanying set of Information Sheets (ISs) (1 – 2 pages and 500 words). The aim of the BNs is to translate the technical (scientific and engineering) reports published by the IEAGHG into simple-to-comprehend documents that would summarise the key points for the benefit of non-expert stakeholders and interested, reasonably well informed, members of the public. The purpose of the ISs is to further simplify the material into short, quick and easy-to-read information sheets for the interested - but less or non-informed - stakeholder or member of the public.

## 2. Methodology

### 2.1 Issue Categorisation

The first stage in the project was to go through the large number of technical documents produced by the IEAGHG and to categorise them into coherent topics (see Appendix Two). We identified eight general topic areas as indicated in Table One.

<b>Topic</b>	<b>Items covered within topic</b>
<b>Environment</b>	Health & safety, environmental impacts (excluding leakage), water use, amine degradation, etc.
<b>Leak</b>	CO <sub>2</sub> leakage / underpinning science / risk assessment / monitoring issues / leakage prevent and remediation of leakage sites / health issues arising from leakage / ecological and other impacts of leakage
<b>Costs</b>	Costs of CCS / efficiency / financial & costing issues / investment / potential markets
<b>Infrastructure</b>	Infrastructural development / network development and ownership / transport / retrofitting
<b>Legal</b>	Legal frameworks / liabilities / regulation / risk assessment rules and guidelines
<b>Public</b>	Public perceptions / public acceptance / engagement / outreach
<b>Context</b>	The context for CCS / energy mixes / suite of low-carbon technologies and responses
<b>Options</b>	Options for sequestration / ability to store and mitigate GHG / database of potential sites

*Table One: List of topics identified from the full set of IEAGHG reports (listed in Appendix Two)*

## 2.2 Identifying Audiences, Information Needs and Current Understandings

In order to understand how to present highly technical and detailed scientific information to non-experts, it is first necessary to understand what the 'information needs' of those non-expert audiences might be. It was our assumption that the BNs would most likely be read and used by science communicators and science writers, e.g. journalists, specialist communicators, those writing for the technical press, experts in school curricula development and so on. The BNs might also be consulted by government and company officials, community groups, elected members and other stakeholders in local councils, districts and provinces where CCS projects are being proposed and discussed. While some members of the public will inevitably access and consult the BNs, it is regarded as unlikely that the main route for accessing and using the BNs will be individual members of the public. We therefore identified the key audiences of the BNs as follows:

- Science and technology journalists
- Science and technical writers for press journals, magazines, professional associations, websites and blog sites
- Science communicators involved in public engagement (e.g. via museums, science festivals)
- Professionals involved in school and college curriculum development
- Representatives of local councils, e.g. elected members and council officials.

In order to understand the information needs of the above groups, we held a number of interviews and focus groups. These are listed in Table Two. The aim of the interviews and focus groups was to consult with representatives of the above groups so as to address the following issues.

- **Identify audiences:** What audiences are represented by the participants? What other audiences do and could the participants communicate to? Briefly explain information needs of each key audience.
- **Determine what topics and sub-topic are of most interest and why.**
- **Determine to what extent the key concepts are understood:** do target audiences know what CO<sub>2</sub> is, and where it comes from? Why does CO<sub>2</sub> need to be captured and stored? Then more specific questions such as: What is an 'aquifer'? How can a rock hold a fluid? How would the gas get there? How do we know it'll stay down there? What does 'capture' of CO<sub>2</sub> mean? How easy would it be to do? What might the costs be?
- **Understand how information is accessed, interpreted and absorbed:** Where do people get information from? Why do they prefer certain information channels? In what format do they prefer to receive information and why? How do participants interpret existing information sources about CCS? Is the 'message' that the information creator or holder intends to convey the one that is being received by the audience? If not, what is making the message difficult to convey?
- **Determine how information should be presented.** In the light of preferences for information needs, how can things be done differently and improved?

The information from the interviews and focus groups was processed and used to inform the writing of the Briefing Notes.

<b>Type of event</b>	<b>Country</b>	<b>Location</b>	<b>Date</b>	<b>Number participants</b>	<b>Topic / focus</b>
Interview	UK	Edinburgh	Jan. and Feb. 2012	4	Professionals involved in: science museum, legal, finance and insurance
Meeting	UK	Peterhead	Feb. 2012	c. 15	Presentation to weekly meeting of Councillors and council officers (Peterhead, Aberdeenshire) followed by Q&A and discussion session
Interview	Australia	Queensland, Victoria , West Australia	Feb. 2012	6	Political advisors
Interview	Australia	Brisbane, Canberra	Feb. 2012	4	Local Councillors
Focus Group	UK	London	Feb. 2012	11	Science and technology journalists, writers and communicators
Focus Group	UK	Bristol	Feb. 2012	6	MSc students studying for a masters in Science Communication (University of the West of England, Bristol)
Focus Group	Australia	Brisbane	Feb. 2012	10	Science communicators
Focus Group	Australia	Brisbane	Feb. 2012	7	Education curriculum developers & writers

*Table Two: Details of the Interviews and Focus Groups undertaken in the UK and Australia in order to understand the information needs of different target audiences*

### 2.3 Selecting the Briefing Note (BN) Topics

The selection of issues to cover in the BNs was decided by: the team's perception of key issues within CCS which require explanation and/or which have previously caused confusion and/or controversy; the range and balance of issues covered in the IEAGHG library of reports (listed in Appendix Two); the perceptions of the interviewees and focus group participants; and discussions with the IEAGHG Communications Manager. The final list of BNs selected and developed is presented in Table Three. It had originally been intended to include an introductory BN on CCS, but it was decided that this would not be needed given that the IEAGHG had recently updated its existing introduction to CCS and it was felt that another introduction would be superfluous and repetitive.

### 2.4 Preparing the Briefing Notes

Preparation of BNs then proceeded with nomination of a lead author, taking account of the findings from the interviews and focus groups. In most cases, two to three persons are responsible for the writing of the BN. A key part of the writing process was internal and external review of the BNs. Firstly, each BN was subject to considerable review, including re-writing, by the project team participants themselves. Secondly, each BN was subject to review by CCS experts within CSIRO and SCCS. In some cases, BN drafts were partly and, on occasions, extensively re-written by scientists and CCS analysts with SCCS. A balance had to be struck between getting the message across in a clear and straightforward manner while conveying sufficient and accurate information to cover a given topic. The BNs were then sent out by the IEAGHG for further external peer review by four independent experts which the team then responded to in finalising the BNs, in some cases meaning quite substantial re-writing.

The BNs are typically from 2 to 3 thousand words. We have aimed to use diagrams, figures, text boxes and photographs to illustrate the points being made in the text and to break-up the text and make it more readable. The BN is intended for use by more engaged stakeholders who might be prepared to spend 20 to 30 minutes in reading the BN.

### 2.5 Information Sheets

From the early stages, it was also our intention to produce much shorter one to two page versions of the Briefing Notes – termed Information Sheets (IS). These are about 500 words long, hence have minimal text and use illustrations, diagrams and photos to convey key messages wherever possible. The information sheet is intended for less engaged stakeholders who might devote just a few minutes to reading and digesting the Information Sheet. It was agreed that the ISs would be produced once the final text of the BNs had been agreed between the contractors, the IEAGHG and the IEAGHG's external reviewers. This process of finalising the BNs took considerably longer than initially anticipated, in part due to staffing issues. Furthermore, one of the key contributors had to be evacuated from the impacts of extreme flooding. As a consequence, the ISs were not finalised as of late March 2013. However, the ISs will be completed and made available as soon as possible following publications of this report, and forwarded under separate cover.

<i>Title of Briefing Note</i>	<i>Main Issues Covered</i>	<i>Lead Author</i>	<i>Contributing Authors, Reviewers &amp; Editors</i>
1. Setting the Scene for CO <sub>2</sub> Capture and Storage: Human-Caused Climate Change	Explains why CCS is necessary by putting the topic into the context of human-caused climate change and the need for deep cuts in emissions of CO <sub>2</sub> by 2050	AMD	SJS
2. A Brief History of CCS Development and its Current Status	Explains how CCS has developed over the past 15 years and the differences between CCS project types	VS	SJS, NM
3. From Sources to Stores: Matching Sources of Carbon Dioxide (CO <sub>2</sub> ) from Power Plants and Industrial Facilities with Potential Geological Storage Sites for CO <sub>2</sub>	Explains the distribution of sources of CO <sub>2</sub> and potential geological storage sites	VS	SJS
4. How is Carbon Dioxide Captured?	Explains the main methods for CO <sub>2</sub> capture	RH	ML, VS, BE, SJS, NM
5. The Costs of Carbon Dioxide Capture and Storage	Examines the costs of CCS and explains why it is so difficult to determine costs with any precision	NM	SJS, VS, RH, AMD
6. What Infrastructure is Needed for the Transport of Carbon Dioxide?	Examines the pipelines and other infrastructure which would be required for the large-scale deployment of CCS, the different ways in which such infrastructure could be organised, the costs and possible risks.	VS	NM, SJS, RH
7. Naturally occurring carbon dioxide (CO <sub>2</sub> ) in underground rocks – what can it tell us about storing CO <sub>2</sub> for carbon dioxide capture and storage?	Examines situations where CO <sub>2</sub> has been found to be naturally-occurring in rock formations and incidents where it has leaked out, including the range of impacts.	VS	AMD, SJS
8. CO <sub>2</sub> Storage Mechanisms and Site Selection	Presents the basic geological arguments surrounding the integrity of deep underground rock formations with respect to storing CO <sub>2</sub> and how integrity can be evaluated	VS	AMD, SJS
9. Impacts of Leakage of CO <sub>2</sub> from Onshore Geological Storage	Examines the possibility and potential impacts of the	VS	AMD, SJS

Sites	leakage of CO <sub>2</sub> from geological storage sites deep beneath the surface onshore		
10. Impacts of Leakage of Offshore CO <sub>2</sub> from Geological Storage Sites	Examines the possibility and potential impacts of the leakage of CO <sub>2</sub> from geological storage sites deep beneath the surface offshore	VS	AMD, SJS
11. Monitoring the Safe Storage of Carbon Dioxide	Examines how CO <sub>2</sub> storage sites can be monitored to ensure that any potential leaks are effectively and rapidly identified	RJS	VS, AMD, SJS
12. What are the Legal Issues Surrounding Carbon Dioxide Capture and Storage?	Presents the key legal frameworks internationally and within several national legislatures (North America, Europe) surrounding CCS and key remaining issues	BE	SJS
13. What do the Public think about Carbon Dioxide Capture and Storage?	Examines the main issues that have arisen amongst the public from plans to develop CCS and provides indications on how these can be responded to	LM	RH, SJS, AMD

*Table Three: List of the Briefing Notes developed, the main issues covered by each, Lead Authors, Contributing Authors, Reviewers and Editors*

Legend: AMD: Anne-Maree Dowd; BE: Benjamin Evar; LM: Leslie Mabon; ML: Mathieu Lucquiaud; NM: Nils Markusson; RH: Rhys Howell; RJS: R James Stewart; SJS: Simon Shackley, VS: Vivian Scott

### 3. Results of the Interviews and Focus Groups

#### 3.1 Key Findings from UK interviews

The key points from the UK interviews are summarised in Table Four. Professionals such as lawyers, financiers and insurers will tend to rely upon their clients for much of the detailed information they require. They also rely heavily upon intermediaries – i.e. agencies, information brokers and networks of professionals which sort through and evaluate technical and scientific information. Hence, communicating to professional groups is a matter of getting information with the appropriate level of detail and context to such intermediaries. As for science communicators, the key message was that CCS is a difficult thing to communicate about because of the number of different arguments which have to be presented and accepted before arriving at the conclusion that CCS could be ‘the’ or at least ‘an answer’. The interviewee also highlighted the importance of being open with the public about uncertainties and unknowns and not to ‘dumb-down’ the science. Finally, the local councillors seemed more concerned about onshore pollution, asking several questions about the emissions from a CO<sub>2</sub> capture unit on a thermal power plant, but far few questions were asked about transporting and storing CO<sub>2</sub> offshore. This concern with capture plant emissions appears to have arisen from a local controversy over an incineration plant in the town where the meeting took place.

<i>Person / Group</i>	<i>Topics</i>	<i>Key points</i>
Finance, law, insurance	Technical maturity / viability/ risk; direct & indirect analyses;  Costs & risks, Laws and Regulations; who is doing what?	Client is major source of info.; due diligence, expert opinions; intermediaries (Lighthill, F4ST); triangulation
Science communication and education	Quite difficult to tell the ‘whole’ story as requires underpinning knowledge.	Avoid ‘dumbing-down’ to the public; uncertainties have to be presented transparently
Local councillors	Concerned mostly about possible air pollution / waste disposal issues	Preference for next generation clean technologies

*Table Four: Key Points from UK Interviews*

#### 3.2 Key Findings from Australia Interviews

##### 3.2.1 Perceptions of CO<sub>2</sub>

- All respondents had limited knowledge of CO<sub>2</sub>
- All respondents were aware of the gas, and many understood basic facts about CO<sub>2</sub> such as that plants absorb it and burning fossil fuels produces it

- The majority found it difficult to describe the specific characteristics or properties of CO<sub>2</sub>.
- Respondents tended to perceive CO<sub>2</sub> negatively as toxic, harmful, flammable or explosive (misperceptions)
- Majority when describing CO<sub>2</sub> were actually referring to carbon monoxide
- Few respondents could describe uses for CO<sub>2</sub>

### 3.2.2 Perceptions of CCS

- Very few had heard of CCS
- Those that had heard of CCS did not know much about the technology in detail
- They questioned the source of the information
- They felt the materials were balanced but would have wanted more of an Australian focus

### 3.2.3 Issues and concerns

- Leakage
- Monitoring
- Long term environmental impacts – water sources and drilling
- How will this technology be applied to Australia with our high use of coal?
- Will this draw resources away from renewable technologies?
- Cost – how much does it cost and can Australia afford this technology?
- Legal and regulatory implications

### 3.2.4 Preference for Information

- Needs to be from a trusted source
- In a format that is easily understandable (easy to read and access)
- References to multiple sources
- List of experts in the various areas of CCS
- Information needs to be updated – kept up-to-date
- Prefer to be in an easily accessible digital (electronic) format
- No limitation on use – allowed to use in other formats and source (reference the material)

### 3.2.5 Providing Others with Information

#### *Political advisors:*

- Indicated that they could be asked to provide briefs to various government staff or produce media releases
- Sometimes asked to put together information packs on various topics requested from the community
- Needs to be credible, up-to-date, comprehensive but easy to understand

#### *Councillors:*

- Would need to present information to committee members, community, media and industry (briefings, presentations, speeches)
- Would want to be confident that the briefing sheets could be openly used to provide engagement with community or with industry
- Reflected a need to have easy to understand information and clear on the source

#### 3.2.6 Missing Information

- Cost – how much? Would want information in relation to other technologies (easier to look at messaging when in the context of other technologies). Interested in using cost estimates to justify effort and commitment (from a financial and policy perspective)
- Regulation – what is already out there and what else would need to be created? What stage are all these at (nationally and internationally). Who is in charge of enforcing the regulations?
- Long term liability – would want to be clear on who is responsible and what repercussions there are if laws and regulations were not met. Have there been any instances of an agreement between a government and industry for long term liability?
- Policy requirements – what would be needed at the local level?
- Role of government vs. industry – funding development and protection of communities
- How does Australia compare to technological development of CCS to other countries?

#### 3.3 Key Findings from UK Focus Groups

The first UK focus group took place in London on 24<sup>th</sup> Feb 2012 and involved a group of eleven distinguished professional science writers and journalists. The key points raised are presented in Table Five. The second UK focus group took place in Bristol on the 29<sup>th</sup> February 2012 and involved six masters-level students studying for an MSc in Science Communication. Hence, the second focus group represented the ‘next generation’ of science communicators and a summary of the results is presented in Table Six. It was decided to organise the Focus Groups around a collection of common images of CCS and to get the science writers and communicators to give their impressions of the image, i.e. in terms of what messages they thought each image was attempting to convey. This turned out to be a useful device as it stimulated a lively discussion on how CCS is commonly conveyed and the pro’s and con’s of such representations. The students were, in general, more positive and optimistic than the science writers who were more sceptical about efforts to communicate CCS and, to some (varying) extent, about CCS itself.

A common theme was that most images and representations of CCS come across as very technical, with an absence of people and lacking, in general, a ‘human-side’. Images can easily be misinterpreted, even by professional science writers. Numerous examples were given during the focus groups and these will be explored in more detail in a proposed journal publication.

<i>Key Issues</i>	<i>Implications</i>
Academics and professional associations (eg. IMechE) important trusted sources; role of trusted individuals / intermediaries	Organisations seen as independent and objective trusted most. IEA GHG may be perceived as too industry-driven?
CCS is 'faceless' – where are the humans? Representations are large bits of equipment in big landscapes but there needs to be a human angle.	Connection between CCS 'doing good' by tackling climate change is lost because big infrastructure is not seen as 'good for environment'. Too industrial and detail unfamiliar to most people.
Terminology and images too technical and sometimes misleading	e.g. 'supercritical', 'seismic' – negative connotations  Need for more interpretation of diagrams, e.g. seismic.
Messages need to be simpler and clearer – many images have too much unnecessary detail – confusing	Image of multiple storage options – looks as if scientists & engineers are trying everything!  'Info-graphics' important here – professional design
Geological layers and formations are not usually understood – no reference points for most people	Need to assume zero geological knowledge on the part of many readers
Cost estimates – floating bar charts are hard to interpret. People not used to evaluating such data.	Again needs to assume very low level of knowledge of economic evaluation methods.
Information on Italian seeps – not reassuring – looks bad	Be careful not to assume people will be reassured by analogues

*Table Five: Key Results and Insights from the UK Science Writers and Communicators Focus Group, February 2012, London*

<i>Key Issues</i>	<i>Implications</i>
Generally MSc students were more positive than the world-weary science writers in London!	Younger people ('generation Y') might be more open to CCS if it is presented in right way
Faceless and non-human presentation of CCS – all shiny pipelines and capture plants	Need for a human-side / way into the issue – may be use 'talking heads', individual narratives, needs range of people from students to professors to industry to NGOs, etc.
Public engagement / citizen science – could a CCS project under development have a public interaction opportunity?	Inputs from public in developing a site? Day-to-day webcam of on-going development with Q&A or even suggestions?
Association of CCS with companies that are not necessarily trusted .....	Some companies trusted more than others ....
How can the association of CCS with positive things be improved?	e.g. trusted individuals, trusted organisations, respected academics, etc.

*Table Six: Key Results and Insights from the UK MSc Students in Science Communication Focus Group, February 2012, Bristol*

### 3.4 Key Findings from Focus Groups in Australia

#### 3.4.1 Perceptions of CCS

- Very few had even heard of CCS – those that had heard did not know much about the technology in detail
- Some questioned the source of the information
- Majority thought the information was balanced
- Few wanted to have more perspectives included
- Some wanted to see how energy efficiency could be used instead of CCS – would be easier and cost a lot less

#### 3.4.2 Issues and concerns

- Leakage
- Monitoring
- Long term environmental impacts – water sources, wildlife and biodiversity
- How will this technology be applied to Australia with our high use of coal?
- Will this draw resources away from renewable technologies

- Cost – how much does it cost and can Australia afford this technology? How much will it add to the cost of electricity in the Australian context?
- Legal and regulation implications – what already exists and what would be created for industry to comply with? Will there be a regulator watchdog to make sure safety procedures are being used?
- Ability to address climate change – how much CO<sub>2</sub> will it actually reduce? How much CO<sub>2</sub> would Australia have to store to really make a difference?
- How long will the technology have to be used?
- The few sceptical participants stated that CCS was just another way for industry to get money out of tax payers – making money off climate change
- Is it still an option to do CCS in collaboration with renewables?
- Few raised an issue about the safety of transport – how safe are pipelines (we can draw upon experience which suggests that there are always accidents)

### 3.4.3 Preference for Information

- Needs to be from a trusted source
- List of experts or other credible sources (helps to get started on research on the topic)
- In a format that is easily understandable (easy to read and access)
- References to multiple sources
- List of experts in the various areas of CCS
- Information needs to be updated – kept up-to-date
- Publicly available and free from any complicated copyright agreements (can use and will provide citation)

### 3.4.4 Providing others with information

Science communicators reflected that they produced communication for the following people or places:

- Newsletters
- Editorials
- Articles
- Museums
- Libraries
- Universities and schools
- Community groups
- Government
- Books
- Websites
- Blogs and other social media sources (e.g. facebook pages and twitter)

- Displays (expos, science fairs)

Education curriculum writers reflected that they produced communication for the following people or places:

- Teachers (notes that accompany curriculum)
- Class curriculum (various levels)
- University, TAFE, colleges
- Lesson plans
- Activities

#### 3.4.5 Missing Information

- Cost – would want to know the costs comparative to other technologies (in particular renewables) – in easy to understand graphs
- Regulation – what is out there already and what gaps need to be filled – heavily reflecting requirement for the Australian context
- Liability – who would be responsible for the long term - examples wanted
- Role of government – what are the long term plans for Australia – government commitment (what have we already become locked into?). What are other countries/governments doing? Information on international agreements
- Role of industry – how much support do they get (financial and R&D)? What commitment do they make – level of risk, financial investment, long term use of CCS?

It is intended to undertake further analysis of the materials collected in the four focus groups and to subject it to more detailed social science scrutiny. The results will be submitted to an appropriate academic journal.

## **4. Suggestions for Future Work on Communicating CCS**

The focus groups and interviews have revealed the need for further, innovative methods for communicating CCS to stakeholders. We present a summary of the main ideas here.

1. There is a need to make a reasonably strong link between CCS and peoples everyday lives. From the non-expert perspective, there has to be a convincing reason for undertaking CCS, otherwise people ask ‘why are they spending our money on CCS?’ We should always start from the point of view that not everyone would agree with ‘us’ in believing that CCS is important and necessary. A substantial minority of the public do not even believe in anthropogenic climate change and/or in the extent of its adverse impacts.
2. Need for clear and informative info-graphics. Info-graphics are graphic representations which are accompanied by call-out boxes presenting clear text descriptions which enhance the information value of the graphic. They are an extremely efficient way of presenting a lot of information in a clear and concise, often entertaining, manner. The text-boxes point to, and focus the viewers’ attention on, particular issues with a view to illuminating the readers’ understanding in an efficient and accessible manner. As such, info-graphics can provide an effective door-opener with a wider, less well-informed public/stakeholders.

3. There is need to present more of a human face of CCS technology. ‘Where are the humans?’ one of the MSc students asked when confronted with a set of images of CCS depicting large power plants, chemical works and other industrial equipment and pipelines. Representing CCS facilities as part of an overall power station type complex and associated infrastructure softened their appearance and provided context. To communicate CCS in a positive light – as a technological option that is helping us cope with climate change and bringing about deep carbon emission reductions – there is a need for a human-centred representation. This might involve using ‘talking heads’ of a range of individuals involved in the sector, not just senior executives, but also those early on in their careers, PhD students, technicians and support staff, and so on. Research using the ‘talking heads’ approach has been successful in creating positive images of CCS amongst an informed public group (as part of the EU SiteChar project). Another option is to seek a CCS champion who is a well known and liked public figure. Communication materials could also make a point of including the people who are involved in testing and developing CCS in films, photos and visual images.
4. The journalists we spoke to also wanted more clarity in what was being presented: fewer numbers, statistics, graphs and figures and more simple and straight forward explanations. The journalists requested better targeting of material for different interest groups and audiences. Different visual representations that show how CCS is a human-based enterprise could also be developed, e.g. locating infrastructure within a social-setting of settlements, other commercial and industrial enterprises (e.g. on- and offshore renewable energy, links with existing oil and gas extraction and processing, indicating links to other marine sectors such as fishing). Scale is also an issue with a need to find an innovative way of showing depth of injection and storage that does not look ridiculous on the one hand or give the impression that injection is just below the surface on the other.
5. Encourage developers of CCS projects to think creatively about stakeholder and public perceptions and communications. Developers of some large projects have used modern web-based and new social media communications to provide more engaging, high quality and reliable information about large new infrastructure projects, e.g. using webcams to provide real-time images of new developments and providing an online forum for questions to be asked and allowing developers to provide answers and explanations. We would advocate similar thinking to be applied to CCS projects as they are developed in the future. Involving groups and stakeholders at a very early (if not necessarily the earliest stage) is an important principle.
6. Giving a voice to those who are not unequivocally supportive of CCS. More controversially, rather than only involving advocates and those with a professional interest in CCS, a voice could be given to those who are not unequivocally supportive of CCS, such as some environmental NGOs, academics and renewable energy developers. The suggestion is to include the perspectives and opinions of those who might support CCS only under particular limiting conditions and might, in general, entertain some reservations. It is worth considering the comments and criticisms of those who oppose CCS and see no role for it. This is important in understanding what views exist ‘out there’ so that public communication materials can be crafted accordingly. The overall objective here would be to illustrate and reflect to stakeholders and the public that a range of opinions and perspectives exists.

## 5. Summary & Conclusions

The information needs of stakeholder groups that are likely recipient audiences for the IEAGHG reports, and to be key to their further and more widespread dissemination, have been elucidated via interviews and focus groups in both the UK and Australia. Based upon our perception of information and knowledge needs, a series of thirteen Briefing Notes have been prepared covering a wide range of CCS activities, including capture, costs, infrastructure, storage, public and legal frameworks. A set

of parallel, much shorter, Information Sheets is also being developed to enable key information to be provided to non-informed but interested stakeholders and members of the public who will devote just a few minutes to each topic.

The bulk of the work in this project has been in writing and editing these thirteen Briefing Notes in order to 'get the tone right' and to achieve the right balance between technical and scientific detail and accuracy on the one hand, and accessibility / readability to a non-specialist audience on the other. The utility of these Briefing Notes and Information Sheets will become evident over time and can be monitored by the IEAGHG.

## **6. Appendix One: Briefing Notes**

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## Briefing Note

### Key terms and concepts

This Briefing Note outlines some of the technical terms and concepts that are used in discussing CO<sub>2</sub> capture and storage (CCS). It is far from being a complete glossary of CCS terminology, though other such glossaries already exist, e.g. that developed by the ECO2 project which is available on the internet at: [www.eco2-project.eu](http://www.eco2-project.eu)

#### 1. Chemicals and their properties:

##### Carbon:

Carbon (symbol C) is an element (a pure chemical substance) which is the basic chemical around which the molecules of life are constructed – including proteins, carbohydrates, and fats. Carbon exists both in pure form (graphite and diamond are types of pure carbon), or chemically bonded with other elements to create different substances, such as charcoal, oil, wood, sugar and hair. While less than 0.1% of the Earth consists of carbon, it is a major constituent of living things – humans are around 18% carbon, and around half of the dry mass (water removed) of most plants is carbon.

Because of its crucial role in the chemistry of life, carbon is constantly taken up and released by living things as they grow, use energy, die and decay. In some cases carbon is exchanged directly between living things (e.g. as food), but the majority of it is taken from or released into the atmosphere, soil and ocean, and, over longer timescales, rocks and minerals (**geological stores**). These stores, along with living things, are sometimes referred to as carbon reservoirs, between which carbon is continually recycled - a process known as the **carbon cycle**. The natural carbon cycle balances the amounts of carbon passing in and out of each of these reservoirs. While it is known to have changed in the distant past (millions of years ago), the carbon cycle has been very stable in more recent times. However, human activity – especially **deforestation** (which releases carbon from the trees as they are burned or decay and from the deforested soils), and burning fossil fuels – coal, oil and gas - which contain large amounts of carbon, is altering the carbon cycle by changing the amounts of carbon in the different atmosphere, ocean, soil, living things and geological reservoirs.

##### Carbon dioxide - CO<sub>2</sub>:

Carbon dioxide (symbol CO<sub>2</sub>) is a chemical made up of one atom of carbon bonded to two atoms of oxygen (another element, symbol O). In normal conditions it is a gas, and it currently makes up around 0.039% of the Earth's atmosphere. It is produced when substances containing carbon, such as food, wood or fossil fuels, react with oxygen (usually by burning) to release energy. Carbon dioxide is a very stable chemical meaning it does not easily react with other chemicals, making it difficult for the carbon and oxygen to be separated again. Fortunately, over many hundreds of millions of years plants have

developed a method to do this using sunlight – known as **photosynthesis**. This hugely complex process is the key to life on Earth and scientists are only just starting to be able to artificially recreate some of the key chemical reactions involved.

Plants absorb CO<sub>2</sub> from the atmosphere and ocean and, through photosynthesis, break it down into carbon and oxygen. The carbon combines with other chemicals (nutrients – especially nitrogen) to make the molecules from which plants are formed. The oxygen is then released into the atmosphere, enabling animals (including humans) to breathe. Oxygen reacts with carbon-containing molecules in food to produce energy and CO<sub>2</sub>, a process known as respiration. Carbon is also combined with oxygen when plant material, such as wood, is burned to produce energy in the form of heat and light.

CO<sub>2</sub> in the atmosphere has an important role in the Earth's climate. It is a **greenhouse gas**, which means it can absorb and emit heat (infrared radiation). Light from the sun reaching the Earth passes through the atmosphere and warms the Earth's surface – the land and ocean. As they become warm, the land and ocean surface emit heat as infrared radiation to the atmosphere. Some of this heat passes through the atmosphere and out into space. Greenhouse gases in the atmosphere absorb a fraction of the infrared radiation and prevent it from escaping into space. As a consequence and in order to keep in radiative balance, the earth's surface warms up somewhat. The main greenhouse gas is CO<sub>2</sub>, but methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) are also important.

The term **greenhouse effect** comes from the way in which a greenhouse for growing plants works – the glass lets in light but prevents infrared radiation from escaping (in the case of a greenhouse, by reflection from the inner surface of the glass back into the space of the greenhouse) so the inside of the greenhouse becomes hotter than the outside world. The greenhouse effect is a key part of what makes the Earth habitable to life. Without it the Earth would be a much colder place, with all liquid water on the surface permanently frozen. However, the increasing amount of greenhouse gases in the atmosphere as a result of human-induced activities such as burning fossil fuels and deforestation is heating up the Earth at a rate which is unprecedented relative to the historical record and thereby changing its climate and the systems on which life depends.

Human activity is releasing CO<sub>2</sub> into the atmosphere much faster than it can be naturally removed by the carbon cycle. Its concentration has now increased by half as much again as the amount that was in the atmosphere before industrial development and it continues to rise by over 2 parts per million per year. This means the warming effect of CO<sub>2</sub> on the Earth is increasing. While CO<sub>2</sub> is not the only greenhouse gas in the atmosphere, its impact is greater over the long term due to the larger amount being added, for example, by human activity, and the length of time it remains in the atmosphere (from decades to centuries).

CO<sub>2</sub> is naturally present in the atmosphere, soils and oceans at low concentrations where it poses no risk to health. However, it is an asphyxiant gas which at high concentrations

(between 1-3%) can affect our ability to breathe properly by preventing blood from carrying oxygen. Higher concentrations (around 5% or higher) can cause unconsciousness and death. These sorts of concentrations do not occur generally but, as CO<sub>2</sub> is heavier than most of the other gases present in air, it can accumulate in low-lying areas if the air is not moving. This hazard was faced by miners working in poorly ventilated mines, where CO<sub>2</sub> could accumulate gradually to dangerous levels.

### **Fossil fuels:**

Coal, oil and gas are fossil fuels – substances derived from organisms that died and accumulated on the Earth's surface and were subsequently buried by geological processes over millions of years. Different fossil fuels are created depending on which living things have been buried and the processes at play over very long periods of time – for example, exposure to high temperatures and/or pressures. All of these carbon-rich materials can be burned, using oxygen from the air, to produce energy. Over 80% of the world's energy comes from burning fossil fuels.

### **Coal:**

Coal is a type of rock formed by the burial of ancient forests under water (swamps and lakes). Over millions of years, the plant material was gradually compressed and heated in an environment where it was unable to decay (little oxygen in the water) undergoing a process called **carbonisation**. Coal is a carbon-rich substance – its carbon content ranges from around 60-75% (known as **lignite**) through to **anthracite** which is over 90% carbon. The other main elements in coal are hydrogen, oxygen and sulphur. Around 8 billion tonnes of coal are extracted and burned every year for energy. Coal is the world's second largest source of energy providing 30% of the total supply and 42% of the energy for generating electricity. Due to the scale of its use and the large amount of carbon it contains, coal combustion is the largest source of CO<sub>2</sub> emissions to the atmosphere from human activity at 40% of the total.

### **Oil:**

Oil is formed from large quantities of tiny marine organisms (algae and zooplankton) that have been buried under layers of other rocks over geological time (hundreds of millions of years), and subjected to high heat and pressure deep underground. This process takes place in what are termed **source rocks**, from which the oil is squeezed by the huge pressure. It then moves through overlying rocks via tiny spaces between individual rock grains until it reaches a layer of rock, known as **cap rock**, which blocks any further movement. Here, it accumulates, filling the spaces in the rock to form an **oil reservoir**. It can then be extracted by drilling through the cap rock, allowing the oil to come to the surface.

Oil is known as a hydrocarbon as it has a chemical structure made primarily of carbon (around 85%) and hydrogen (around 12%). Oil is an energy-rich substance – with a calorific

value around two to three times that of sugar - and is the largest source of energy used by humans - 35% of the total - mostly for transportation. When extracted, oil is a thick black or dark brown substance, known as **crude**. Its use as a fuel requires **refining** – to break the oil down into purer chemicals using a combination of heating and reacting with other chemicals, such as hydrogen. Around 4 billion tonnes of oil is extracted, refined and used each year, making it – at 18% of the total - the third<sup>1</sup> largest source of human CO<sub>2</sub> emissions.

### **Gas:**

Generally referred to as natural gas to distinguish it from other types of gas, natural gas is, like oil, a hydrocarbon, made from the remains of ancient living organisms that have been buried deep in underground rocks. In fact, although it occurs on its own in reservoirs, gas is also often found in the same reservoirs as oil – flaring is the burning off of this gas at an oil well when there are no pipelines available to transport the gas for sale. While most of the natural gas we use is found in reservoirs similar to oil reservoirs, industry has recently developed techniques for extracting gas found trapped in rocks through which it cannot naturally move. These include hydraulic fracturing, also known as fracking – using high pressure to fracture the rocks allowing the gas to be extracted.

Chemically, natural gas is mostly (70-90%) methane – 1 carbon atom bonded to 4 hydrogen atoms, with the rest made up of varying proportions of similar chemicals also made of carbon and hydrogen – ethane, propane and butane. Other chemicals are also found in lesser amounts including CO<sub>2</sub> and hydrogen sulphide (commonly known as ‘rotten egg’ smelling gas)<sup>2</sup>. To transport and burn the gas it needs to be purified to near-pure methane. Facilities that do this – known as gas processing plants – can emit a lot of CO<sub>2</sub> which has been ‘scrubbed’ or taken out of the gas. In a few cases, instead of being released to the atmosphere, this CO<sub>2</sub> is collected, transported and injected into rocks deep underground. This is an example of CO<sub>2</sub> capture and storage (CCS), and is taking place at gas processing plants in the US, Norway and Algeria where millions of tonnes of CO<sub>2</sub> per year are stored instead of being emitted.

Natural gas is used for many purposes. It is used for domestic cooking and heating, for electricity generation, and as a chemical feedstock for making other chemicals like hydrogen and fertilisers. It is a much cleaner fuel for electricity generation than coal, and when burnt at a power plant produces around half the CO<sub>2</sub> per unit electricity compared with coal as well as far fewer other air pollutants. However, it remains a high carbon fuel compared to renewables and the use of natural gas makes a major contribution to human CO<sub>2</sub> emissions (10% of the total).

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<sup>1</sup> The second largest source of human CO<sub>2</sub> emissions is deforestation.

<sup>2</sup> In fact, natural gas (methane) has no smell. The smell we associate with it is a chemical added to the gas when it is distributed to homes and businesses to alert people in case of a leak.

## **2. Rocks and geological terms:**

There are many types of rocks, but they can broadly be classed into three types depending on how they were made. Igneous rocks are formed from cooling molten rock (magma or lava), sedimentary rocks are formed from the accumulation of lots of individual rock grains (and other materials) and metamorphic rocks are formed from the transformation of igneous or sedimentary rocks by extreme pressures and temperatures to form new rock. Sedimentary rocks are where fossil fuels are found, and where CO<sub>2</sub> storage can take place.

### **Sedimentary rock:**

Sedimentary rocks are created by the accumulation (over many millions of years) of lots of little rock and other material particles which have been ground and carried away from their place of origin by wind and water, gradually becoming stuck together to form a rock. Sandstone – made from ancient beaches or deserts that have been buried and compressed - is a common sedimentary rock. Because of its structure, sedimentary rock is not always solid. Depending on the size and shape of the individual grains, and how well they are stuck together, tiny spaces (known as pores) can be found in between the grains. The measure of how much of the rocks volume is pores is known as the porosity, and can be as high as a half – meaning that half of the rock's volume is pores. These pores are not empty – they contain other substances including air, water, natural gas, oil and CO<sub>2</sub>. However, how easily these substances can move through the rock (from pore to pore) depends on how well connected the pores are to each other. This is a property known as permeability.

### **Reservoir rock:**

Sedimentary rocks in which oil or gas are found are often called reservoir rocks. These tend to have a high porosity (lots of the rock volume is pores), and high permeability (the pores are well connected to each other). This means that when a well is drilled into the rock, the oil or gas can move through the rock and be extracted. Reservoir rocks are excellent candidates for storing CO<sub>2</sub> as lots of CO<sub>2</sub> can be injected into them.

### **Cap rock:**

What stops the oil or gas moving through the rock to the surface of its own accord? In some cases, there is nothing to stop this happening – generally this means that the oil or gas is long gone as it escaped many millions of years ago, but in some places oil, gas and other substances including CO<sub>2</sub> naturally leak to the surface at places known as seeps. The La Brea Tar pits in Los Angeles (USA) are the world's most famous oil seep. However, in most cases, reservoir rocks are overlain by layers of other (usually also sedimentary) rocks. Sometimes these rocks have a lower porosity and permeability so that substances can't move through them very easily (or at all). These rocks can 'seal' a reservoir by preventing the escape of the

oil, gas, water or CO<sub>2</sub> in the reservoir rock and are often called cap rocks. When a well is drilled to extract oil or gas from a reservoir, the cap rock is drilled through – this hole is what allows the oil or gas to come to the surface. In truth, there are usually many different overlapping layers of cap rocks and reservoir rocks – sometimes with faults (cracks) which can allow limited movement of substances between different reservoirs.

### **Saline aquifer:**

Another type of reservoir rock where CO<sub>2</sub> can be stored is a saline aquifer. A saline aquifer is a reservoir rock where the pore spaces in the rock are filled with salty water called brine which is of no use for drinking or irrigating agriculture. The saline aquifers being considered for CO<sub>2</sub> storage are also so deep (generally about 1 km below the surface) that they would not be considered as a source of drinking water.

If a saline aquifer has a suitable cap rock above it, CO<sub>2</sub> can potentially be injected for storage. Unlike depleted oil and gas fields, injecting CO<sub>2</sub> into a saline aquifer increases the pressure, but as many saline aquifers are huge structures (many tens of kilometres in extent), provided the porosity and permeability are appropriate, very large volumes of CO<sub>2</sub> can be injected with only a very slight increase in pressure. CO<sub>2</sub> is currently injected for storage at commercial scale (in the order of millions of tonnes per year) into saline aquifers in Norway, and smaller research injections are underway in many parts of the world as part of investigating possibilities for CO<sub>2</sub> storage for CCS.

### **Depleted oil and gas fields:**

One of the places where CO<sub>2</sub> storage could take place is in old oil and gas reservoirs, where as much of the oil or gas as possible has been extracted. Because these reservoirs have contained oil and gas we know a lot about their properties – we know the porosity and permeability of the rock, and that the cap rock has sealed the reservoir without it leaking for millions of years until drilled through. Also, extracting the oil or gas has reduced the pressure in the reservoir, so CO<sub>2</sub> can be injected to bring the reservoir back to its original pressure with very little risk. However, a number of things still need to be considered. CO<sub>2</sub> is a different substance to oil and gas so behaves a bit differently in the reservoir – for instance it might be able to move through faults that oil cannot. Also, multiple wells are often drilled into oil or gas reservoirs to improve the amounts extracted. When they are no longer used they are closed-down and sealed with cement and mud. For CO<sub>2</sub> storage, these old wells need to be checked carefully to make sure that the sealing was properly performed and is appropriate for containing CO<sub>2</sub>.

### **Enhanced oil recovery:**

Large amounts (up to 50 million tonnes per year) of CO<sub>2</sub> are currently injected into old oilfields where the level of oil production has decreased. Injecting CO<sub>2</sub> both keeps the pressure in the reservoir high and, when CO<sub>2</sub> mixes with oil, it makes oil less viscous (sticky),

which allows it to flow through the rock better. This process is known as CO<sub>2</sub> enhanced oil recovery (often just called CO<sub>2</sub>-EOR) and, as well as allowing more oil to be extracted, has taught geologists a huge amount about how to inject CO<sub>2</sub> and how it behaves in deep underground rocks.

Authors: Vivian Scott and Simon Shackley

## Briefing Note 1

### Setting the Scene for CO<sub>2</sub> Capture and Storage: Human-Caused Climate Change

#### What is climate change?

While weather can change from day to day, climate is about long-term averages (typically over three decades or longer) and trends in the weather in a particular place. **Climate change** is persistent, long-term variation in climate averages, such as rainfall or temperature. Persistent and long term changes in climate can result in greater variability in day to day weather and more extreme weather events.

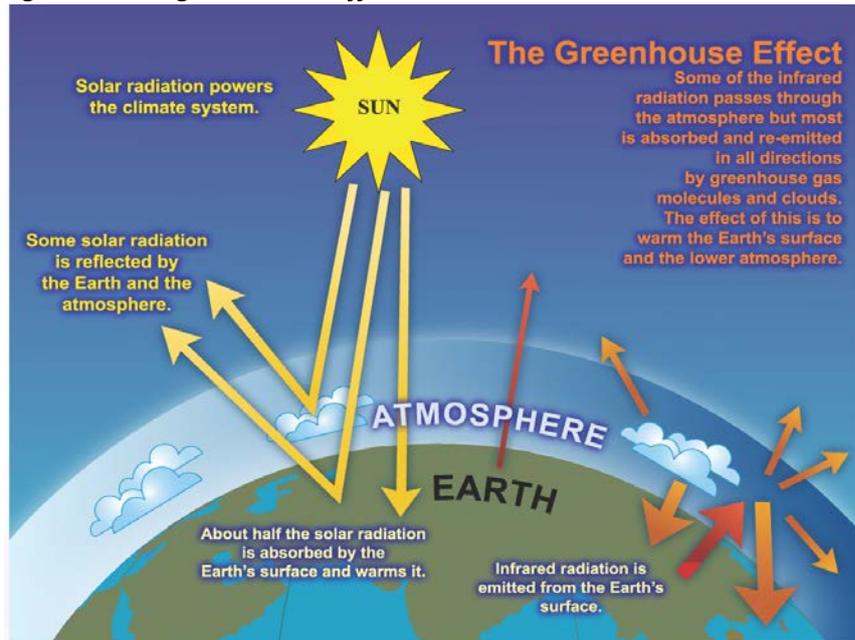
Climate change may result from natural processes, such as changes in solar radiation or the concentration of greenhouse gases (GHGs) in the atmosphere induced by human activity. This Briefing Note aims to provide a scientific foundation to the debate about how we are affecting our climate, and how it affects us.

#### We live in a greenhouse

The glass in a greenhouse prevents some of the sun's heat from escaping and so keeps the greenhouse warm. Similarly, some gases in the Earth's atmosphere prevent a proportion of solar energy from radiating back out into space, thereby keeping the planet warm. These gases are therefore called **greenhouse gases** (Figure 1).

GHGs such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) occur naturally and, particularly in the case of CO<sub>2</sub>, are necessary to support life on earth by keeping the planet at a habitable temperature. Maintaining the Earth's temperature within a range tolerable to life is a delicate balance, however. Increasing or decreasing the volume of GHGs causes the planet to retain too little or too much heat which, over time, changes the Earth's average temperatures and climatic conditions.

Figure 1: The greenhouse effect.



Source: page 115, IPCC (2007), *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* in Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.), Cambridge University Press, Cambridge, UK and New York, NY, USA.

The Earth's average surface temperature has risen by 0.74°C since the late 1800s. Whilst this temperature rise may seem small, the short timeframe in geological terms makes it important. By comparison, the last major global warming occurred at the end of the last great Ice Age (about 15,000 years ago); it involved a temperature increase of approximately 5°C over a time span of 5,000 years. Contemporary climate change has the potential to reach a similar level of temperature increase over a fraction of this time and is starting from an already warm climate (relative to the end of the last Ice Age).

Rising temperatures and other climatic change (such as rainfall, climate extremes, climate variability, sea-level change, etc.) have the potential to cause a range of disruptive impacts on ecosystems, natural resources and human communities throughout the world. Additionally, changes in temperature, humidity and rainfall patterns can alter the types and timing of pest and disease outbreaks, which farmers and healthcare organisations must then manage. Finally, sea levels, which rose by 10-20 cm during the 20th century, may rise by up to 90 cm by 2100 due to oceanic expansion and melting glaciers and ice caps.

### Human impact

The Intergovernmental Panel on Climate Change (IPCC) has concluded that: "[most] of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." The IPCC defines "very likely" as indicating a probability of greater than 90%, based on expert judgement. The IPCC's attribution of recent global warming to human activities is a view shared by most scientists and is also supported by a number of scientific research organisations and publications. The increase in GHG concentrations (especially CO<sub>2</sub>) is a result of over 150 years of industrialisation during which time societies have burnt ever-

greater quantities of oil, gas, and coal, and cleared large areas of forest for agriculture and other development. All of these activities release CO<sub>2</sub> and other GHGs into the atmosphere.

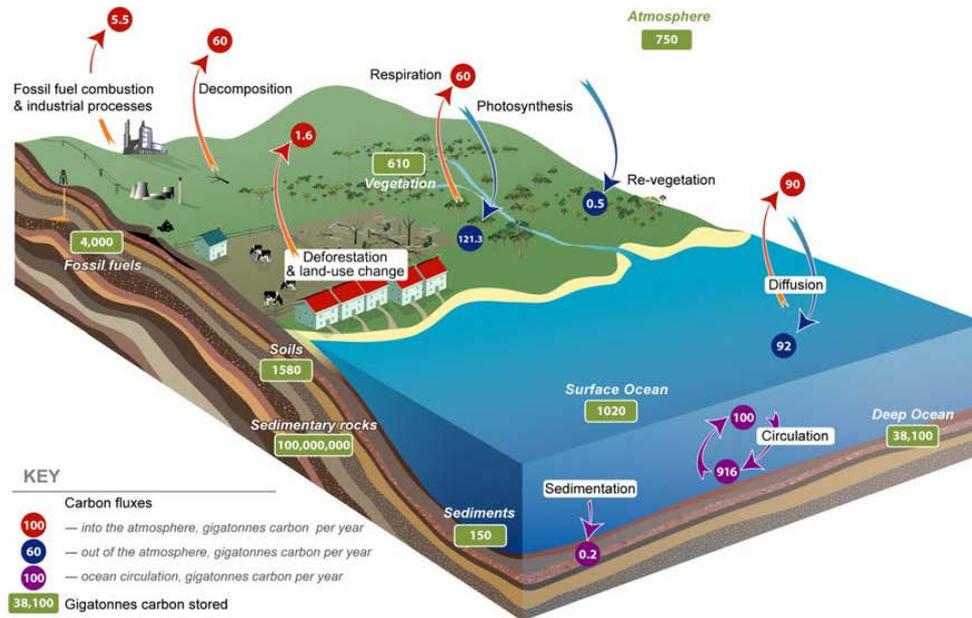
### **What is carbon dioxide?**

The major greenhouse gas, CO<sub>2</sub>, is a naturally occurring substance made up of one carbon and two oxygen atoms, two of the most common chemical elements on earth. Under normal atmospheric conditions CO<sub>2</sub> is a gas, but it can be compressed into a liquid, frozen into a solid (dry ice) or dissolved in water (it can be seen in sparkling water and carbonated beverages such as beer and sparkling wines). In the atmosphere, CO<sub>2</sub> currently comprises about 0.04% of the air we breathe. It occurs naturally in freshwater and seawater, in some rock formations and in the soil. CO<sub>2</sub> is not flammable or toxic, nor does it explode. However, CO<sub>2</sub> can cause drowsiness at 0.1 – 0.25% atmospheric concentration and adverse health effects at 0.25 to 0.50%. At very high atmospheric concentrations (above 10% atmospheric concentration) it can result in asphyxiation and death.

### **The carbon cycle**

Carbon is present in all of the Earth's systems (atmosphere, water, soils, rocks, plants and animals) and all life is based upon **hydrocarbons** – molecules containing both carbon and hydrogen, from small to very large, which form the building blocks of all life forms. All the carbon present in the Earth today was present when the solar system emerged 4.5 billion years ago. Figure 2 shows the carbon cycle – the movement of carbon between different “reservoirs” (stores) in land, ocean and atmosphere. The total amount of carbon in the cycle does not change – it is merely exchanged between land, air, sea and the organisms existing within them, humans included. Nature's carbon cycle normally keeps CO<sub>2</sub> levels in balance, but human activity, mostly the burning of fossil fuels, produces more CO<sub>2</sub> than nature can absorb. The arrows in Figure 2 show that the human contribution is relatively small, but enough to throw the cycle off balance. The extra CO<sub>2</sub> stays in the atmosphere, where it causes climate change. This concept is explained in more detail below.

Figure 2: Annual flows of carbon in billion tonnes (metric tons)



Source: NASA Earth Science Enterprise and the International Energy Agency

During photosynthesis, plants absorb  $\text{CO}_2$  and release oxygen back into the atmosphere. Animals (and plants, at night) inhale oxygen from the air and exhale  $\text{CO}_2$ .  $\text{CO}_2$  is also exchanged between the atmosphere and the oceans and is emitted during other natural processes, e.g. from volcanoes, from natural 'seeps' in the ground as well as being absorbed, e.g. into rocks and soils. The collective effect of all these processes has been to keep  $\text{CO}_2$  concentrations relatively stable within a given climate envelope. As the global average temperature goes up,  $\text{CO}_2$  concentrations also rise, and vice versa.

Fuels derived from (once) living things, such as wood and fossil fuels, contain carbon. When they are burned, the carbon inside the fuel is released and combines with oxygen to form  $\text{CO}_2$ , which enters the atmosphere, producing energy in the process.

In burning fossil fuels and releasing carbon into the atmosphere that would otherwise have remained stored underground in oil, gas and coal, we have disrupted the balance of the carbon cycle such that there is a rising concentration of  $\text{CO}_2$  in the atmosphere. The sinks which usually absorb  $\text{CO}_2$ , such as vegetation and the oceans, are not able to increase their uptake at a sufficiently rapid rate to compensate for these additional human-induced  $\text{CO}_2$  emissions.

$\text{CO}_2$  has many practical uses. It is used in a variety of industries: chemicals, including urea production for fertilisers, metals, food and drinks, healthcare, pulp and paper, electronics and waste treatment. It is also used in its frozen form as dry ice, for example, to add 'atmosphere' in films and theatre. The amount of  $\text{CO}_2$  needed for all these uses, however, is minute (< 1%) compared to the amount emitted into the atmosphere by burning fossil fuels.

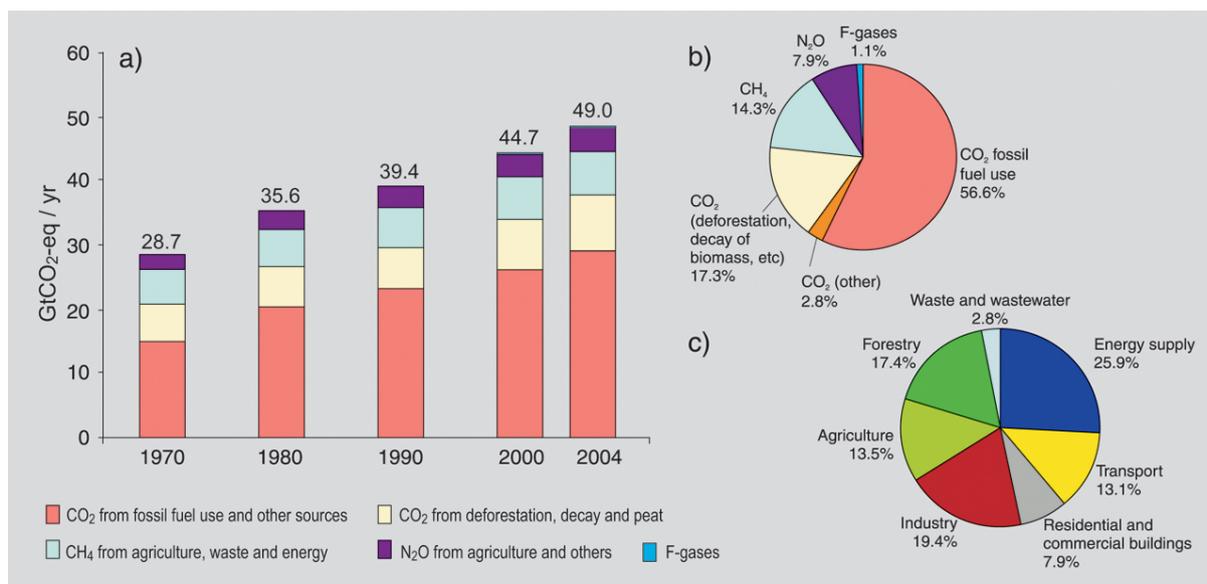
### Too much carbon dioxide and other greenhouse gases in the atmosphere is problematic

In order to avoid dangerous levels of climate change it is necessary to substantially reduce the levels of GHGs in the atmosphere. There are six main greenhouse gases: carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), sulphur hexafluoride (SF<sub>6</sub>), and hydrofluorocarbons and perfluorocarbons (F-gases). When all six greenhouse gases are taken into account, CO<sub>2</sub>-equivalent (CO<sub>2</sub>-e) is referred to. Figure 3 shows that CO<sub>2</sub> is the major contributor to increased atmospheric GHG levels, with most CO<sub>2</sub> coming from burning fossil fuels.

The measure parts per million (ppm) is used to describe the concentration of GHG levels in the atmosphere. The current level is 430 ppm CO<sub>2</sub>-e, and it is rising by more than 2 ppm each year. It is estimated that GHG levels must be stabilised at between 450 and 550 ppm or 0.045 and 0.055% by volume CO<sub>2</sub> equivalent (CO<sub>2</sub>-e). In order to reach this target, it would require a global effort to cut emissions by at least 25% (perhaps much more) below the current levels by 2050. If the target was set more towards the 450 ppm level of the scale, then global emissions would need to be halved by 2050.

The continually rising average for global temperature each decade is seen as the most important indicator of climate change. In addition to the 0.74°C temperature rise already recorded, further temperature increases (of between 1.8 - 4.5°C) are predicted to occur by 2100 if GHG emissions are not reduced. Even if GHG concentrations were stabilised now, we could still experience a rise of 1.1°C by 2100.

Figure 3: (a) Global annual emissions of human-induced GHGs from 1970 to 2004 (b) Share of different human-induced GHGs in total emissions in 2004 in terms of CO<sub>2</sub>-e (c) Share of different sectors in total human-induced GHG emissions in 2004 in terms of CO<sub>2</sub>-e (Forestry includes deforestation.)



Source: page 36, IPCC (2007), *Climate change 2007: Synthesis Report Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* in B. Metz et al (Eds). Cambridge, UK and New York, Cambridge University Press.

## The challenge ahead

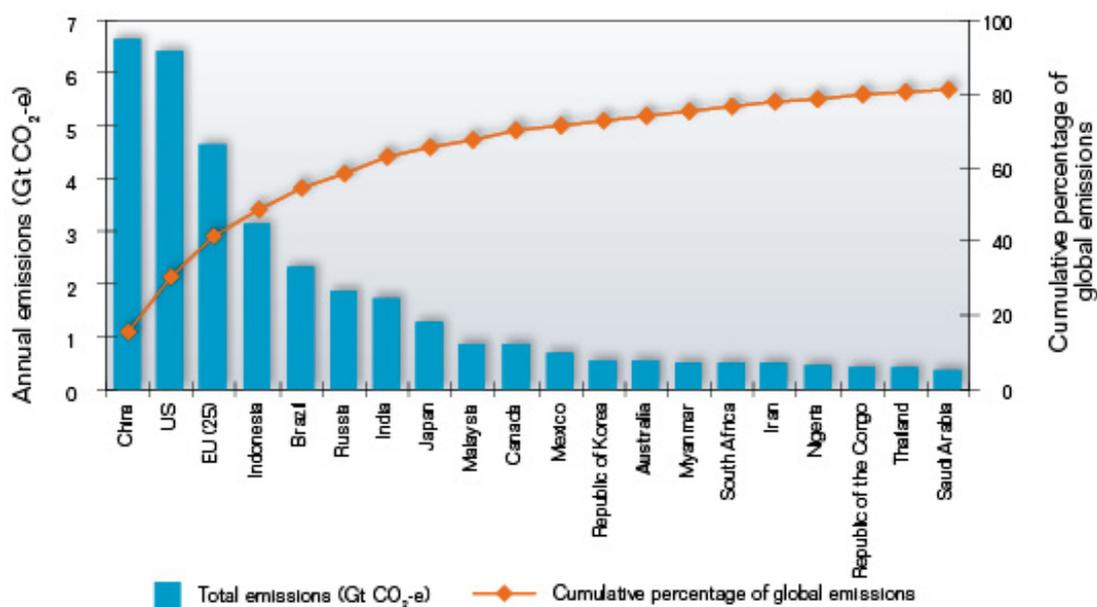
Society as a whole must stabilise GHG emissions because climate change will bring about dangerous short-term and long-lasting social, economic and environmental effects. For instance, spread of diseases, displaced communities, food shortages, extreme weather events, water shortages, drought and much more.

There are two main ways to reduce the amount of carbon being emitted to the atmosphere – transforming the ways we use energy so that we need less or developing sources of energy that produce fewer or even zero emissions per unit of energy. As the global population and economy continue to expand, it is likely that the world’s demand for energy will likewise increase. Developing low-carbon forms of energy is therefore essential to stabilising emissions. Carbon dioxide capture and storage (CCS) is a technology which has the potential to produce large quantities of energy from coal and gas in power plants and industrial facilities but, crucially, without emitting CO<sub>2</sub> into the atmosphere.

## Global problem, global response

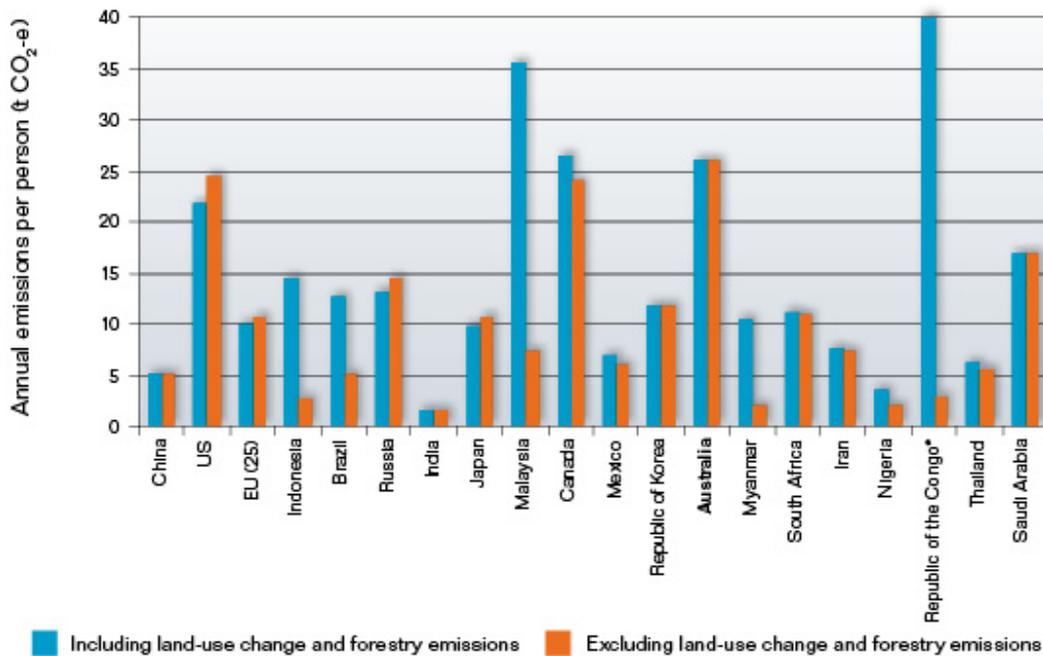
Every country produces GHG emissions, but some contribute more than others. Figure 4 shows the countries that emit the largest amount of gases. The bulk of GHG emissions arise from the countries at the centre of global economic and manufacturing activity. The largest emitters are China, the US and the European Union (which comprises 27 countries), which between them are responsible for more than 40% of global emissions. The 20 largest emitters are responsible for more than 80% of global emissions. As Figure 5 shows, richer countries emit more per person. It also highlights the contribution of land use and forestry to total emissions in each country.

Figure 4: The 20 largest greenhouse gas emitters: total emissions and cumulative share (%) of global emissions in 2004.



Source: The Garnaut Climate Change Review: Final Report, 2008.

Figure 5: The 20 largest greenhouse gas emitters: per capita emissions including and excluding emissions from land-use change and forestry in 2004.



Source: The Garnaut Climate Change Review: Final Report, 2008.

## Conclusion

Climate change caused by human activity, particularly through burning fossil fuels, carries many risks for society and the environment. The impacts of climate change, which are to some extent unpredictable, have the potential to be devastating, costly and long-term. To avoid the worst effects of climate change, we must significantly reduce CO<sub>2</sub> emissions in order to stabilise the level of GHGs in the atmosphere. CCS is one technology, alongside demand reduction, greater energy efficiency and renewable forms of energy, that could be used to help achieve this.

## Glossary

**Parts per million:** Describing the concentration of a gas in the air, 450 ppm CO<sub>2</sub> means that for every million litres of air, there are 450 litres of CO<sub>2</sub> in the air.

**CO<sub>2</sub> Equivalent (CO<sub>2</sub>-e):** For simplicity, all greenhouse gases are converted to CO<sub>2</sub> equivalents (CO<sub>2</sub>-e), as CO<sub>2</sub> is the most common greenhouse gas. Different greenhouse gases have different 'global warming potentials', for example methane = 25 CO<sub>2</sub> equivalents. In other words, one molecule has 25 times more impact on global warming than a molecule of CO<sub>2</sub> over a 100-year period.

## Further Reading

Intergovernmental Panel on Climate Change (IPCC) (2007). Climate change 2007: Synthesis report contribution of Working Groups I, II and III to the Fourth Assessment Report of the

Intergovernmental Panel on Climate Change in B. Metz et al (Eds). Cambridge, UK and New York, Cambridge University Press.

N. Stern (2006). The economics of climate change: The Stern Review, Cambridge, Cambridge University Press.

R. Garnaut (2008). The Garnaut climate change review: Final report from <http://www.garnautreview.org.au/index.htm>, accessed 16 February 2010.

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## Briefing Note 2

### Carbon Dioxide Capture and Storage – a brief history and current status

This Briefing Note explores the history of Carbon Dioxide Capture and Storage (CCS). It looks at different definitions and types of Carbon Dioxide Capture and Storage (CCS) projects and the industrial technologies and activities from which it has been developed. The current status of CCS projects and related activity is then detailed.

#### The early days of CCS

The idea of capturing and storing CO<sub>2</sub> from large industrial sources to keep it out of the atmosphere and limit climate change was first suggested by the Italian scientist Cesare Marchetti in 1977. While he suggested a new purpose, much of the basic technology was already in use. Carbon Dioxide (CO<sub>2</sub>) capture technology was developed in the 1920s and 1930s for separating CO<sub>2</sub> sometimes found in natural gas reservoirs from the methane gas. This process is often known as CO<sub>2</sub> scrubbing as it “cleans” up the natural gas making it pure enough to burn. In the early 1970s, some CO<sub>2</sub> captured in this way from the Val Verde gas processing facility in Texas (USA), was piped to the nearby SACROC oil field and injected into the oil field to help recover extra oil once the ‘easy’ oil had been extracted. This process, known as Enhanced Oil Recovery (EOR) has proven very successful and millions of tonnes of CO<sub>2</sub> both from natural accumulations of CO<sub>2</sub> in underground rocks and captured from industrial facilities are now piped to and injected into oil fields in the USA and elsewhere every year.

In 1996, following the introduction of the world’s first tax on CO<sub>2</sub> emissions by the Norwegian government, the Statoil oil and gas company started the world’s first large CO<sub>2</sub> capture and injection project for the purpose of preventing the emission of CO<sub>2</sub> to the atmosphere. Located in the Norwegian North Sea, the Sleipner project separates CO<sub>2</sub> found with natural gas in an undersea reservoir and instead of releasing it to the atmosphere, injects it into a rock formation called a saline aquifer deep in the rocks beneath the sea. Around one million tonnes of CO<sub>2</sub> per year has been captured and injected at Sleipner and careful monitoring has shown the CO<sub>2</sub> to be trapped in the rock as intended. In the 2000s, another two similar projects were also started – at the In Salah gas processing facility in Algeria (2002), and the Snhøvit gas processing facility in the Barents Sea offshore Norway (2007).

Carbon dioxide capture and storage (CCS) consists of three basic steps: (1) the selective capture of the CO<sub>2</sub> resulting from the burning of fossil fuels such as coal, oil and gas (and biomass); (2) the compression and transportation of the captured CO<sub>2</sub>; and, (3) the injection of the CO<sub>2</sub> into rock formations hundreds of meters below the Earth's surface where it can be securely stored for hundreds of thousands of years. CCS is a vital tool in reducing global carbon emissions as it is the only technology available which can 'decarbonise' burning fossil fuels to generate electricity and heat, as well as allowing major industrial sectors manufacturing steel, cement and many other products to be decarbonised.

*Figure 1: The Statoil Sleipner gas processing facility platform in the Norwegian North Sea started the world's first large scale injection of CO<sub>2</sub> to prevent its emission in 1996. The CO<sub>2</sub> is injected into a saline aquifer rock formation 1km beneath the seafloor.*



Source: © Statoil (used with permission)

The demand for CO<sub>2</sub> for injection into oilfields for EOR also established some other projects. In 2000, a gasification plant making synthetic gas from coal in Daktota (USA) starting piping CO<sub>2</sub> produced in the gasification process 200 miles across the border for injection into the Weyburn-Midale oilfields in Canada, and several more gas processing facilities in the Southern USA started transporting their scrubbed CO<sub>2</sub> to oilfields in Texas and Mississippi.

However, while all of these projects capture and inject CO<sub>2</sub> that would otherwise be released to the atmosphere to what extent they are CCS projects is open to some debate. For instance, while the CO<sub>2</sub> is captured when the natural gas is processed, it is not captured when the natural gas is later burned – a process that creates lots of CO<sub>2</sub>. The same can be said for EOR because injecting the CO<sub>2</sub> allows more oil to be extracted which produces CO<sub>2</sub> that isn't captured when it is burned. Nonetheless, projects like these are playing a key role in developing and establishing the technologies required for CCS including CO<sub>2</sub> capture processes, CO<sub>2</sub> transportation pipelines, and CO<sub>2</sub> injection and monitoring methods.

Alongside these early project developments, CCS became internationally recognised as a key technology for reducing CO<sub>2</sub> emissions and limiting climate change. For example, in 2007 the governments of the European Union called for a programme to demonstrate CCS on power plants and industry, and in 2008 the G8 (Group 8) nations summit announced a goal to “launch 20 large-scale demonstration CCS projects on power plants and industrial facilities to enable commercial deployment by 2020”. Such activity lead to the creation of

government supported CCS demonstration programmes intended to accelerate CCS deployment in many industrialised countries, and the creation of laws to regulate CO<sub>2</sub> storage from CCS.

### **Types of CCS project**

There are different definitions for a carbon dioxide capture and storage (CCS) project. A broad definition that includes the projects mentioned above could be “a technical system that captures CO<sub>2</sub> from large industrial sources and intentionally stores it deep underground in rock formations”. By contrast, a stricter definition might be “a technical system that prevents CO<sub>2</sub> emissions from the burning of fossil fuels or other industrial processes by capturing the CO<sub>2</sub> and intentionally storing it deep underground in rock formations.” Interpreting these definitions matters for our understanding of how much CCS has been done in the past, how much is operating now and how much there may be in the future.

There are several general types of CCS project depending both on the source of the CO<sub>2</sub>, the product made by the facility, the way in which the CO<sub>2</sub> is stored and the scale of the project. CCS can theoretically be applied to any large stationary source of CO<sub>2</sub>, but in some cases it is easier or less expensive than in others. Gas processing facilities like those described above have to scrub the CO<sub>2</sub> out of the gas in order to sell the gas for use, so the CO<sub>2</sub> capture is an essential part of their gas production process. Synthetic gas production, refining oil to make diesel and petrol, bioethanol production and fertiliser manufacture are other examples of processes that can generate near-pure CO<sub>2</sub> from the production process.

By contrast, power plants burning fossil fuels (the largest source of human made CO<sub>2</sub>) don't have to capture the CO<sub>2</sub> from the chimney to produce useable electricity. Capturing the CO<sub>2</sub> requires additional energy which increases the cost of the overall process and makes the electricity more expensive. The situation is similar for many other industrial manufacturing processes that result in lots of CO<sub>2</sub> emissions such as making steel, cement, glass and paper. However, CCS is the only currently available option to significantly reduce CO<sub>2</sub> emissions while continuing to burn fossil fuels to produce the electricity and manufacture the materials and products from which modern society is powered and built.

The way in which the CO<sub>2</sub> is stored is also important. As mentioned above a lot of experience with injecting CO<sub>2</sub> into underground rocks comes from EOR injection into oilfields to increase the amount of oil produced. This is sometimes termed Carbon Dioxide Capture, Use and Storage (CCUS). While the extra oil produces CO<sub>2</sub> when it is burned, as the operators of the oilfield buy the CO<sub>2</sub> this can help towards the cost of CCS project. As a result EOR is playing an important role in establishing and developing early CCS projects.

Some of the injected CO<sub>2</sub> will remain in the geological formation, and some will leave the formation with the oil. Because the CO<sub>2</sub> is expensive to purchase, the oilfield operator will capture the CO<sub>2</sub> as it comes out with the oil and re-inject it into the rock formation for more EOR. As the CO<sub>2</sub> is recycled in this way, more of the CO<sub>2</sub> is trapped and retained within the rock. Exactly how much CO<sub>2</sub> is retained in the long-term is unclear as there has in general not been the close monitoring of the CO<sub>2</sub> inputs and outputs that would be required to know this. It is estimated that at least half of the CO<sub>2</sub> become trapped in the field, and higher proportions can be achieved depending on how the CO<sub>2</sub> injection is carried out.

This highlights an important consideration for storing CO<sub>2</sub>, as part of EOR or in depleted oil and gas fields or saline aquifers, that to know how effective the CCS procedure is the amount of CO<sub>2</sub> injected and stored needs to be recorded. This is often called measurement, monitoring and verification (MMV) after the different processes that should be undertaken so that both the storage operator and the regulator can confirm the amount of CO<sub>2</sub> stored. Many EOR projects do not currently undertake detailed MMV so the amount of CO<sub>2</sub> that they store is not known accurately, though some like the Weyburn-Midale project in Canada are being used to develop measurement and monitoring methods.

Lastly, the scale of a CCS project is important. In 2011, fossil fuel burning resulted in over 30 Gt (billion tonnes) CO<sub>2</sub> emissions to the atmosphere. For CCS to help reduce this level of emissions many millions of tonnes of CO<sub>2</sub> needs to be captured and stored. EOR operations currently inject around 15 million tonnes of CO<sub>2</sub> captured from industrial sources per year, and around 4 million tonnes of captured CO<sub>2</sub> is injected into saline aquifers. While a good start this is not enough. A single large coal burning power plant produces around 20-30 million tonnes of CO<sub>2</sub> per year – many hundreds of CCS projects each capturing and storing millions of tonnes of CO<sub>2</sub> per year are needed.

### Current status of CCS (2012)

As CCS is an area of active development the picture is continually changing. However, for CCS to deliver the expected CO<sub>2</sub> emissions reductions its rate of deployment will have to massively increase from that seen to date. Currently there are only a small number of large (storing around a million tonnes or more) CCS projects in the world on facilities where the CO<sub>2</sub> capture is part of the production process. The very first few power plants fitted with CCS technology to capture and store a significant fraction of their emissions are under construction and expected to start operating around 2015. There are also around another 60-70 large CCS projects proposed around the world in varying degrees of planning and preparation. A small number are very advanced and awaiting final confirmation of commercial and government backing, but many more are still in relatively early stages of development. Figure 1 shows a map giving an overview of operating and in advanced development CCS projects in 2012. The Global CCS Institute publishes an annual review of the global status of all CCS projects every year, and regularly updated maps of the global situation are also maintained by various organisations (see further reading).

Figure 2: Global overview of CCS projects (2012)



Source: © SCCS

In addition to operating and planned large scale CCS projects, there are also many smaller research and testing pilot projects being undertaken to improve for instance the efficiency of the CO<sub>2</sub> capture or develop better ways to monitor injected CO<sub>2</sub>. Most of these focus on one component (e.g. CO<sub>2</sub> capture) of the CCS process, but a few, such as the Lacq project located in SW France, include all the components and have taught scientists and engineers a lot about how to join together and integrate the CCS process.

*Figure 3: The Schwarze Pumpe pilot CO<sub>2</sub> capture plant run by Vattenfall in Germany started operations in 2008. Capable of capturing up to 75,000 tonnes of CO<sub>2</sub> per year it is used to test a CO<sub>2</sub> capture technology called oxyfuel combustion. Some of the captured CO<sub>2</sub> has also been used to test CO<sub>2</sub> injection.*



Source: © IEAGHG

As CCS remains a relatively new concept there is also a large amount of activity in areas like developing new CO<sub>2</sub> capture methods happening in both commercial and academic research establishments. As this research becomes more advanced it may be tested in pilot facilities and may eventually be applied at large scale on commercial facilities. While there remains a lot of potential for improvement, current CCS technology and experience is sufficiently advanced to allow the first generation of large scale projects to be built and operated.

### **Summary**

CCS builds on technologies originally developed to clean CO<sub>2</sub> found along with natural gas, and experience using CO<sub>2</sub> injection into oilfields to extract additional oil. Since the late 1990s CCS has been applied at a handful of gas processing facilities each capturing and storing around 1 million tonnes of CO<sub>2</sub> per year. The first few fossil fuel burning power plants with CCS are now (2012) being constructed and some tens of others are in preparation. Considerable research and development activity to improve the processes used in CCS is also underway. For CCS to deliver emissions reductions and allow the continued

use of fossil fuels to produce electricity and the products that underpin the modern world like steel and cement many hundreds of large CCS projects are required.

**Glossary:**

EOR: Enhanced Oil Recovery involves injecting CO<sub>2</sub> into oil reservoirs when they are nearing the end of production to allow extra oil to be extracted.

G8: Annual international summit of the governments of the “Group of Eight” large developed and industrial economies – Canada, France, Germany, Italy, Russia, UK, USA, Japan.

Oxyfuel: A method of CO<sub>2</sub> capture from fossil fuel power plants where the fuel is burned in oxygen rich air making a highly concentrated CO<sub>2</sub> waste gas that requires minimal processing to be transported and stored.

Saline aquifer: A formation of porous (space between the individual tiny rock grains) rock filled with salty water into which CO<sub>2</sub> can be injected.

**Further reading:**

Global CCS Institute Status of CCS

[www.globalccsinstitute.com](http://www.globalccsinstitute.com)

Global maps of CCS project activity

<http://www.sccs.org.uk/map.html>

[http://sequestration.mit.edu/tools/projects/map\\_projects.html](http://sequestration.mit.edu/tools/projects/map_projects.html)

Authors: Vivian Scott, Simon Shackley and Nils Markusson

## Briefing Note 3

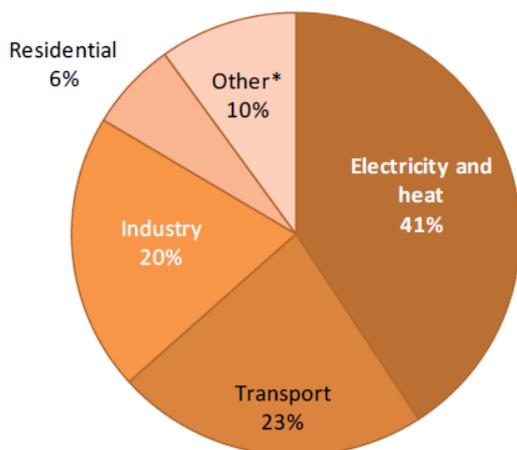
### From sources to stores – matching carbon dioxide (CO<sub>2</sub>) sources with potential geological storage sites for CO<sub>2</sub>

This Briefing Note considers where the main sources of the greenhouse gas carbon dioxide (CO<sub>2</sub>) from burning fossil fuels (oil, coal, gas) are currently to be found and examines which of these sources could be addressed through applying carbon dioxide capture and storage (CCS). It then moves on to explore, in a global context, where the major rock (geological) formations are to be found which could potentially be used for safely storing CO<sub>2</sub>. Bringing these two pieces of information together, this note evaluates how well the current locations of CO<sub>2</sub> sources match with potential CO<sub>2</sub> storage locations and examines what this might mean for the effectiveness of CCS as a method to reduce CO<sub>2</sub> emissions at a global scale.

#### Sources of CO<sub>2</sub> from Fossil Fuel Combustion

The burning of fossil fuels – oil, coal and gas - accounts for the majority of human-caused global CO<sub>2</sub> emissions (over 80%) with the remainder coming from processes such as deforestation. Fossil fuels are burnt to provide energy which is used to transport people and goods, to make electricity, to produce heat and to manufacture products. In 2010, 41% of global CO<sub>2</sub> emissions came from electricity and heat generation, 23% from transportation, 20% from industry and 6% from residential sources, with the remaining 10% from other sources such as agriculture (Figure 1).

*Figure 1: World CO<sub>2</sub> emissions by sector in 2010. CCS is proposed as a method to reduce emissions from large stationary sources of CO<sub>2</sub> such as the electricity and heat sector (power plants) and industry. Other sources of CO<sub>2</sub> include emissions from sectors such as agriculture, forestry and commercial/public services.*



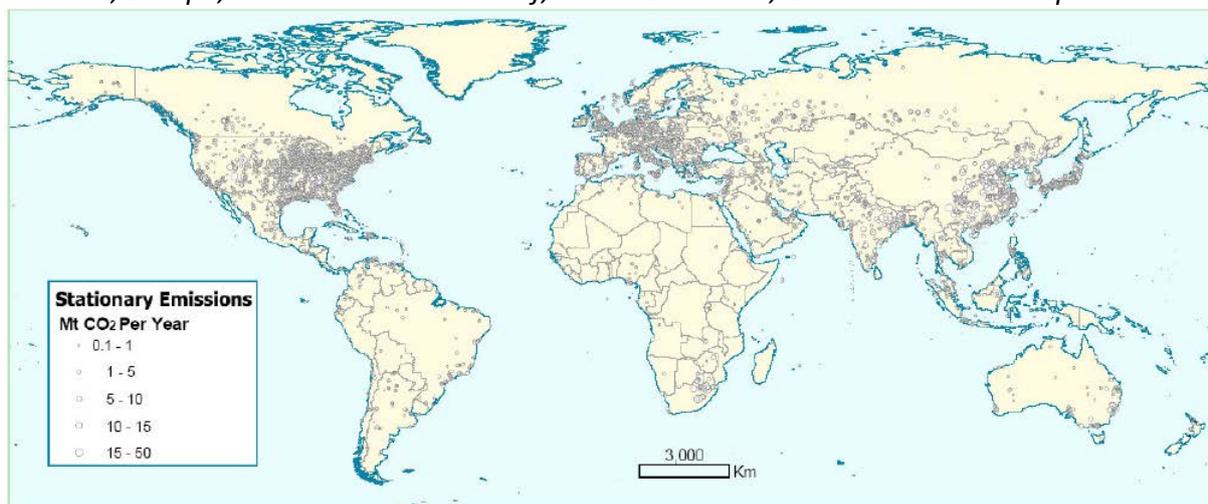
Source: IEA (2012), CO<sub>2</sub> Emissions from Fuel Combustion: Highlights, © OECD/IEA

Carbon dioxide capture and storage (CCS) consists of three basic steps: (1) the selective capture of the CO<sub>2</sub> resulting from the burning of fossil fuels such as coal, oil and gas (and biomass); (2) the compression and transportation of the captured CO<sub>2</sub>; and, (3) the injection of the CO<sub>2</sub> into rock formations hundreds of meters below the Earth's surface where it can be securely stored for hundreds of thousands of years. CCS is a vital tool in reducing global carbon emissions as it is the only technology available which can 'decarbonise' burning fossil fuels to generate electricity and heat, as well as allowing major industrial sectors manufacturing steel, cement and many other products to be decarbonised.

CCS is proposed as a method for reducing CO<sub>2</sub> emissions from large stationary sources of CO<sub>2</sub>, such as coal or gas power plants, or CO<sub>2</sub> producing industrial facilities such as steel, cement, and chemicals factories and oil refineries. These are often described as 'point sources', as they produce large amounts of CO<sub>2</sub> in a fixed location. This makes them ideal candidates for CCS which could be fitted to existing facilities, or built in to new facilities like the many new coal power plants expected to be constructed to meet growing energy demand in the developing world. As shown in Figure 1, in 2010 point sources accounted for around 60% of the total CO<sub>2</sub> emissions.

Figure 2 shows the locations of major CO<sub>2</sub> point sources across the world. At a global scale, the largest point source concentrations are in North America, Europe, around the Persian Gulf, North-East India, Eastern China and Japan, but there are also many other smaller concentrations e.g. around major cities in Eastern Australia, and very large but relatively isolated sources e.g. in Russia.

*Figure 2: Large point source CO<sub>2</sub> emissions in 2005. The greatest concentrations are in North America, Europe, around the Persian Gulf, North-East India, Eastern China and Japan.*



Source: IPCC (2005), *Carbon Dioxide Capture and Storage*, in B. Metz, O. Davidson, H. de Coninck, M. Loos and L. Meyer (Eds.), Cambridge University Press, Cambridge, UK and New York, USA.

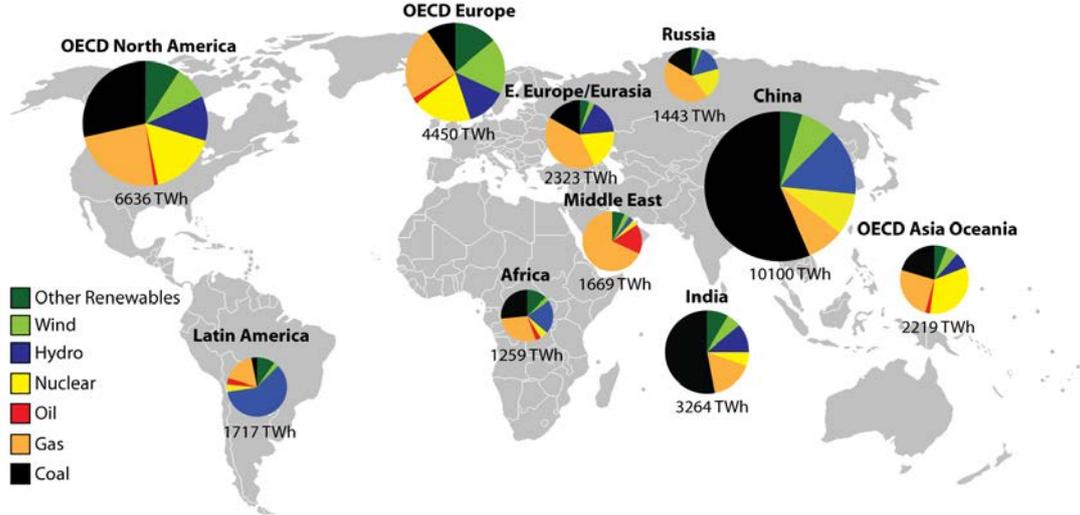
However, as an emerging technology the key question for CCS is where the major point sources are likely to be located in the future – say over the next 10 to 30 years. While it is impossible to know the future, it is possible to suggest likely scenarios based on estimates of economic growth and the resulting industrial development and energy demand. Generally, it is expected that the CO<sub>2</sub> emissions from point sources in the developed world regions – North America and Europe – will remain stable or decline slightly. In contrast, CO<sub>2</sub> emissions

from point sources in the developing world, especially in rapidly industrialising countries and regions – e.g. China, India, Indonesia, South Africa and Brazil are currently increasing and are expected to continue to increase as more fossil power plants and new factories are built. The precise locations of these new point-sources are also difficult to predict, but are mostly expected to be in areas matching to current ones as this is where customers, workforce and the infrastructure for delivering raw materials and despatching products are already in place. However, there could be some significant exceptions – e.g. new industrial development in western China.

Adding CCS to a facility will increase the cost of the product – e.g. through increasing the cost of purchasing the electricity generated by a fossil fuel burning power plant. For some industries e.g. making steel, CCS is the only option currently available to de-carbonise the process. However, for others there are alternatives. For instance, generating electricity from renewables or nuclear power could in some locations or cases be more cost-effective than fitting CCS to fossil burning power plants, so there might be less of a demand for CCS in these places.

Figure 3 presents a prediction for the sources of electricity generation in 2035 in global regions, showing that burning fossil fuels is expected to remain the largest source of electricity globally, and provide at least half the electricity in all but Latin America, Europe and developed East Asia (Japan, South Korea) and Australasia. This strongly suggests that CCS could play a major role in the efforts to de-carbonise many nations and regions, especially North America, China and India.

Figure 3: Expected global power sources in 2035. Fossil fuels continue to dominate power generation in many developed and developing regions.



Source: Vivian Scott et al. in *Nature Climate Change* (2012), adapted from IEA WEO 2011

**Locations of rock formations suitable for storing CO<sub>2</sub>**

All fossil fuels are taken from the Earth’s crust from rocks known as sedimentary rocks – rocks formed from lots of little particles (grains) which accumulated under water. Some sedimentary rocks are fossil fuels – coal is a sedimentary rock that is mined for use. Other sedimentary rocks contain the fossil fuels oil and gas and other substances including water

and naturally occurring CO<sub>2</sub>, held in the many microscopic spaces between the individual grains of the rock. Drilling into these rocks, known as reservoir rocks, allows for the oil or gas to be extracted for use.

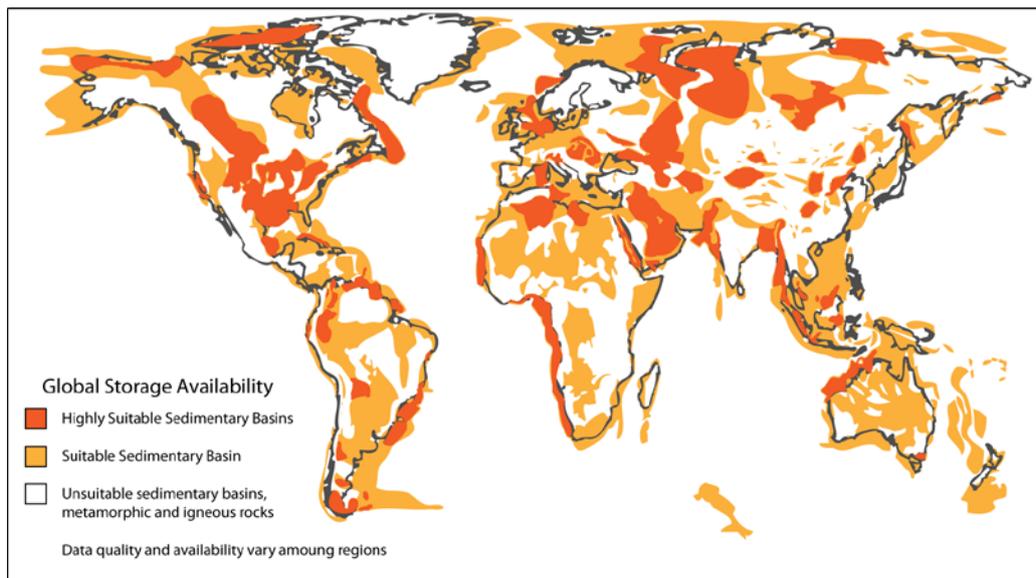
CCS proposes reversing this process by injecting captured CO<sub>2</sub> into appropriate sedimentary rock formations where it is expected that it can be securely contained for geological time periods (many thousands to millions of years). To be a good store for CO<sub>2</sub> the rock needs to have certain properties. These include having plenty of space between the grains (known as porosity), and good connection between these spaces (known as permeability) so that lots of CO<sub>2</sub> can be injected. Sandstones are a good example of this type of rock.

To stop some of the CO<sub>2</sub> moving through the rock back to the surface, the reservoir rocks need to be overlaid by another rock through which the CO<sub>2</sub> cannot move. This can be another less permeable sedimentary rock like a shale or clay, or a layer of salt and is often called a “cap rock”. Structures like this with a reservoir rock overlaid by a cap rock have securely trapped and held oil and gas for many tens of millions of years until the oil and gas has been extracted by drilling into the reservoir through the cap-rock.

Two more things are needed for a reservoir and cap-rock arrangement to be a good place for CO<sub>2</sub> storage. First, they need to be sufficiently deep (800m or below) so that the CO<sub>2</sub> is at such pressure that it behaves like a liquid – allowing a lot more CO<sub>2</sub> to be stored in the available volume between the rock grains. Second, possible CO<sub>2</sub> storage sites should be located away from geologically active areas – such as fault lines, where powerful earthquakes are common, as these could fracture the cap-rock.

Because of the way sedimentary rocks are formed, ‘sedimentary basins’ – large expanses of sedimentary rocks - are most commonly found in the middle or on the edges of continents. Figure 4 shows a map of sedimentary basins where sites suitable for CO<sub>2</sub> storage could be found. As expected, these are also the places where oil and gas has been found – e.g. the South-East US, the North Sea and the Middle East. Seen at this global scale, there is reasonable coverage of suitable possible CO<sub>2</sub> storage sites across the world, but the large-scale geology in some regions – notably India and also some large parts of China and East Africa is not so suitable.

*Figure 4: Map showing sedimentary rock basins (regions) where suitable sites for storing CO<sub>2</sub> could be found. Sedimentary basins are found both in the middle of continents (e.g. North America), and around the edges of continents (e.g. the North Sea).*



Source: Vivian Scott, adapted from IPCC (2005), *Carbon Dioxide Capture and Storage*, in B. Metz, O. Davidson, H. de Coninck, M. Loos and L. Meyer (Eds.), Cambridge University Press, Cambridge, UK and New York, USA.

### Global Capacity for CO<sub>2</sub> Storage in Rock Formations

Using data on the locations, types, thickness, and properties of sedimentary rocks it is possible to estimate the amount of CO<sub>2</sub> storage that might be available. There are three main types of possible CO<sub>2</sub> storage sites (geological structures featuring a reservoir rock and cap-rock) that have been considered. First, **depleted oil and gas reservoirs** where as much oil or gas as possible has been extracted which could be refilled with injected CO<sub>2</sub>. Second, **saline aquifers** which are reservoir rocks containing salty water (so not suitable for drinking or agricultural use) in the spaces between the rock grains. Third, **deep un-mineable coal seams** – coal that is too difficult to be extracted as it is too deep in the crust to be mined. We only have limited data on these different structures, so we have to assume some of their properties such as the amount of space between the rock grains. To reflect this, we can make low (assuming less favourable rock properties) and high (assuming more favourable rock properties) estimates of the amount of storage that could be available. In the case of depleted oil and gas wells, because they have been assessed and drilled for oil and gas extraction we have good data on their number, size and properties so the low and high estimates are not that different. In contrast, we have much less information on the properties of saline aquifers and un-mineable coal seams so the difference between the low and high storage capacity estimates is very large.

Table 1 presents low and high estimates (in billions of tonnes) of global CO<sub>2</sub> storage capacity in the three types of CO<sub>2</sub> storage site showing the wide range in estimated storage capacity. Current CO<sub>2</sub> emissions resulting from human activity are around 33.5 billion tonnes per year (2011) of which around 20 billion tonnes come from large point-sources such as power plants and industrial facilities. **Even the low estimates for global CO<sub>2</sub> storage capacity indicate that there is potentially sufficient storage capacity for between 50-100 years of this level of CO<sub>2</sub> emissions showing that CCS could play a very large role in addressing climate change.**

*Table 1: Low and high estimates of the global CO<sub>2</sub> storage capacity in the three different types of geological CO<sub>2</sub> storage sites.*

CO <sub>2</sub> storage site type	Global storage capacity (in billions of tonnes of CO <sub>2</sub> )	
	LOW ESTIMATE	HIGH ESTIMATE
Depleted oil & gas reservoirs	675	900
Deep saline aquifers	1,000	Not well established, possibly greater than 10,000
Deep un-mineable coal seams	3	200
Total	1,678	Possibly greater than 11,000

*Note: Data on depleted oil and gas reservoirs is much better than on saline aquifers and un-mineable coal seams so the difference between the low and high estimates is less. 1 Billion = 10<sup>9</sup> = 1,000,000,000 tonnes.*

In some countries and regions such as the USA and Europe, more detailed examinations of potential CO<sub>2</sub> storage capacity have been made. In general, these have improved upon the low estimates with, for instance, a recent in-depth study (published 2012) carried out by scientists at the Massachusetts Institute of Technology finding that saline aquifers in the USA have the capacity to store at least 100 years of the current yearly amount of CO<sub>2</sub> emissions from all the fossil fuel burning power plants in the USA.

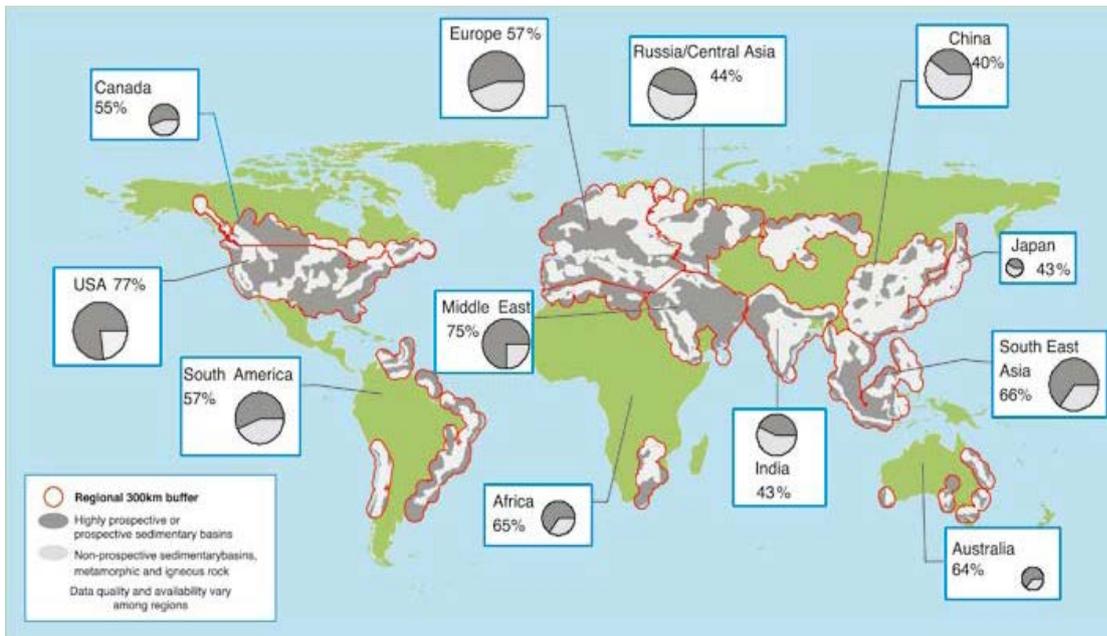
### **Matching CO<sub>2</sub> Sources and Storage**

Having established that there is sufficient possible CO<sub>2</sub> storage available globally for expected future levels of CO<sub>2</sub> emissions from large point sources we now have to ask how well the locations of the sources match with locations of the possible stores. At a simple level, given that fossil fuels are taken from where they are found in sedimentary basin regions and transported all around the world for use, it should be possible to transport the CO<sub>2</sub> back to the sedimentary regions for storage. As an example, the International Energy Agency has developed global CO<sub>2</sub> emissions reductions scenarios which suggest that 20% of the total CO<sub>2</sub> emissions reductions in 2050 should result from CCS. This would mean capturing, transporting and storing around 8 billion tonnes of CO<sub>2</sub> per year. In comparison, around 4 billion tonnes of oil, 8 billion tonnes of coal and 2 billion tonnes of natural gas per year are currently extracted and transported worldwide. Certainly, this amount of CO<sub>2</sub> transport would be a huge undertaking but is not impossible to achieve.

However, the closer the CO<sub>2</sub> sources are located to the possible CO<sub>2</sub> storage sites the easier and less costly it will be to apply CCS. By comparing the locations of current and expected CO<sub>2</sub> emissions point sources with the locations of possible CO<sub>2</sub> storage it is possible to investigate how easily CCS could be applied in different countries and regions. Figure 5 shows a possible interpretation of this exercise by looking at the geology within 300km of major CO<sub>2</sub> emitting regions and assessing what proportion of that geology might be appropriate for finding sites to store CO<sub>2</sub>. In this analysis, the USA and Middle East have the best fit between locations of large CO<sub>2</sub> point sources and appropriate geology. A moderate to good fit (50%-75% of the geology might contain suitable CO<sub>2</sub> storage sites) is found for Canada, Europe, Africa, Australia and SE Asia. The regions or countries where the fit

between sources and sinks is less good (under 50% of the geology might contain suitable CO<sub>2</sub> storage sites) are China, Russia and Central Asia, Japan and India.

Figure 5: Major regions of CO<sub>2</sub> emissions with underlying geology (within 300km of emissions source) detailed. Pie charts identify the proportion of the underlying geology that is suitable (dark grey) for CO<sub>2</sub> storage, e.g. 55% of the geology within 300km of Canada's major sources of CO<sub>2</sub> emissions could contain sites suitable for CO<sub>2</sub> storage.



Source: IPCC (2005), *Carbon Dioxide Capture and Storage*, in B. Metz, O. Davidson, H. de Coninck, M. Loos and L. Meyer (Eds.), Cambridge University Press, Cambridge, UK and New York, USA.

In general, this result is encouraging as it indicates that a large proportion of the CO<sub>2</sub> emissions from major industrial regions could potentially be addressed by applying CCS. However, comparing Figure 3 (predicted electricity generation sources) with Figures 4 and 5 shows that there are some regions where continued and increased major fossil fuel use for power generation is expected that might have a quite limited possibility for CO<sub>2</sub> storage – most notably in China and India. With regards to China, a more recent and detailed study of CO<sub>2</sub> storage potential undertaken in 2009 by scientists in the USA and China concluded that the rock formations in China had the capacity to store as much as 2,300 billion tonnes of CO<sub>2</sub>, sufficient for at least 100 years of storage from current point-source emissions and that 90% of the current major point sources are located within 100 miles (160km) of possible storage sites.

Even where nearby storage is unavailable or insufficient, CCS could still play a significant role in decarbonisation either by transporting the captured CO<sub>2</sub> over long distances or by relocating the point sources. Natural gas pipelines many thousands of km in length are in use around the world bringing gas from the remote regions where it is extracted to where it is used, and oil and liquefied natural gas tankers provide transport across oceans. For example, it might be possible to ship CO<sub>2</sub> captured in India to the Middle East where there is likely to be abundant CO<sub>2</sub> storage available. Alternatively, for instance in Europe, it might prove less costly to site the CO<sub>2</sub> sources such as power plants closer to better storage options like the

North Sea and transport the electricity over a greater distance to where it is used; however, many other technical, social-economic and policy issues influence the location of power plants.

### **Summary**

Comparing the possible demand for CCS attached to facilities like fossil fuel burning power plants and factories with the availability and location of potential geological CO<sub>2</sub> storage sites shows that CCS could play a major role in efforts to de-carbonise human activity. In many areas of the world, rocks that could contain suitable sites with capacity for storing at least many decades worth of CO<sub>2</sub> emissions are located reasonably close to regions with high CO<sub>2</sub> emissions. This suggests that connecting these CO<sub>2</sub> sources to CO<sub>2</sub> stores could prove relatively straight forwards, making CCS a promising option for de-carbonisation.

However, in a few cases, countries with very large industrial CO<sub>2</sub> emissions have less favourable geology for finding large amounts of CO<sub>2</sub> storage. These include China – the world’s largest CO<sub>2</sub> emitting nation and biggest user of fossil fuels; India – the world’s fourth largest CO<sub>2</sub> emitting nation (both countries where CO<sub>2</sub> emissions are expected to increase to satisfy growing energy demand); and Japan – the world’s second largest developed economy and fifth largest emitter of CO<sub>2</sub>. This does not mean that CCS cannot play a significant role in decarbonising these countries, as much like transporting fossil fuels for use today, it would be possible to transport CO<sub>2</sub> over very long distances to more suitable areas for CO<sub>2</sub> storage by pipeline or ship.

Overall, these results are encouraging for CCS. While this conclusion is based on a relatively simplistic global perspective and data, in regions like the USA and Europe where much more detailed work has been done, the existence of appropriate amounts of suitable CO<sub>2</sub> storage has generally been confirmed. More work on other regions to establish more precise locations and suitability of storage sites will enable the potential of CCS to be further clarified.

### **Glossary:**

Depleted oil and gas reservoirs: When as much oil or gas as can be extracted from a reservoir it is referred to as being depleted. CO<sub>2</sub> can be injected to fill the pore space (tiny spaces between the individual rock grains) that was occupied by the oil or gas.

Saline aquifer: A formation of porous rock (lots of space between the individual tiny rock grains) filled with salty water into which CO<sub>2</sub> can be injected.

Un-mineable coal seams: Layers of coal underground that are too deep or narrow to be mined. CO<sub>2</sub> can potentially be injected into these for storage.

### **Further Reading:**

International Panel on Climate Change: Special Report on Carbon Dioxide Capture and Storage (Chapters 2 and 5) <http://www.ipcc-wg3.de/special-reports/special-report-on-carbon-dioxide-capture-and-storage>

IEA GHG CO<sub>2</sub> pipeline infrastructure: an analysis of global challenges and opportunities <http://www.ccsassociation.org/docs/2010/IEA%20Pipeline%20final%20report%20270410.pdf>

European Commission Directorate General Energy: Feasibility study for Europe-wide CO<sub>2</sub> infrastructures [http://ec.europa.eu/energy/coal/studies/doc/2010\\_10\\_co2\\_infrastructures.pdf](http://ec.europa.eu/energy/coal/studies/doc/2010_10_co2_infrastructures.pdf)

Joint Research Centre: The evolution of the extent and the investment requirements of a trans-European CO<sub>2</sub> transport network <http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/15100/1/ldna24565enn.pdf>

Authors: Vivian Scott and Simon Shackley

## Briefing Note 4:

### Capturing Carbon Dioxide

In order to store carbon dioxide (CO<sub>2</sub>) underground the gas must first be captured. This is done by separating the CO<sub>2</sub> from the other gases which it is mixed with in the exhaust gases from the combustion of fossil fuels, for example in power plants. This briefing note explains how CO<sub>2</sub> can be captured ready for storage.

#### What is CO<sub>2</sub>?

CO<sub>2</sub> is a naturally occurring substance made up of one carbon and two oxygen atoms, two of the most common chemical elements on earth. In everyday conditions CO<sub>2</sub> is a gas, but it can be compressed into a liquid, frozen into a solid (dry ice) or dissolved in water like in sparkling water and carbonated beverages such as beer and sparkling wines. In the atmosphere CO<sub>2</sub> currently comprises about 0.04% of the air we breathe. It occurs naturally in freshwater and seawater, in some underground rock formations and in the soil. CO<sub>2</sub> is not flammable or toxic, nor does it explode. However, exposure to high concentrations of CO<sub>2</sub> is hazardous – concentrations around 0.5% can cause drowsiness, and concentrations above around 3% can result in unconsciousness or fatality if the victim is not moved away from the high CO<sub>2</sub> area or treated. High CO<sub>2</sub> concentrations do in general not occur even near sources of very concentrated CO<sub>2</sub> as air movement quickly mixes the CO<sub>2</sub> with the other gases in air reducing the concentration to normal levels. Only if air movement is restricted and there is a depression into which CO<sub>2</sub> (which is a heavier gas than most others in air) can sink can dangerous concentrations of CO<sub>2</sub> accumulate.

#### When is carbon dioxide produced?

CO<sub>2</sub> is produced when fossil fuels (coal, natural gas, oil) are burnt in a power station to create electricity. It is also produced when petroleum or diesel is burnt in a vehicle engine or generator, and when firing up domestic gas boilers for hot water. Fossil fuels such as oil, gas and coal are “hydrocarbons” which when burnt react with oxygen in the air producing energy and CO<sub>2</sub>. CO<sub>2</sub> is also produced during some industrially used chemical reactions such as those used for making fertilisers. As the CO<sub>2</sub> usually only makes up a small proportion (up to around 15%) of the waste gases it is impractical to transport and store the huge volume of all of the waste gases, so the CO<sub>2</sub> needs to be separated out.

Carbon dioxide capture and storage (CCS) consists of three basic steps: (1) the selective capture of the CO<sub>2</sub> resulting from the burning of fossil fuels such as coal, oil and gas (and biomass); (2) the compression and transportation of the captured CO<sub>2</sub>; and, (3) the injection of the CO<sub>2</sub> into rock formations hundreds of meters below the Earth's surface where it can be securely stored for hundreds of thousands of years. CCS is a vital tool in reducing global carbon emissions as it is the only technology available which can 'decarbonise' burning fossil fuels to generate electricity and heat, as well as allowing major industrial sectors manufacturing steel, cement and many other products to be decarbonised.

#### Where can CO<sub>2</sub> be captured from?

In theory, CO<sub>2</sub> can be captured from any source or perhaps even directly from the atmosphere. However, in reality, it is currently only cost effective to capture CO<sub>2</sub> from

facilities known as “point sources” which produce large amounts (hundreds of thousands to many millions of tonnes per year) of CO<sub>2</sub> at relatively high concentrations of a few per cent or more. Examples of such sources are coal or natural gas burning power plants, or industrial facilities making cement, steel, processing natural gas, refining oil or producing chemicals like fertilisers. Power plant and industrial point sources contribute around 45% of the total human-produced CO<sub>2</sub> emissions so de-carbonising these offers a major opportunity to mitigate climate change.

### **How is CO<sub>2</sub> captured?**

There are a variety of methods that can be used for capturing CO<sub>2</sub> from point sources. Some of these have a long history of use, others are more recent innovations. There is a lot of research being undertaken into both improving existing processes and developing new methods. Currently there are three main methods of CO<sub>2</sub> capture – “post-combustion”, “pre-combustion” and “oxyfuel-combustion”. These are outlined below.

### **Post-combustion CO<sub>2</sub> capture**

The first industrial methods for selectively capturing CO<sub>2</sub> from among other gases were developed in the 1930s for use in the natural gas industry. Sometimes natural gas is found to contain a proportion of CO<sub>2</sub> which has to be scrubbed from the natural gas before the gas can be put into the gas grid for use. To perform this scrubbing, chemicals called amines which preferentially absorb CO<sub>2</sub> from other gases are used. These amines can then be heated which releases the CO<sub>2</sub> allowing the amines to be re-used to scrub more CO<sub>2</sub>. This is the process used at natural gas processing CCS projects like the Sleipner project in the Norwegian North Sea which has been injecting and storing around one million tonnes of CO<sub>2</sub>, scrubbed from the natural gas, each year since 1996.

These CO<sub>2</sub> scrubbing methods can be adapted to capture the CO<sub>2</sub> from the waste gases of other large point sources of CO<sub>2</sub> like power plants. As the CO<sub>2</sub> capture is performed after the combustion of the fuel, this is termed “post-combustion” CO<sub>2</sub> capture. Typically the waste gases are fed into the base of a column, sometimes called a “scrubber”, down which the amine (or similar) capture chemicals are rained. As the rising waste gases mix with the falling capture chemical the CO<sub>2</sub> is absorbed. The remaining gases are released from the top of the column, while the CO<sub>2</sub> containing capture chemical is collected at the bottom of the column. This CO<sub>2</sub> rich capture chemical is then piped to a separate (closed) chamber sometimes called the “stripper” where it is heated to release the CO<sub>2</sub>. The CO<sub>2</sub> is then processed for transport and storage, while the capture chemical is cooled and returned to the waste gas column to capture more CO<sub>2</sub>. This process can be operated as a continuous cycle, with the capture chemical gradually replenished as it becomes degraded (its ability to absorb the CO<sub>2</sub> reduced) by reactions with impurities in the waste gases.

Post-combustion capture can be fitted to many types of CO<sub>2</sub> source including coal and gas power plants and industrial facilities like cement and steel factories. At present, post-combustion capture facilities are large – an absorption column can be tens of metres high and use a lot of energy, especially in heating the capture chemical to release the CO<sub>2</sub>. However, a lot of research is underway to improve the process, both developing new capture chemicals, designing materials that maximise the contact between the capture chemical and the CO<sub>2</sub> containing waste gases, and reducing the energy input needed to

release the CO<sub>2</sub> from the capture chemical. Many other innovative methods for separating CO<sub>2</sub> from other gases are also being researched and developed.

### **Pre-combustion capture**

As the name suggests, “pre-combustion” capture separates the CO<sub>2</sub> from the fuel before it is burnt, making use of technologies developed in the chemicals industry for producing hydrogen from hydrocarbons such as natural gas. The pre-combustion capture process involves three stages. First, the hydrocarbon fuel is reacted (but not combusted) with steam and oxygen to produce a gas consisting primarily of hydrogen, and carbon monoxide (one carbon atom bonded to one oxygen atom). This mixture is called “synthesis gas” or “syngas”. Second, the syngas is reacted with more steam to convert the carbon monoxide to carbon dioxide and hydrogen. This process is called a “shift reaction” as it shifts the oxygen from the steam (H<sub>2</sub>O) to the carbon monoxide (CO) to create CO<sub>2</sub>. Third, the hydrogen is burnt with air in a turbine to generate energy, producing only water as a by-product, while the CO<sub>2</sub> is dried and compressed for transport and storage. The hydrogen can also be used as a chemical for making ammonia for producing fertiliser, in refining petroleum products or potentially used as a transport fuel in fuel cells.

### **Oxyfuel combustion**

In a conventional coal or gas power plant the fossil fuel is burnt in air which is largely made up of nitrogen (78%) and oxygen (21%). The fossil fuel combusts in the oxygen, but most of the nitrogen does not react in any way so the waste gases contain lots of nitrogen from which the CO<sub>2</sub> needs to be separated (post-combustion capture). An alternative approach is to remove the nitrogen first, so that the fuel is burnt in a high oxygen environment which produces a waste gas consisting mostly of water and CO<sub>2</sub>. CO<sub>2</sub> and water are easily separated by condensing the water allowing the CO<sub>2</sub> to be captured for transport and storage. To perform this process, an air separation unit which separates the oxygen from the other gases, especially nitrogen, in air is used to produce an oxygen-rich (usually 90% or more) gas which is fed into the boiler with the fuel. To control the combustion temperature some of the CO<sub>2</sub> rich waste gas is sometimes re-cycled into the boiler to slightly dilute the oxygen, as burning fuel in pure oxygen produces a very hot reaction – as used in oxyacetylene metal cutting and welding.

While the CO<sub>2</sub> requires very little processing, separating oxygen from the air is an energy intensive process: the most common method is a cryogenic process (cooling to very low temperatures). However, lots of research is underway to find improved methods for removing oxygen from air so it can be combusted with hydrocarbon fuels to produce only CO<sub>2</sub> and water. This includes a process known as chemical looping where metallic compounds are used as catalysts in a two-reaction system. The metallic compounds are first reacted with the oxygen in air (oxidised) producing heat. This heat can be used to generate electricity. Waste heat is then used to react the oxidised catalyst with the hydrocarbon fuel in a reaction known as a “reduction”. In this reduction the carbon and hydrogen react with the oxygen removing it from the catalyst to produce CO<sub>2</sub>, water and a now un-oxidised catalyst that can be reused.

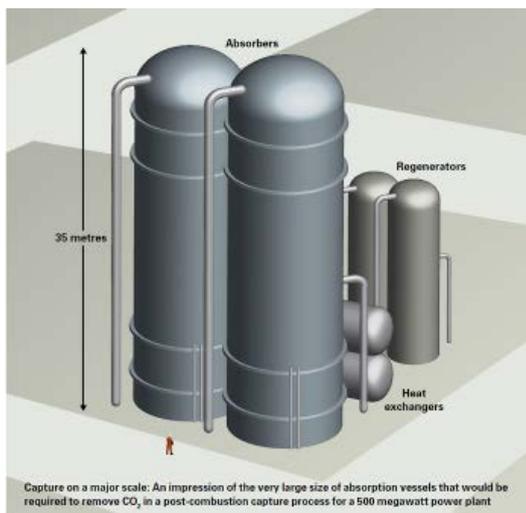
### How much CO<sub>2</sub> can be captured?

Current CO<sub>2</sub> capture processes are designed to capture around 85-95% of the CO<sub>2</sub> produced from the combustion of fossil fuels – and in doing so achieve a huge reduction in the emissions associated with fossil fuel usage in electricity production and industrial processes. Higher proportions of CO<sub>2</sub> capture are theoretically possible but become prohibitively expensive with current technologies. As well as the CO<sub>2</sub> emissions from the facility itself, it is also important to think about the CO<sub>2</sub> emissions associated with the production and transportation of the fuel.

### What size are CO<sub>2</sub> capture facilities?

CO<sub>2</sub> capture on commercial scale facilities like power plants will have to process very large (millions of tonnes) of gas per year, so will be industrial in scale. For applying current post-combustion CO<sub>2</sub> capture technologies to a power plant, a footprint of a similar scale to the turbine hall is probably needed (Figure Two) and the CO<sub>2</sub> scrubbing columns might be around 30-40m in height (Figure One). Future developments could reduce the scale of capture facilities but they will likely remain industrial in scale because of the amounts of gas they need to process.

*Figure One: Artist's impression of the absorber scrubber towers required for a current technology post-combustion capture plant at a 500MW power station*



Source: © BP (used with permission)

### How much energy is required to capture the CO<sub>2</sub>?

Capturing CO<sub>2</sub> by any method requires energy so reducing that available for generating electricity to be sold into the electricity grid. This energy requirement is often termed the “energy penalty” of the CCS process. The energy penalty in post-combustion capture arises because some of the hot steam is diverted from electricity generation to the stripper where it is used to heat up the capture chemical to release the CO<sub>2</sub>. In pre-combustion capture, energy is used to create the steam used in the reactions, while in oxyfuel combustion separating oxygen from the air requires lots of energy. For all three methods energy is also needed to process and compress the captured CO<sub>2</sub> so it can be transported. With current technology it is estimated that the overall efficiency of a power plant is reduced by between 5-15% when CO<sub>2</sub> capture technology is installed.

*Figure Two: Artist's impression of a post-combustion capture plant at a 1600MW coal fired power station with two 800MW turbines. The red oval indicates the capture plant.*



Source: © RW

A modern coal-fired power plant might achieve an efficiency of up to 45% (efficiency being defined as the proportion of the energy in the coal turned into useable electricity). Installing CO<sub>2</sub> capture would reduce this overall efficiency to around 35% which is about the same efficiency as many coal power plants built in the 1970s and 1980s which are still in operation today. Modern gas-burning power plants are more efficient approaching around 60% efficiency in converting the energy in the gas into electricity. Experience of operating commercial scale CCS on both coal and gas power stations will help government and industry to decide which is overall the more cost effective.

Because the same amount of saleable product such as electricity is desired, the energy penalty of adding CCS increases the amount of fuel that is used to produce the same product. This extra fuel produces more CO<sub>2</sub>, a large proportion of which is also captured. For this reason, “captured” emissions will be greater than the “avoided” emissions – the CO<sub>2</sub> emissions of the same facility without CCS.

### **What is the cost of CO<sub>2</sub> capture?**

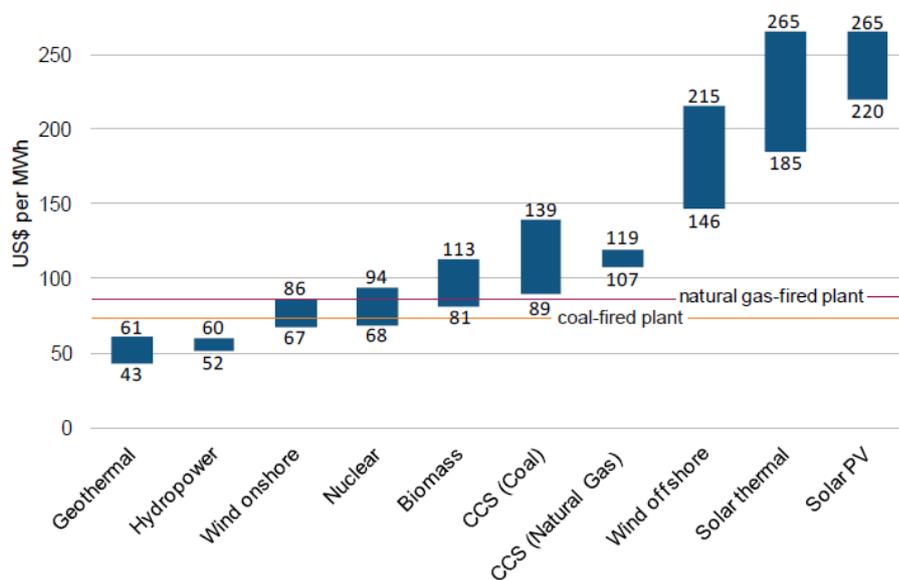
Reducing CO<sub>2</sub> emissions by CCS involves both a capital cost for the construction of the CCS facilities and an operating cost due to the energy penalty reducing the efficiency of the production process. For some CO<sub>2</sub> emission sources from industrial processes post-combustion CO<sub>2</sub> capture is the only applicable capture method. For electricity generation from coal estimated costs are similar for the three different capture methods, while for gas power plants post-combustion capture is currently the preferred option. Which of coal-with-CCS or gas-with-CCS will produce overall cheaper electricity will depend to a large extent on the relative costs of the coal and gas fuel.

Post-combustion capture can in some cases be added to an existing facility – known as “retrofitting” – thereby potentially reducing the construction cost. Existing power plants can also be converted to use an oxyfuel CO<sub>2</sub> capture method. However, building a purpose designed facility in which the capture is fully integrated into the original design might in some cases prove more cost-effective than retro-fitting. Pre-combustion capture facilities

are more like a chemicals plant than a conventional power plant so will in general be built as brand-new facilities.

At present, estimates of the cost of fitting and operating current CCS technology on coal and gas power plants predict electricity prices that are competitive with other forms of low-carbon electricity generation (Figure Three). Operating experience on the first commercial scale CCS facilities will increase certainty about overall costs, and future technology development may be able to reduce the cost. As CCS power generation still uses fossil fuels it is also important to consider how the prices of coal and gas may change in the future.

*Figure Three: Estimated cost range in \$ per MWh electricity of different low-carbon electricity generation methods including CCS compared with electricity generation from conventional coal and gas power plants*



Source: GCCSI (2011), The Costs of CCS and Other Low-Carbon Technologies

### Where is CO<sub>2</sub> capture happening?

CO<sub>2</sub> capture technology has been used for many decades on a commercial scale in natural gas processing. Separating CO<sub>2</sub> from the waste gases of power plants and industrial facilities is a more recent development. A number of small scale “pilot” facilities – up to around 10% of the scale of commercial facilities – have been successfully operated and continue to be used to improve and test all three CO<sub>2</sub> capture methods. The first commercial scale CO<sub>2</sub> capture projects on fossil power plants - combined with CO<sub>2</sub> transport and storage - are being constructed and will begin operations around 2015. The experience gained in building and operating these early facilities will give scientists and engineers important experience of CCS at scale allowing for further improvement of the process. This experience will also give governments and industry important information on the costs involved in reducing emissions using CCS, allowing them to take informed decisions as to the size of the role that CCS should play in de-carbonising electricity production compared to alternatives like renewables and nuclear power. For industrial processes such as making steel, CCS is the only currently available CO<sub>2</sub> emissions reduction technology so even if it is not widely used in

electricity generation it is expected to play a key role in controlling future emissions from industry.

### **Are there any environmental or health impacts arising from CCS?**

As with nearly all large scale industrial processes CCS must be managed to reduce potential environmental and health impacts. In addition to CO<sub>2</sub>, burning fossil fuels – especially coal – produces other pollutants. Some of these such as nitrous oxides and sulphur oxides from coal burning are currently scrubbed from the waste gases of power plants in countries with stringent pollution regulations. These chemicals also potentially interfere with CO<sub>2</sub> capture processes so in CCS fitted facilities they will need to be scrubbed out. As a result, power plants with CCS will have very clean emissions. However, the chemicals used for capturing CO<sub>2</sub> by post-combustion degrade over time and need to be disposed of and replaced. Some of these chemicals can form potentially harmful waste by-products such as nitrosamines and nitramines, so it is important that CO<sub>2</sub> capture is regulated to ensure that these pollutants are correctly managed and their disposal undertaken appropriately. CCS developers are working closely with government regulators to develop safe practices to control and manage any potential pollutants. Concentrated CO<sub>2</sub> also presents a potential health hazard. Where relevant, CO<sub>2</sub> specific health and safety measures can be added to working practice regulations at the facility.

CO<sub>2</sub> capture will often require increased water consumption, which could potentially put further strain on limited water resources in some regions. In order to deal with this issue some CCS proposals include water purification facilities to allow the water to be safely re-used. Another possible issue is the increased fossil fuel requirement due to the reduction in efficiency. This means that for the same facility more fossil fuels will need to be used, increasing the environmental impacts of the mines, infrastructure and transportation networks associated with fossil fuel extraction and delivery. However, applying CCS may reduce the overall use of fossil fuels for energy by making other low-carbon generation technologies more competitive.

### **Summary**

CO<sub>2</sub> capture at fossil fuel burning power stations and industrial processes has the potential to dramatically reduce the amount of CO<sub>2</sub> released into the atmosphere. There are three ways of capturing CO<sub>2</sub> and each method has advantages and disadvantages so may better suit different uses. The main limitations of CO<sub>2</sub> capture at present are the additional costs and energy requirements of the technology, but there is potential to reduce these through improved technology and innovation.

CO<sub>2</sub> capture will increase the cost of electricity generation from fossil fuels; however the additional cost is estimated to be competitive with the cost of electricity from other low-carbon generation technologies. For many industrial processes CCS is currently the only option available to reduce CO<sub>2</sub> emissions. Early commercial scale CCS facilities provide major learning opportunities for both industry and governments.

**Further Reading:**

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IEA (2011), Cost and Performance of Carbon Dioxide Capture and Power Generation, Paris

International Panel on Climate Change (2011), Special Report on Carbon Dioxide Capture and Storage (Chapter 3) <http://www.ipcc-wg3.de/special-reports/special-report-on-carbon-dioxide-capture-and-storage>

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## Briefing Note 5

### The Costs of Carbon Dioxide Capture and Storage (CCS)

#### Introduction

Among climate change mitigation options, carbon dioxide capture and storage (CCS) is the only technology that can lead to deep cuts in carbon dioxide (CO<sub>2</sub>) emissions from fossil fuelled power plants as well as industries such as steel and cement. However, one of the key challenges in the development of CCS technology is its cost.

#### Why do the costs of CCS matter?

CCS is a new technology, which means that, like most new technologies, the initial costs of developing it are high. As CCS is so important to reducing the CO<sub>2</sub> emissions from electricity generation, it is important that industry is able to develop and install the technology. However, as the costs are high, and in many cases unknown, investing in CCS is not necessarily an attractive option, as if costs over-run the company could end up taking a financial hit.

Depending on market conditions and the rules under which the power industry works, the costs of CCS could be passed on to consumers either through their energy bills or through government subsidies. Given the current economic conditions in many countries, rising energy costs may not be welcomed by householders. For policy makers high costs can mean facing opposition from both voters and industry.

#### Two different way of looking at costs

The most straightforward way to think about the costs of CCS is that, when a capture unit and pipelines are built, and when geological storage sites are developed, it all costs money. These extra costs increase the overall cost of generating electricity and subsequently the price at which electricity is sold.

CCS costs money both because of the need to install additional equipment and the costs of operating it. In the most common type of CO<sub>2</sub> capture process, a chemical (such as an amine) is used to capture the CO<sub>2</sub> from the power plant flue gas. The chemical is then heated to release the CO<sub>2</sub> into a near pure CO<sub>2</sub> stream for transport and storage. This heating requires large amounts of energy, which could otherwise have been converted to electricity and sold. It also costs energy and money to compress the CO<sub>2</sub> into a liquid form and transport and inject it into the porous rock formation where it will be stored.

Carbon dioxide capture and storage (CCS) consists of three basic steps: (1) the selective capture of the CO<sub>2</sub> resulting from the burning of fossil fuels such as coal, oil and gas (and biomass); (2) the compression and transportation of the captured CO<sub>2</sub>; and, (3) the injection of the CO<sub>2</sub> into rock formations hundreds of meters below the Earth's surface where it can be securely stored for hundreds of thousands of years. CCS is a vital tool in reducing global carbon emissions as it is the only technology available which can 'decarbonise' burning fossil fuels to generate electricity and heat, as well as allowing major industrial sectors manufacturing steel, cement and many other products to be decarbonised.

Starting from the assumption that it is necessary to substantially reduce our CO<sub>2</sub> emissions over the course of the next few decades, then it is more or less inevitable that this will have a price. Whichever mix of low-carbon technologies are to be used for the purpose (e.g. wind, wave, solar, bioenergy, nuclear or CCS) the costs of electricity will be higher than if we were to continue to emit CO<sub>2</sub>. It is not possible to know in advance which of these technologies will be cheapest to use, and so it is sensible to develop and invest in a number of them, and it is very likely that we will need several to meet demand. It is however also important to consider the substantial costs that will be incurred by society if we do not reduce CO<sub>2</sub> emissions and instead allow climate change to continue unhindered.

Having the option of CCS could shrink the overall cost to society of reducing CO<sub>2</sub> emissions from the power industry, but only if CCS costs are competitive against the alternatives and the technology attracts investment. Whether the costs of CCS are higher or lower than other methods of producing low-carbon electricity (e.g. nuclear power or renewables) is therefore likely to be very important. Cost estimates tend to suggest that whilst fossil fuel power with CCS will always be more expensive than fossil fuel power without CCS, it can be competitive with other low-carbon power technologies.

There are too many uncertainties at present to state exactly how much cheaper it would be to have CCS as a low-carbon energy option as opposed to not having it. However, most energy experts believe that including CCS in the 'energy mix' will reduce the overall costs to society of achieving deep carbon cuts.

Using a range of low-carbon technologies is also useful and important in other ways. For example, days without wind will result in 'intermittency' of supply from wind power. There is therefore a need for back-up from power plants that can be turned on or off quickly, such as hydro power or gas turbines, when demand cannot be met by renewables. Such back-up power can be provided by coal and gas power plants and, if fitted with CCS, these can have a vital role in enabling a low-carbon energy economy.

### **What is known about CCS costs?**

In a very real sense, CCS costs do not yet exist for power plants. No large scale CO<sub>2</sub> capture and storage system attached to a power plant has been built and operated, and no one has as yet incurred such costs, although a few plants are now under construction in North America. Until such plants are actually built, we will not know what the real costs are, and have to rely on estimates of what the costs are likely to be.

CCS is a combination of technologies that have already been used for other purposes, for example techniques for separating CO<sub>2</sub> from gas mixes in natural gas production. We can draw on this experience to estimate what some of the costs of CCS will be. For example, at the In Salah installation in Algeria, which removes CO<sub>2</sub> from natural gas and stores it in a deep bed of sandstone, it is anticipated that over a 25 – 30 year period, 17 million tonnes of CO<sub>2</sub> will be stored. The additional cost of installing and operating the CO<sub>2</sub> compression and injection is \$100 million, a storage cost of CO<sub>2</sub> of about \$6 per tonne.

The problem with this approach is that it does not include the capture costs (since in this case, as also at the off-shore gas fields of Sleipner and Snøhvit in Norway) the CO<sub>2</sub> has to be

removed anyway, whether it is then stored in geological formations or not. Furthermore, with current technologies, the capture costs from coal-fired power plants are much higher than those from gas processing. Capture technologies need to be modified and integrated in new ways to work for CCS from power plants, and this implies a fair degree of uncertainty as to what the costs will actually be.

Another source of knowledge about CCS costs is data from CCS pilot projects and equipment suppliers. For example, projects like ROAD receive European Union money to share results of the developing technology (<http://www.ccsnetwork.eu/>). The Longannet project in Scotland placed the results of its FEED (Front End Engineering Design) study in the public domain to assist with knowledge sharing. However, commercial confidentiality and competition limits the amount of such data being made publicly available as well as raising questions about its reliability. Analysing cost data is also made more difficult by there being different CCS related costs that matter. There is the extra cost per unit of power when using CCS to reduce emissions as compared to when not using CCS. This is different from the cost per tonne of CO<sub>2</sub> captured and stored. This is in turn different from the cost per tonne of CO<sub>2</sub> avoided (since this also includes the cost of reducing the emissions from the extra power needed to operate the CCS system).

Ideally, CCS cost estimates should be presented with an estimated range of uncertainty, or better still as part of a set of scenarios exploring different possible technologies and associated costs.

### What do experts say?

The recent International Energy Agency report *World Energy Outlook 2011* estimates the cost to the generator of producing electricity to rise between 39-64% with the use of CCS technology. The impact of this on the price paid by consumers depends on several things, including company overheads and profits, as well as government policy, subsidies and taxes.

The engineering consultancy Mott MacDonald analysed the comparative costs of low carbon generation technologies for the UK Committee on Climate Change in 2011, the results of which are shown in Table 1. CCS on gas or coal power plants is clearly thought to be among the more competitive options based on the criterion of cost alone.

*Table 1 Costs of low carbon generation technologies*

<b>Technology</b>	<b>Costs (U.S. cents/kWh) in 2011</b>
Gas without CCS	6.4 - 11.6
Nuclear	8.5 - 20.3
Gas CCS	9.8 - 26.4
Onshore wind	10.2 - 14.4
Coal CCS	13.8 - 33.0
Offshore wind	17.1 - 30.5
Tidal stream	25.7 - 61.2
Wave, fixed devices	34.9 - 78.3
Solar PV	35.3 - 66.0

Notes: Costs reported are levelised costs, that is they take all the costs over the lifetime of the investment into account. The cost estimates depend on a range of assumptions. The variation shown is partly due to varying assumptions about discount rates. The cost estimates are produced for the UK and will vary by country. The exchange rate used was £1=US\$1.55. 'Low carbon' here means anything less carbon intensive than coal plants without CCS.

It is generally thought that the largest share of CCS costs relate to CO<sub>2</sub> capture, rather than to transport, storage or monitoring. This is due both to the cost of building large capture plants and to the large amount of energy needed to separate CO<sub>2</sub> from the other gases in the power plant flue gas stream.

CO<sub>2</sub> capture can be included in new power plant designs or on existing power plants, called retrofitting. Retrofitting capture technology is more expensive than investing in capture on new plants. However, retrofitting is less expensive than building completely new plants and is an important way of abating power plants that still have a considerable life time left.

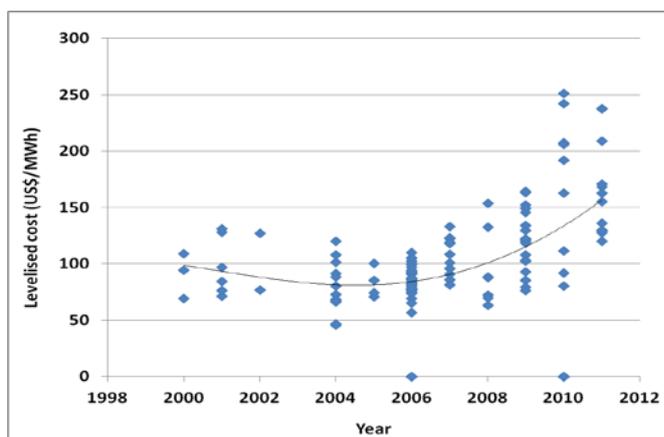
### Will CCS costs change over time?

If it is challenging to estimate what CCS costs might be today, it is all the more difficult to estimate how these costs may develop over time. The further into the future we seek to estimate them, the larger the uncertainties, and therefore the more likely it is that are our estimates today are wrong. The estimates can be either too low or too high. The factors that influence such estimates include assumptions made about future energy and carbon prices, exchange rates and technology development.

Most estimates of CCS costs are primarily based on data available now (from pilot plants, suppliers etc., as discussed above), and refer to current CCS costs (what they might be now had a plant been built). It is expected that the costs associated with CCS will reduce as the number of plants being designed and operated increase.

CCS cost estimates have already varied over time as shown in Figure 1. This increase in cost estimates over the past decade is likely due – in large part – to underlying trends in the costs of fuels, materials costs and supply chain bottlenecks. However, the cost-estimate increases are also likely to be a consequence of the early experience in developing integrated CCS demonstrations. Other power technologies have exhibited similar cost trends, see Figure 2.

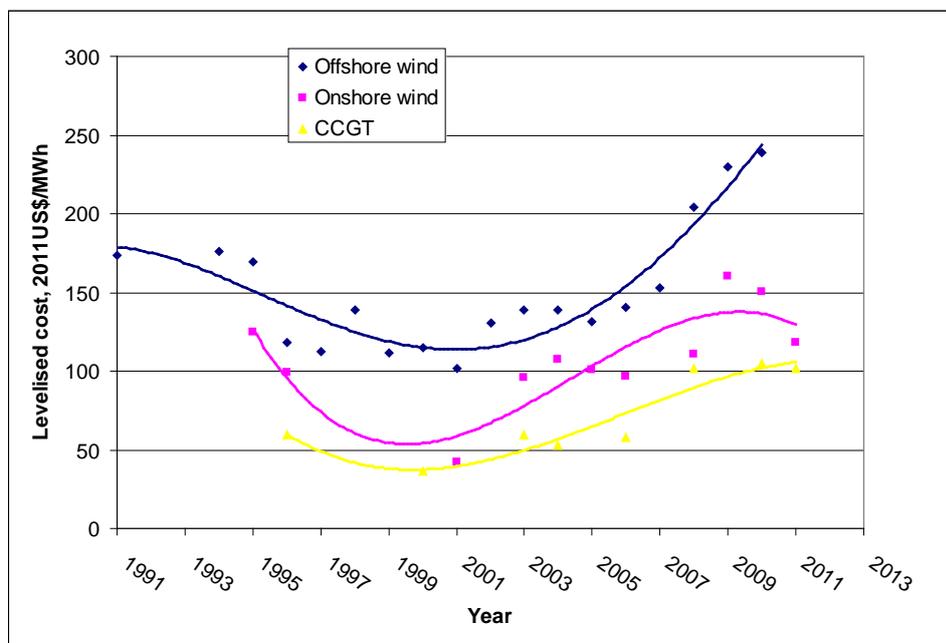
Figure 1: Cost estimates for CCS plants



Note: £1=US\$1.55 assumed. Each point in the diagram represents one cost estimate made that year, and the line shows how the average cost estimate has changed over time.

Source: Adapted from Jones (2012) *Carbon Capture and Storage (CCS) Cost Estimates*. Working Paper for Project: 'Electricity Costs Methodologies', UK Energy Research Centre, London.

Figure 2: Estimated costs of other power supply technologies

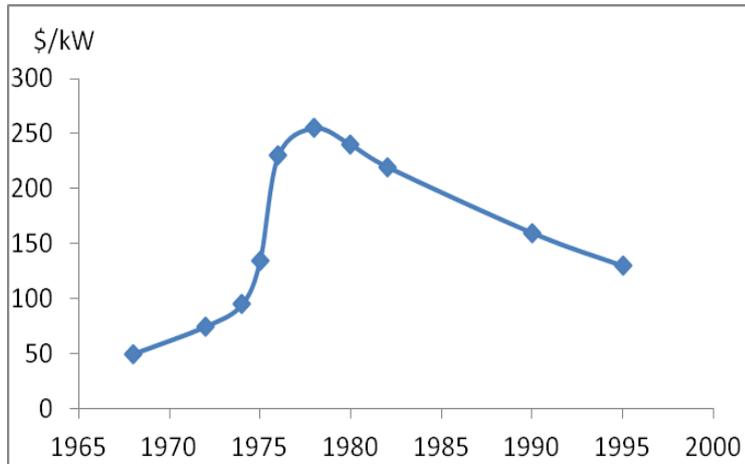


Source: Imperial College, London

Notes: Assumes £1=1.55US\$. In-year average. Data for Europe. CCGT = Combined Cycle Gas Turbines – a kind of technology for gas fired power plants.

A general observation can be made that many technologies do exhibit costs reductions over time. The size of such cost reductions can be estimated, and have been shown to be sizeable. However, it is also a general pattern that costs tend to go up in the early stages of technology development, due to unforeseen technical problems requiring costly changes to designs and operating procedures. Figure 3 shows both these mechanisms at play for a comparable technology, flue gas desulphurisation, used to remove sulphur emissions from power plant flue gases.

Figure 3: Capital costs of flue gas desulphurisation plants in the United States



Note: Figures are in 1997 US dollars

Source of data: Rubin, E. et al. (2004) *The Effect of Government Actions on Environmental Technology Innovation: Applications to the Integrated Assessment of Carbon Sequestration Technologies*. Department of Engineering and Public Policy. Paper 96. Pittsburgh, USA, Carnegie Mellon University.

### Are there any revenues to offset the costs of CCS?

Today there is no market for CO<sub>2</sub> large and lucrative enough to utilise the volumes that capture from power plants would generate. It is possible to use the gas in profitable ways though. Not least, there are ways in which the CO<sub>2</sub> gas can be used to extract more oil and natural gas from the ground. CO<sub>2</sub> is routinely used in the United States to extract additional oil from wells (40 to 50 million tonnes of naturally-occurring CO<sub>2</sub> are used in this way in the U.S. each year). Such operations can be profitable enough to offset some, if not all, of the costs of CCS.

This means that CCS is dependent on government policy support, in the form of, for example, a carbon tax or emissions trading. So far, these policy incentives have not been strong enough to drive CCS investment, and there is therefore a need for additional policy support for CCS to happen. In the EU, the EU Emissions Trading Scheme allows for trading of CO<sub>2</sub> emission allowances between companies within the 27 Member States. In 2008, it was agreed that CCS could be part of this scheme, meaning that an energy company can store CO<sub>2</sub> through CCS and count this as a CO<sub>2</sub> emission allowance. The volatile and low carbon price (as of 2012) limits the effectiveness of this scheme for the time being as a major driver of CCS.

All efforts to reduce CO<sub>2</sub> requires investment but having to adapt to the effects of not doing anything to deal with CO<sub>2</sub> emissions is likely to cost much more both in terms of money and impacts on society and the environment.

### Glossary

CCGT	Combined Cycle Gas Turbines – a kind of technology used for gas fired power plants, with high (60%) efficiency
kWh	kilo Watt hour – a unit of measurement for energy
Levelised cost	A measure of the cost of an energy technology that takes into account all the costs over the lifetime of an investment in it
Intermittent	A term describing energy technologies whose capacity to produce power varies over time. For example wind power, which can only deliver electricity when it is windy.
Retrofitting	Adding or changing a part of a power station after it has been operational for some time.

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## Briefing Note 6

### Transporting carbon dioxide

This Briefing Note examines the options for transporting carbon dioxide (CO<sub>2</sub>) as part of carbon dioxide capture and storage (CCS) from where it is captured to where it is injected for geological storage. Existing experience with the transport of CO<sub>2</sub> is detailed and possible arrangements for transporting CO<sub>2</sub> from multiple capture facilities to multiple stores considered.

#### Why transport CO<sub>2</sub>?

In some instances, the locations of the sources of CO<sub>2</sub> from which it is captured and suitable locations to inject the CO<sub>2</sub> into rocks deep underground are the same, but most often this is not the case. It might be possible to relocate some of the CO<sub>2</sub> sources but in many cases this might not be viable – the CO<sub>2</sub> sources may already exist, or be located for best access to raw materials or demand for their product. As a result, captured CO<sub>2</sub> often needs to be transported to the CO<sub>2</sub> injection site.

Applying CCS at scale involves capturing and injecting many millions of tonnes of CO<sub>2</sub> per year. As with oil and gas which are currently transported in similar quantities, this amount of CO<sub>2</sub> makes pipelines and ships the most practical options.

#### Existing CO<sub>2</sub> transport

CO<sub>2</sub>, mostly taken from naturally occurring sources in underground rock formations, has been transported by pipeline since the 1970s for use in a process called enhanced oil recovery (EOR). EOR injects CO<sub>2</sub> into oilfields nearing the end of their production to help extract some extra oil. Since first performed in 1972, CO<sub>2</sub> use for EOR has expanded and around 50 million tonnes of CO<sub>2</sub> is now transported every year along pipelines approaching 6000km in total length. Most of this EOR activity is taking place in the south west USA where long distance pipelines like Cortez (808 km long) and Sheep Mountain (660 km long) are being extended via new branches to connect more natural and human-made CO<sub>2</sub> sources such as natural gas processing facilities to the oil producing region.

While much less common, pipelines have also been developed for transporting CO<sub>2</sub> offshore. The best example is the Snøhvit project in Norway, where the CO<sub>2</sub> is transported from an island based natural gas processing facility 145 km to the injection facility on the seafloor of the Barents sea. All of this transport of CO<sub>2</sub> by pipeline both on and offshore has a proven safety record with no major accidents or leakages over many decades of operation.

Carbon dioxide capture and storage (CCS) consists of three basic steps: (1) the selective capture of the CO<sub>2</sub> resulting from the burning of fossil fuels such as coal, oil and gas (and biomass); (2) the compression and transportation of the captured CO<sub>2</sub>; and, (3) the injection of the CO<sub>2</sub> into rock formations hundreds of meters below the Earth's surface where it can be securely stored for hundreds of thousands of years. CCS is a vital tool in reducing global carbon emissions as it is the only technology available which can 'decarbonise' burning fossil fuels to generate electricity and heat, as well as allowing major industrial sectors manufacturing steel, cement and many other products to be decarbonised.

A small amount of shipping of CO<sub>2</sub> also occurs, for instance around Europe, supplying high purity CO<sub>2</sub> for use in the food (packaging and fizzy drinks) and chemicals industries. Undertaking shipping of the much larger amounts of CO<sub>2</sub> resulting from CCS projects is able to build on the experience of the Liquefied Natural Gas (LNG) shipping industry which now transports millions of tonnes of natural gas worldwide every year. LNG shipping has a long-proven safety record with no major incidents or leakages in over 50 years of operation.

*Figure 1: A Liquefied Natural Gas (LNG) transport ship – a technology that could be adapted to transport CO<sub>2</sub> especially over distances greater than around 500km. LNG ships currently carry gas across oceans from gas producing regions to distant markets.*



Source: By Pline (Self-photographed) [GFDL (<http://www.gnu.org/copyleft/fdl.html>), CC-BY-SA-3.0 (<http://creativecommons.org/licenses/by-sa/3.0/>), via Wikimedia Commons

### **Technical considerations of CO<sub>2</sub> transport by pipeline**

CO<sub>2</sub> pipelines can be of varying sizes. Typical pipeline diameters range up to around 100 centimetres, but larger ones are possible though it may prove more efficient to add parallel pipelines to increase capacity rather than build a larger diameter pipeline.

To efficiently transport CO<sub>2</sub> in a pipeline it must be kept in a dense rather than gaseous state. This means that it is less compressible so that putting CO<sub>2</sub> into one end of the pipe will force it along the pipe and out the other end. To achieve this dense state the CO<sub>2</sub> must be pressurised and this pressure maintained along the pipeline. Typical CO<sub>2</sub> pipeline pressures are between 10 and 80 Mega Pascals (MPa). By comparison, a car tire is inflated to a pressure of between 0.1 and 0.2 MPa. To achieve this pressure, compressor units are generally needed after the initial capture of the CO<sub>2</sub>. For CO<sub>2</sub> transport by pipeline to work effectively it is necessary to maintain sufficient pressure throughout the pipe network to ensure that the dense state of the CO<sub>2</sub> is maintained. In long pipelines (many hundreds of kilometres) interim re-pressurising of the CO<sub>2</sub> with compressors is used to maintain the pressure of the system.

Maintaining the pressure is necessary in both on and offshore pipelines – so engineers have to consider the different surrounding temperatures of the pipeline and how any temperature change such as moving from on the land to under the sea can be managed in terms of its influence on the pressure. Heating the CO<sub>2</sub> and insulating the pipeline are possible approaches to managing any temperature change in the surroundings. All pipelines

have both day-to-day operation and emergency pressure-relief systems which can be used to address any unexpected pressure build-up.

*Figure 2: A pipeline under construction.*



Source: By btr (Own work) [CC-BY-SA-2.5 (<http://creativecommons.org/licenses/by-sa/2.5>)], via Wikimedia Commons

A CO<sub>2</sub> pipeline network may also need to include temporary storage facilities in a similar way to temporary storage of natural gas in natural gas networks. The purpose of temporary storage would be to even out the flow of the CO<sub>2</sub> as the amount captured at the source facility might not be constant – power plants often change their output to meet changing demand for electricity.

From a design perspective, CO<sub>2</sub> pipelines and most pipelines used in the oil and gas industry must comply with stringent regulations. Carbon-manganese steels are generally used for pipelines carrying dry CO<sub>2</sub> where there is little possibility for corrosion. Corrosion of pipelines occurs at a higher rate when there is water present in the CO<sub>2</sub>, so a corrosion resistant alloy or ‘stainless steel’ can be used where required. Water content in the transport of CO<sub>2</sub> is an important issue, because when CO<sub>2</sub> is under high pressure with traces of water it can react with other trace chemicals to create corrosive chemicals. CO<sub>2</sub> pipelines and the systems that process the CO<sub>2</sub> before transport are specifically built and designed to consider such issues. Additionally, elements such as the local environment, potentially unstable slopes, possible earthquake activity, and risk of frost heave should be examined to make sure the pipeline is appropriately routed.

### **Transporting CO<sub>2</sub> by ship**

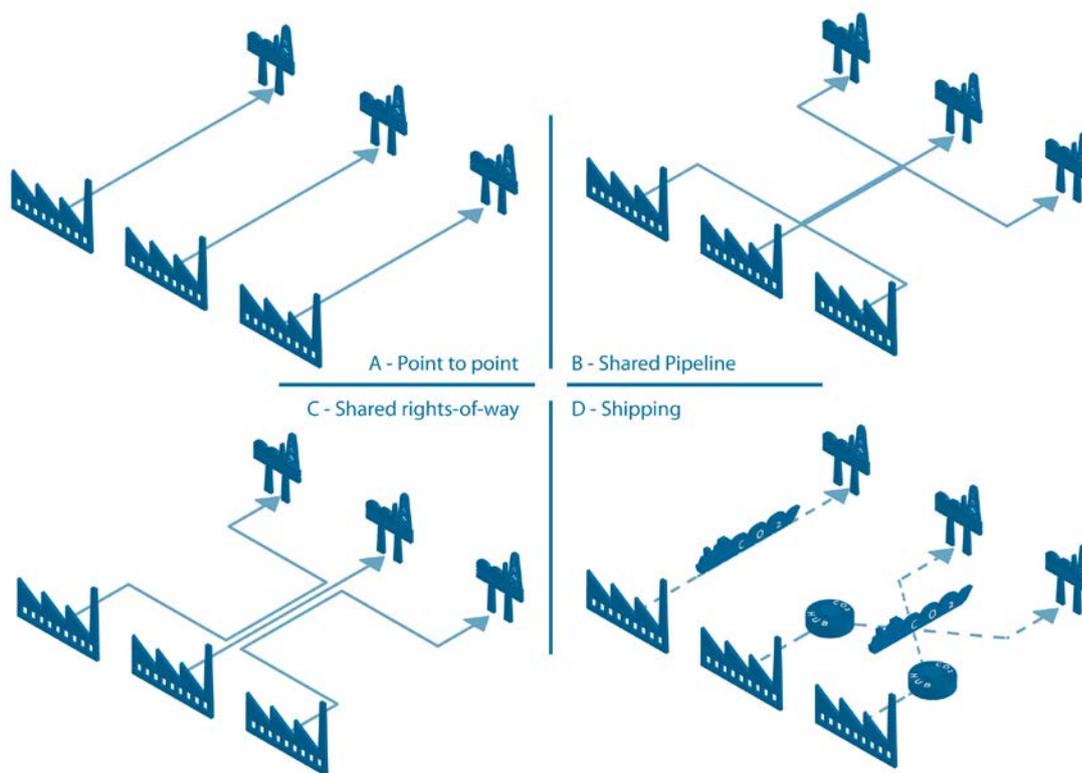
Shipping CO<sub>2</sub> offers an alternative to pipelines offshore, or onshore by using barges on major river systems like the Rhine. In general pipeline is cheaper over shorter distances, but as the transport distance increases beyond around 500km the re-compression costs for pipeline increase so shipping can be competitive. Shipping also offers potential benefits in terms of flexibility with regard to coping with varying transport volumes, and being able to take CO<sub>2</sub> to and from different locations as required. Shipping requires port facilities for storage and loading of the CO<sub>2</sub>, and offshore platforms to which the ships can dock from which the CO<sub>2</sub> can be injected into the storage rock formations deep underground. While this might sound complex, constructing these facilities might prove easier than finding and

developing routes for long pipelines possibly across borders and existing natural gas and oil pipeline networks. As a result, shipping could play an important role in establishing CCS.

### Transport network design

The design of CO<sub>2</sub> transport networks may vary. The simplest design is a point-to-point structure, connecting one CO<sub>2</sub> source – say a power plant – with a suitable storage site. The main alternative is to connect multiple sources and storage facilities to a more complex network either with shared pipes or shared corridors for laying the pipes. Shipping offers the most flexible system as ships can connect sources to storage (offshore) as required.

*Figure 3: Possible arrangements of CO<sub>2</sub> transport networks – the chosen structure will depend on many different factors and considerations.*



Source: Andrew Rutherford, SCCS

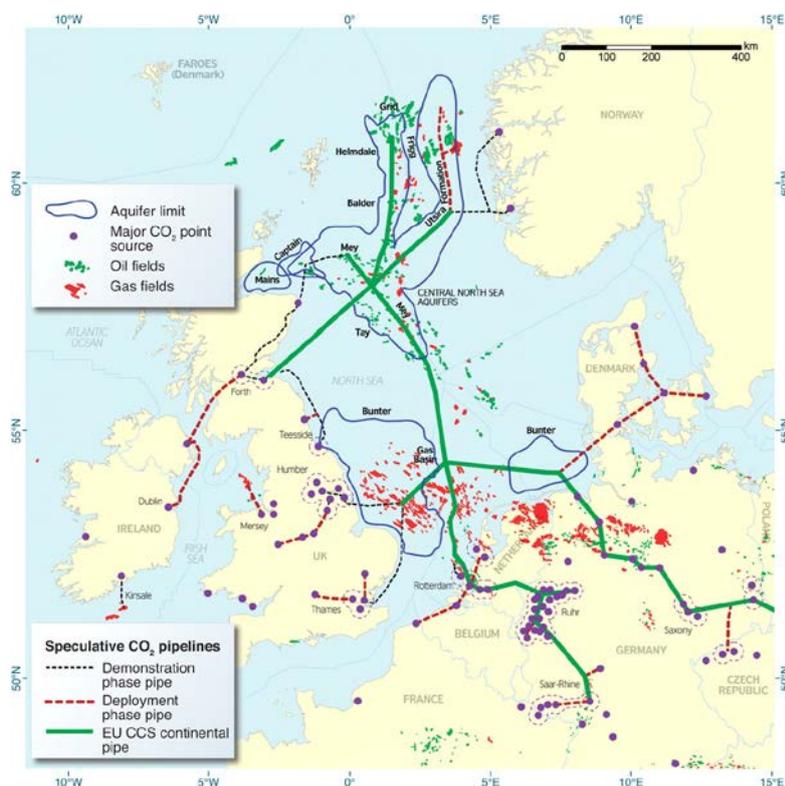
Many factors influence the transport structure chosen. Shared transport networks often offer benefits in terms of overall shorter pipelines, potentially reduced overall costs, and investment risk sharing. Sharing transport facilities however requires coordination between the different users, for instance agreeing to technical standards for the CO<sub>2</sub> pressure, temperature, impurities and flow rates. Shared transport also requires contracts between the users that share the risk and benefits. The sharing of transport facilities is commonplace in the oil and gas industry so there is lots of experience to draw on for developing shared CO<sub>2</sub> transport networks.

Given the uncertainties regarding the amount of CCS that might be used, it is difficult to plan future CO<sub>2</sub> transport networks in detail. Early projects will most likely adopt a point-to

point or very local network structure, but where sensible these should be designed to allow further integration into larger future networks. This might include leaving space for parallel pipelines to be installed, or oversizing key components so that they can cope with additional CO<sub>2</sub> in the future.

In the short term, the existing distribution of CO<sub>2</sub> sources is relatively fixed, and the challenge is to connect these CO<sub>2</sub> sources with suitable sinks. In the future, applying CCS widely might have some impact on the choice of location for power plants and other industrial CO<sub>2</sub> sources to reduce the transport needs.

*Figure 4: An illustration of the type of CO<sub>2</sub> pipeline network that could develop to take CO<sub>2</sub> from sources in NW Europe to storage sites in rocks deep beneath the North Sea.*



### Re-using existing pipelines and networks

There is some scope for re-using existing pipelines such as those originally built for natural gas to save on the costs of building new ones. It may also be possible to reuse some of the infrastructure at oil and gas fields, e.g. the offshore platforms when using depleted oil and gas reservoirs for CO<sub>2</sub> storage. To re-use existing pipelines and platforms they need to be available at a time that matches the need for CO<sub>2</sub> transport. They also need to have sufficient remaining operational life expectancy to last for the planned CO<sub>2</sub> injection period. As well as re-using pipeline there may be opportunities to build new CO<sub>2</sub> pipeline alongside existing pipeline networks. This could take advantage of the existing access arrangements maintenance facilities and local experience.

### Who will plan for, build and operate CO<sub>2</sub> infrastructure?

The lead in building CO<sub>2</sub> transport pipeline or shipping facilities may be taken by the organisation owning the CO<sub>2</sub> source (e.g. a power company), the one owning the storage site (e.g. an oil and gas company), a dedicated transport company, or a consortium with several stakeholders represented. With a widespread deployment of CCS involving CO<sub>2</sub> being captured from multiple sources and stored in multiple sites international markets for CO<sub>2</sub> transport like those for natural gas might develop over time.

[

### **Costs of CO<sub>2</sub> transport**

CO<sub>2</sub> transport is in general the least expensive component of CCS. Typical costs may be in the order of a few US\$ per tonne CO<sub>2</sub> transported – one model of funding pipeline is for a small charge to be levied for each tonne of CO<sub>2</sub> carried. However, constructing pipeline, ships and other associated transport facilities involves a large upfront investment. Depending on the diameter, materials, location and terrain, new CO<sub>2</sub> pipeline can cost anything from hundreds of thousands of dollars per kilometre to millions of dollars per kilometre. Re-using existing pipeline is cheaper but still generally requires some upgrading work to be undertaken. As a result CO<sub>2</sub> transport developers need confidence that the pipeline or shipping route will be used to transport enough CO<sub>2</sub> over the lifetime of the transport installation to recover the costs of its construction.

### **Possibility of CO<sub>2</sub> leakage during transport and its effects**

Whenever a substance is transported there is a potential risk of leakage, but this is usually very low provided a system of good management is in place. For example, natural gas leaks during pipeline or ship transport are very rare. In normal atmospheric concentrations, CO<sub>2</sub> is harmless, but at concentrations around a hundred times higher it can be dangerous to plants and animals, including humans. CO<sub>2</sub> is odourless and heavier than the other main gases in air, so if there is insufficient air movement to keep the air mixed, concentrated CO<sub>2</sub> from a leak could accumulate in dangerous concentrations in low-lying areas such as pits, depressions or valleys. Because of this where CO<sub>2</sub> is used and transported - such as in EOR operations - there are safety procedures to test CO<sub>2</sub> levels in areas of possible risk (e.g. a below ground tunnel) before personnel are allowed to enter them.

Pipelines on land are usually buried to a depth of one meter and marked above ground at regular intervals. Pipelines in operation are monitored internally by remotely controlled inspection vehicles called 'pigs' and externally by regular inspection for corrosion and damage. Where pipelines are routed near housing public education programmes are often undertaken which inform residents about how they might be alerted to a leak and what procedure to follow should a leak occur. As CO<sub>2</sub> is odourless, in some cases an odour-additive could be included to alert people to a leak. This is already done with domestic natural gas supply networks for the same reason as natural gas is also odourless.

Offshore, pipelines are generally laid in relatively shallow water, and are often trenched, and buried to protect them from fishing, shipping and dredging activity. Over many decades, the oil and gas industry has developed the techniques to construct, connect, maintain and inspect offshore pipelines using a variety of methods including unmanned submersibles, acoustic and chemical sensors and monitoring the pressure of the pipeline system.

### **Summary**

Applying CCS at a large scale will most likely require the transport of many millions of tonnes of CO<sub>2</sub> every year from the facilities where it is captured to appropriate places for injection into geological storage sites. Pipeline and ship are the most viable methods for transporting such large amounts of CO<sub>2</sub>. CO<sub>2</sub> pipelines networks are already in use for supplying CO<sub>2</sub> to EOR operations, and also at early CCS operations. Transporting CO<sub>2</sub> by ship can build on decades of experience from shipping natural gas in LNG tankers. Pipeline and ships offer different advantages in terms of the distances that they can cover and their flexibility to connect different sources and storage sites. Early CCS projects will probably be connected individually or in small clusters to their storage facilities, but larger CO<sub>2</sub> transport networks may develop if CCS usage expands. Transporting CO<sub>2</sub> comes with a risk of leakage, but this can be minimised by appropriately regulating the construction, operation and monitoring of CO<sub>2</sub> transport pipelines, ships and associated facilities.

### **Glossary**

EOR: Enhanced Oil Recovery involves injecting CO<sub>2</sub> into oil reservoirs when they are nearing the end of production to allow extra oil to be extracted.

MPa: Mega Pascal, a unit of measuring pressure. 1 Mpa is equal to 10 bar. Car tyres are usually at a pressure of around 1.5 bar (0.15 MPa).

LNG: LNG refers to Liquefied Natural Gas which is a method of transporting large amounts of natural gas compressed to a liquid usually by ship. Many millions of tonnes of natural gas are shipped each year on specially designed LNG tankers – for instance taking gas from the Arabian Gulf to markets in Europe and the Far East.

### **Further reading**

International Panel on Climate Change: Special Report on Carbon Dioxide Capture and Storage (Chapter 4) <http://www.ipcc-wg3.de/special-reports/special-report-on-carbon-dioxide-capture-and-storage>

IEA GHG CO<sub>2</sub> pipeline infrastructure: an analysis of global challenges and opportunities <http://www.ccsassociation.org/docs/2010/IEA%20Pipeline%20final%20report%20270410.pdf>

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## Briefing Note 7

### Naturally occurring carbon dioxide (CO<sub>2</sub>) in underground rocks

This Briefing Note examines the sources and behaviour of carbon dioxide (CO<sub>2</sub>) that occurs naturally in the subsurface (in underground rocks). Naturally occurring CO<sub>2</sub> in the subsurface can be used to teach us about storing CO<sub>2</sub> in underground rocks as part of carbon dioxide capture and storage (CCS). In some locations, naturally occurring underground CO<sub>2</sub> leaks to the surface. Mostly, such leaks are harmless, but in a few cases it can cause environmental damage and present a serious hazard to human health. Examples of these are detailed and their relevance to CCS explored.

#### Sources of CO<sub>2</sub> in underground rocks

CO<sub>2</sub> is a naturally occurring chemical found in the atmosphere, ocean, soil, underground water, crust (upper rocks), and mantle (deep rocks) of the earth. CO<sub>2</sub> is the major chemical in which carbon is transported around the carbon cycle. The carbon cycle describes the movement of carbon between different parts of the Earth system – the atmosphere, ocean, soils, biosphere (living organisms), and rocks. The CO<sub>2</sub> released to the atmosphere or the bottom of the ocean from deep in the Earth (e.g. by volcanoes) is a major source of natural carbon into the carbon cycle. This release is balanced by processes that remove CO<sub>2</sub> from the atmosphere and ocean such as the growth and burial of plants or chemical reactions between CO<sub>2</sub> and surface rocks.

CO<sub>2</sub> found in the subsurface and released to the atmosphere or ocean from deep in the Earth comes from two main sources – volcanic and magmatic (molten rock) activity, and from CO<sub>2</sub> contained in fluids and reservoirs in sedimentary basins - large areas of rocks such as sandstones produced from the laying down of sediments over long periods of time.

In volcanic areas, magma (molten rock) rises towards the Earth's surface. As this happens the pressure is lowered and substances dissolved in the magma including CO<sub>2</sub> are released. CO<sub>2</sub> can also be released by chemical reactions between the molten magma and crustal rocks. Volcanic regions are often very geologically active with processes like volcanic eruptions, earthquakes and tremors breaching and cracking the rocks of the Earth's crust enabling material (including CO<sub>2</sub>) from deep in the Earth to escape to the surface. CO<sub>2</sub> can be released during volcanic eruptions, or find a way to the surface through vents and fractures – both as a gas on its own or dissolved into water for instance at hot springs. In some cases, CO<sub>2</sub> can reach the surface very rapidly as part of an eruption or earthquake, but often it becomes trapped under overlying rock layers through which the CO<sub>2</sub> either cannot, or can only very slowly, pass through. This can result in the formation of reservoirs of CO<sub>2</sub> in the subsurface which can slowly leak CO<sub>2</sub> to the surface long after volcanic activity has ceased. While volcanic activity releases lots of CO<sub>2</sub> (estimated to be between 130 – 440 million tonnes per year globally), it is around a hundred times smaller than the CO<sub>2</sub> emissions from human activity – 35 billion (3500 million) tonnes of CO<sub>2</sub> per year in 2010.

Carbon dioxide capture and storage (CCS) consists of three basic steps: (1) the selective capture of the CO<sub>2</sub> resulting from the burning of fossil fuels such as coal, oil and gas (and biomass); (2) the

compression and transportation of the captured CO<sub>2</sub>; and, (3) the injection of the CO<sub>2</sub> into rock formations hundreds of meters below the Earth's surface where it can be securely stored for hundreds of thousands of years. CCS is a vital tool in reducing global carbon emissions as it is the only technology available which can 'decarbonise' burning fossil fuels to generate electricity and heat, as well as allowing major industrial sectors manufacturing steel, cement and many other products to be decarbonised.

CO<sub>2</sub> also naturally occurs in sedimentary basins – areas of sedimentary rocks (e.g. sandstones and mudstones) – where it can have been introduced dissolved in water, the result of the chemical breakdown of buried organic matter, or generated by magma reacting with crustal rocks deep beneath the sedimentary basin. Many substances including water, oil, natural gas and CO<sub>2</sub> are held in sedimentary basins filling the tiny spaces between the individual rock grains. Depending on the properties of the rock – the porosity (the amount of space between the grains), and the permeability (how well connected these spaces are) these substances can move through the rock. However, if the water, CO<sub>2</sub>, oil or gas meets a layer of impermeable rock (a rock through which they can't move) they can become trapped forming reservoirs. If the trapping rock (known as a cap rock) is fractured, then these fluids can slowly escape along the fracture cracks, otherwise they remain securely trapped unless artificially released by drilling a well. Sometimes CO<sub>2</sub> is found trapped in reservoirs along with other substances like natural gas, but it can also occur on its own. The McElmo Dome in Colorado is the best known example of a pure CO<sub>2</sub> reservoir. Trapped beneath 700m of salt, shale and sandstone layers it contained an estimated 1.6 billion tonnes of high purity CO<sub>2</sub> when discovered in 1948. Wells drilled into it allow the CO<sub>2</sub> to be extracted and it is now the largest commercial supply of CO<sub>2</sub> in the world. The CO<sub>2</sub> is piped to and injected into oilfields that are coming to the end of their productive life to increase the amount of oil that is extracted – a process called enhanced oil recovery (EOR).

### **CO<sub>2</sub> leaks – potential environmental and health concerns**

CO<sub>2</sub> is a very common chemical, produced by burning substances containing carbon such as fossil fuels and wood, and by respiration in animals, humans and plants (the process that extracts energy from the chemicals in food). However, as with many other substances, high concentrations of CO<sub>2</sub> are dangerous to living things. Air is typically around 0.04% CO<sub>2</sub>. In humans, concentrations of around 1-3% cause no lasting damage but lead to rapid breathing, headaches and tiredness. Higher concentrations (above 3%) are more dangerous as a condition called hypercapnia - where there is too much CO<sub>2</sub> in the blood - can quickly develop leading to unconsciousness and possibly death if the casualty is not moved to a place with a lower CO<sub>2</sub> concentration. Very high concentrations of CO<sub>2</sub> are also damaging to plants.

Usually, even if there is a source of CO<sub>2</sub>, dangerous concentrations of CO<sub>2</sub> do not occur outside enclosed spaces as air movement quickly mixes the CO<sub>2</sub> with the other gases in the air. However, CO<sub>2</sub> is denser (heavier) than the other main gases in air, so if there is no air movement and the landscape has depressions (e.g. pits or deep valleys), dangerous concentrations of CO<sub>2</sub> can accumulate and pose a serious hazard.

### **Natural CO<sub>2</sub> disasters and incidents**

There are a small number of examples of sudden releases of large amounts of CO<sub>2</sub> from

volcanic activity causing large loss of life. In 1979 the Dieng volcanic complex in Indonesia released a large amount of CO<sub>2</sub> (around 200,000 tonnes) when fractures opened in the build-up to an eruption allowing a trapped reservoir of CO<sub>2</sub> to rapidly escape. In still conditions, the CO<sub>2</sub> flowed down the side of the volcano and settled in a layer on the plains below asphyxiating 142 people.

The two other recorded disasters involving volcanic CO<sub>2</sub> occurred in Cameroon in West Africa. In these cases, two lakes sited in craters – Lake Monoun and Lake Nyos – have volcanic CO<sub>2</sub> leaking into the bottom of them. Due to their tropical location, the temperature of the environment is very stable (no discernible seasons), so the water in the lakes does not heat and cool through the year and so mix the water. As a result, separate layers of water form in the lake (stratification) with the bottom layer becoming saturated in the CO<sub>2</sub> leaking from the lake-bed.

Tragically, at Lake Monoun in 1984 an earthquake suddenly upset the water layers and the CO<sub>2</sub> was rapidly released. The cold dense CO<sub>2</sub> flowed down valleys below the crater asphyxiating 37 people and many animals. A similar event took place at the nearby Lake Nyos in 1986. An unknown event, perhaps a landslide, disturbed the layers within the lake's water leading to the sudden release of over a million tonnes of CO<sub>2</sub>. The CO<sub>2</sub> flowed out of the crater down two valleys to the north which contained several villages. 1700 people and around 3500 livestock were asphyxiated. Following experimental work, pipes have been installed in Lake Manoun and Lake Nyos to link the CO<sub>2</sub> saturated deep water layer with the surface enabling the CO<sub>2</sub> to escape and in doing so preventing the buildup of deadly amounts of CO<sub>2</sub> (see Figure 1). The process works, but scientists suggest that several more pipes should be installed to make the lakes even safer.

*Figure 1: Pipe in Lake Nyos (Cameroon) installed to reduce the build-up of volcanic CO<sub>2</sub> in the deep water layer of the lake by linking it to the surface allowing the CO<sub>2</sub> to escape. A pump is initially used to pull water up, then the loss of pressure as the CO<sub>2</sub> separates from the water as it climbs towards the surface makes the process self-sustaining.*



Source: [http://www.geo.arizona.edu/geo5xx/geos577/projects/kayzar/html/lake\\_nyos\\_disaster.html](http://www.geo.arizona.edu/geo5xx/geos577/projects/kayzar/html/lake_nyos_disaster.html)

While these tragedies show the very real dangers of large releases of CO<sub>2</sub> from underground they are particular to a certain set of very rare geological and environmental conditions. In addition to Lake Manoun and Lake Nyos, only one other similar CO<sub>2</sub> saturated lake is known – Lake Kivu in the Democratic Republic of Congo.

There have been a number of other (smaller-scale) accidents caused by natural CO<sub>2</sub> leaks, which have led to the asphyxiation of people, animals and damage to plant life. Places where there is a relatively slow release of CO<sub>2</sub> from underground sources are quite common – for instance there are around 300 known natural CO<sub>2</sub> seeps in Italy. In most cases, the CO<sub>2</sub> quickly mixes with air and presents no danger to life. In fact, some natural CO<sub>2</sub> seeps are used commercially (for instance making carbonated drinking water in south-east France), or form tourist attractions such as the famous ‘Old Faithful’ geyser in Yellowstone National Park, Wyoming, USA, where hot water rich in CO<sub>2</sub> erupts around every 90 minutes (Figure 2). However, if the leak is situated in a depression in the landscape where airflow is restricted then dangerous concentrations of CO<sub>2</sub> can accumulate. This can cause local damage to plants, and present a hazard to humans and animals if they do not move away quickly.

*Figure 2: Old Faithful geyser in Yellowstone National Park, Wyoming, USA. The hot water rich in CO<sub>2</sub> erupting high into the air around every ninety minutes is one of the Parks most famous sights.*



Source: [http://commons.wikimedia.org/wiki/File:Old\\_Faithful\\_\(3679482556\).jpg](http://commons.wikimedia.org/wiki/File:Old_Faithful_(3679482556).jpg)

As well as those on land, there are also many natural CO<sub>2</sub> leaks on the seabed. At some, the CO<sub>2</sub> is dissolved in the water, changing the chemical properties of the water near the leak. At others, the CO<sub>2</sub> emerges as a gas and bubbles to the surface where it quickly dissipates. While these offshore CO<sub>2</sub> leaks pose no risk to humans, the CO<sub>2</sub> often has a local effect on living organisms. Some marine plants and animals are better able to cope with higher CO<sub>2</sub> concentrations than others, and high CO<sub>2</sub> concentrations found near leaks generally reduce the amount and number of species of plants and animals in the near vicinity.

### **Using natural sources and leaks of CO<sub>2</sub> to understand CO<sub>2</sub> storage for CCS**

Studying and analysing the behavior of natural underground CO<sub>2</sub> is extremely valuable for scientists working on storing captured CO<sub>2</sub> for CCS. CO<sub>2</sub> reservoirs found in sedimentary basins such as the McElmo Dome reservoir described above provide a natural example of the type of CO<sub>2</sub> storage that is suggested for CCS. Many of these reservoirs have securely held millions of tonnes of CO<sub>2</sub>, with scientific investigations not finding any evidence of leakage for many millions of years. Studying their geology helps scientists understand how the CO<sub>2</sub> is trapped and what to look for in identifying good sites for artificial CO<sub>2</sub> storage.

Studying natural CO<sub>2</sub> leaks also helps scientists understand how CO<sub>2</sub> moves in underground rocks, what processes influence how much CO<sub>2</sub> escapes, develop methods for measuring and monitoring CO<sub>2</sub> leaks and explore how much danger leaking CO<sub>2</sub> poses to humans, animals and plants. Understanding that geological activity (e.g. volcanoes and earthquakes) can fracture the rock and release trapped CO<sub>2</sub> such as took place in Dieng in Indonesia means that potential CO<sub>2</sub> storage sites need to be located well away from such areas – for example, not near to known earthquake faults. Similarly, the disasters at Lake Monoun and Lake Nyos tell us that if CO<sub>2</sub> leakage were suspected into the bottom of a lake it should be very closely monitored to make sure that a dangerous build-up of CO<sub>2</sub> does not occur.

Offshore leaks are being studied to understand their impact on the marine environment, and develop methods and techniques to detect and measure CO<sub>2</sub> leakage.

Naturally occurring CO<sub>2</sub> leaks have also been used to assess the possible dangers of leakage from engineered CO<sub>2</sub> storage. Scientists have used records of human fatalities recorded at naturally occurring onshore CO<sub>2</sub> leaks in Italy to calculate the risk posed to local populations. Out of around 300 naturally occurring CO<sub>2</sub> leaks, most of which have no access restriction or warning signs, only a relatively small number (13) were responsible for loss of human life, with a total of 19 fatalities recorded over the last fifty years (see Figure 3). It is calculated that the risk of death by CO<sub>2</sub> poisoning from such leaks is around 1 in 100 million, many times smaller than the risk of fatality from lightning strike (around 1 in 100 thousand) or in a motoring accident (around 1 in 10 thousand).

Engineered CO<sub>2</sub> storage would likely pose an even lower risk, as sites should be carefully selected. Only places where the appropriate geology is found would be considered, and a lot of work undertaken to ensure the site is suitable long before any CO<sub>2</sub> is injected. Once the suitability of the site is confirmed, the injection operation can be adjusted for local conditions to ensure safe operation. The injected CO<sub>2</sub> would be required to be carefully monitored enabling any potential leakage to be quickly detected, injection ceased and the necessary safety measures taken.

*Figure 3: Mefitiniella Polla, one of around 300 natural CO<sub>2</sub> seeps in Italy. Scientists have been able to use these to assess the risk to human life of CO<sub>2</sub> leaking from underground.*



Source: © Jen Roberts, University of Edinburgh

### **Summary**

CO<sub>2</sub> naturally occurs in subsurface rocks, and in some places leaks out to the surface or the seabed. While the majority of these leaks pose very little risk to humans or other living things, in a few isolated incidents a combinations of factors – large amounts of CO<sub>2</sub> suddenly released, low-lying terrain, still weather conditions and no warning systems have caused serious incidents with large loss of life. Studying and understanding naturally occurring CO<sub>2</sub> both underground and where it leaks to the surface is an important tool for learning and planning how and where to safely store CO<sub>2</sub> in deep underground rocks as part of CCS.

The major disasters associated with CO<sub>2</sub> release are located in volcanic regions – areas that are not considered suitable for storing man-made CO<sub>2</sub>. In contrast, some natural reservoirs

of CO<sub>2</sub> in sedimentary basins (areas of sedimentary rock like sandstones) have been found to contain large quantities of CO<sub>2</sub> that has been securely trapped for many millions of years. These give an excellent model and confidence that safe storage of human-made CO<sub>2</sub> in sedimentary basin areas can be achieved. Studying these CO<sub>2</sub> reservoirs has helped develop understanding of the processes by which the CO<sub>2</sub> is trapped and methods for monitoring CO<sub>2</sub> deep underground.

Natural CO<sub>2</sub> leaks also tell us a lot about the effects of what could happen if leakage did occur from a CO<sub>2</sub> storage site. They help us to assess the level of risk, develop detection and measurement methods, and design regulation to make sure that any leakage could be quickly identified and properly dealt with. All of this information, along with that from testing of CO<sub>2</sub> storage at a number of sites around the world, means that scientists, engineers and regulators are becoming more confident that man-made CO<sub>2</sub> can be safely injected into and stored in rocks deep underground for many many thousands of years. AExperience in closely monitored early CO<sub>2</sub> storage projects will continue to develop knowledge and improve the reliability of risk assessment procedures.

**Glossary:**

EOR: Enhanced Oil Recovery involves injecting CO<sub>2</sub> into oil reservoirs when they are nearing the end of production to allow extra oil to be extracted.

Sedimentary basin: A region of sedimentary rock – rock made of lots of individual rock grains (like sand grains) that have accumulated and bonded together over very long periods. Sandstone and mudstone are examples of sedimentary rocks. Sedimentary basins often contain layers of different rocks laid down at different times.

**Further Reading:**

International Panel on Climate Change: Special Report on Carbon Dioxide Capture and Storage (Chapter 5) <http://www.ipcc-wg3.de/special-reports/special-report-on-carbon-dioxide-capture-and-storage>

2005/08: A Review of Natural CO<sub>2</sub> Occurrences and Releases and their Relevance to CO<sub>2</sub> Storage

2011/03: Summary Report of the IEAGHG Workshop - Natural Releases of CO<sub>2</sub>: Building Knowledge for CO<sub>2</sub> Storage Environmental Impact Assessments

Roberts, J.J., Wood, R.A., Haszeldine. R.S. Assessing the health risks of natural CO<sub>2</sub> seeps in Italy. Proceedings of the National Academy of Sciences, 2011, <http://www.pnas.org/content/108/40/16545.full>

Authors: Vivian Scott, Anne-Maree Dowd and Simon Shackley

## Briefing Note 8

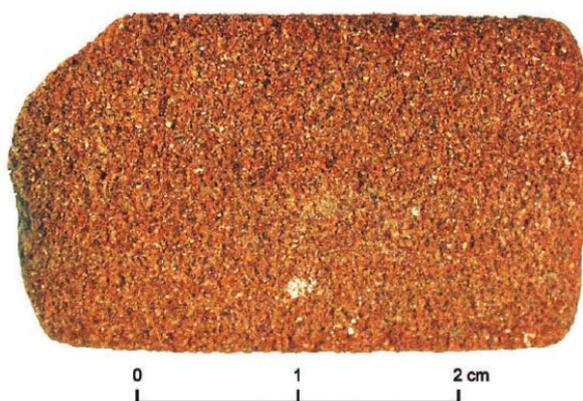
### Geological CO<sub>2</sub> storage mechanisms and site selection

This Briefing Note examines how and where carbon dioxide (CO<sub>2</sub>) captured as part of carbon dioxide capture and storage (CCS) projects can be stored in underground rocks. The geological conditions required for storing CO<sub>2</sub>, the mechanisms by which it is contained, and different types of possible storage site are introduced.

#### Where can CO<sub>2</sub> be stored?

Certain types of rocks are made up of many, many tiny individual rock grains stuck together. This can leave large numbers of tiny spaces (pores) between the individual rock grains. Figure 1 shows a coarse sandstone – a rock made up of lots of individual grains of sand which have accumulated under water, and been compressed and chemically stuck together over a very long time to form a type of rock known as a sedimentary rock. These tiny spaces are not empty. They contain fluids – which, depending on the location of the rock, can be one or a combination of many different substances including air, water, oil, natural gas and CO<sub>2</sub>.

*Figure 1: A coarse sandstone in which the individual rock grains, and the spaces (pores) between them can be seen with the naked eye. Around a quarter of the volume of this rock is empty space, which is able to contain fluids like water, oil gas or CO<sub>2</sub>.*



Carbon dioxide capture and storage (CCS) consists of three basic steps: (1) the selective capture of the CO<sub>2</sub> resulting from the burning of fossil fuels such as coal, oil and gas (and biomass); (2) the compression and transportation of the captured CO<sub>2</sub>; and, (3) the injection of the CO<sub>2</sub> into rock formations hundreds of meters below the Earth's surface where it can be securely stored for hundreds of thousands of years. CCS is a vital tool in reducing global carbon emissions as it is the only technology available which can 'decarbonise' burning fossil fuels to generate electricity and heat, as well as allowing major industrial sectors manufacturing steel, cement and many other products to be decarbonised.

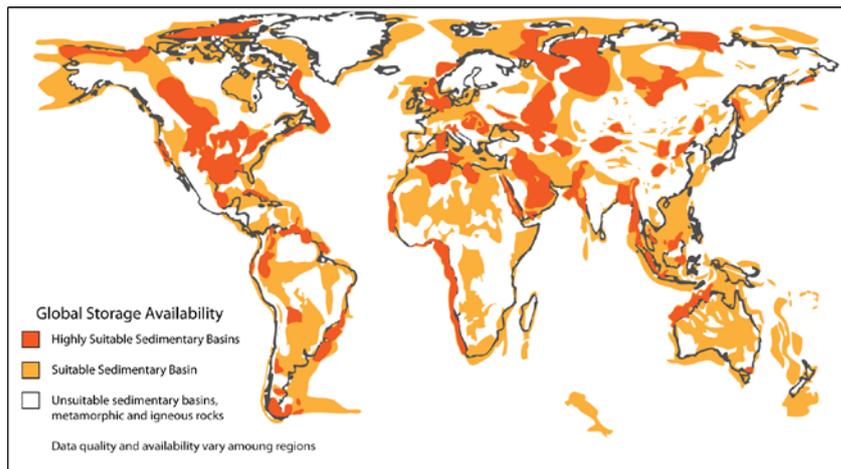
The proportion of pore space in a rock compared to the rock's total volume is known as its "porosity". Dense rocks (e.g. crystals) can have essentially zero porosity – no pores in the rock. Sedimentary rocks like that shown in Figure 1 can have a porosity up to around 0.5 meaning that half the total volume of the rock is made up of spaces between the rock grains.

While there can be lots of space within a rock, this doesn't necessarily mean that a fluid can easily move around inside it. This depends on another property known as the "permeability" which is a measure of how well connected to each other the different pores are. In general, more porous rocks (rocks with a larger volume of pores) will also have higher permeability (connection between the pores) but this is not always the case. The rock grains could be stuck together in such a way that the spaces between them are not that well connected.

Porous and permeable rocks containing fluids in the underground are hugely important to humanity. It is in these rocks that we find many substances crucial to our way of life including water for drinking and agriculture, and the fossil fuels oil and natural gas. Regions of rock that contain these important substances in the underground are often referred to as reservoirs. We extract the water, oil and gas from these rock reservoirs for our use. Reservoirs containing natural CO<sub>2</sub> (originating from deep in the Earth) are also found underground, and in some cases this CO<sub>2</sub> has been extracted for industrial use.

The basic concept of CCS is to reverse this extraction process. Instead of releasing large amounts of CO<sub>2</sub> to the atmosphere when we burn coal or gas to make electricity, it could be captured and injected into appropriate reservoir rocks where it is unable to affect the Earth's climate. As shown in Figure 2, there are huge regions of sedimentary rocks (known as sedimentary basins) around much of the world where the types of rock that CO<sub>2</sub> could be injected into are found.

*Figure 2: Map showing sedimentary rock basins (regions) where suitable sites for storing CO<sub>2</sub> could be found. Sedimentary basins are found both in the middle of continents (e.g. North America), and around the edges of continents (e.g. the North Sea).*



Source: Stuart Gilfillan, adapted from IPCC (2005), *Carbon Dioxide Capture and Storage*, in B. Metz, O. Davidson, H. de Coninck, M. Loos and L. Meyer (Eds.), Cambridge University Press, Cambridge, UK and New York, USA.

However, injecting captured CO<sub>2</sub> into reservoir rocks will only help to prevent the effect of CO<sub>2</sub> emissions on the Earth's climate if the CO<sub>2</sub> remains in the rock. The CO<sub>2</sub> has to be prevented from moving through the rock back to the surface and the atmosphere. Fortunately, rocks in sedimentary basins often occur in broadly horizontal layers laid down on top of each other at different times. These layers of rocks can have quite different properties as the material from which they are made and the conditions in which they form can be different. If a reservoir rock is overlain by a type of rock with a much lower porosity and permeability (a rock in which fluids cannot be contained or move through), then any fluids in the reservoir rock are trapped. This layer of rock is known as the cap rock and it is this mechanism that traps substances like oil and gas in the underground and prevents them rising to the surface. To get them out, the cap rock has to be breached by drilling a well.

The same cap rock mechanism can be used to prevent CO<sub>2</sub> injected into rocks for storage from escaping. Geologists working on CO<sub>2</sub> storage look for locations where a suitably porous and permeable reservoir rock is overlain by a layer, or layers of non-porous and non-permeable capping rock. Geologists already know where many such arrangements of rock layers can be found as they are the same places where they have previously found oil and gas. These areas of reservoir rocks overlain by capping rocks are possible CO<sub>2</sub> storage sites, but to work out how much CO<sub>2</sub> they could safely contain, their properties need to be understood in detail.

### **Properties of cap rocks**

Many types of rock can act as a cap rock; however shales - fine-grained rock composed of clay and other minerals such as quartz and calcite, and evaporites - layers of salt and similar minerals, are the most common. It is these cap rocks which trap oil and gas deep underground for many millions of years until they are released by drilling a well.

In order to determine whether a site is suitable for CO<sub>2</sub> storage it is necessary to understand the ability of the cap rock to prevent CO<sub>2</sub> escaping from the reservoir. This is called the cap rock's "seal potential". The seal potential is determined by

evaluating the properties of the cap rock to determine its “seal capacity”, “seal geometry” and “seal integrity”.

The seal capacity determines the maximum amount of CO<sub>2</sub> that can be stored underneath the cap rock before the increased pressure causes the CO<sub>2</sub> to migrate through the cap rock. Like oil and gas, CO<sub>2</sub> is lighter than water, so when CO<sub>2</sub> is injected into a reservoir it rises upwards and outwards (sideways) through the reservoir until it meets the cap rock. As the amount of CO<sub>2</sub> inside the reservoir increases so does the pressure exerted onto the cap rock. At a certain point the pressure could become strong enough to force the CO<sub>2</sub> into, and potentially through, the cap rock, so the amount of CO<sub>2</sub> injected has to be kept to a level that means this pressure is not reached.

The seal geometry refers to the orientation, sideways extent and vertical thickness of the cap rock. The cap rock needs to be appropriately orientated and extend widely enough to cover all of the area of the reservoir that the CO<sub>2</sub> is being injected into. Sometimes areas where the cap rock forms a dome (often called a trap) can be found. This creates an area of the reservoir which is higher than the rest of the reservoir so any buoyant fluid will be trapped within it. This is the typical structure of the areas of reservoir rocks where oil and gas are found. The thickness of the cap rock is also important. The thicker it is, the more pressure it is likely to be able to withstand so the greater the seal capacity.

The seal integrity describes the condition of the cap rock. If the cap rock is fractured (cracked), these cracks could provide potential pathways through which CO<sub>2</sub> could escape. Checking the integrity also involves checking if any oil or gas extraction wells have been drilled into the rock and the condition of these wells. Old wells are sealed with cement when they are closed, but need to be checked to make sure the cement can prevent the migration of CO<sub>2</sub>. Different types of cap rocks are also more or less likely to fracture. A more pliant (bendy) rock will be less likely to fracture if the pressure changes so will be a better cap rock.

### **Types of CO<sub>2</sub> storage reservoir**

There are two main types of CO<sub>2</sub> storage site – depleted hydrocarbon (oil and gas) reservoirs and saline aquifers. The basic geology of both is the same: a reservoir rock overlain by a capping rock, and both are generally found deep underground (one kilometre or more). The difference is in the substances the rock already contains, and the amount of pressure that this substance is under.

Depleted hydrocarbon reservoirs are old oil or gas reservoirs where all the oil and gas that could be extracted has been removed. This doesn't mean that they contain no oil or gas (a proportion remains), but because some has been removed the pressure in the reservoir has been reduced. Until the well was drilled the oil or gas in the reservoir had been trapped for millions of years by the cap rock. This means that the cap rock properties are well known. These include how much pressure the cap rock can contain, and that any fractures have not been sufficiently open to allow the oil or gas to escape. This suggests that CO<sub>2</sub> can be injected into the reservoir up to

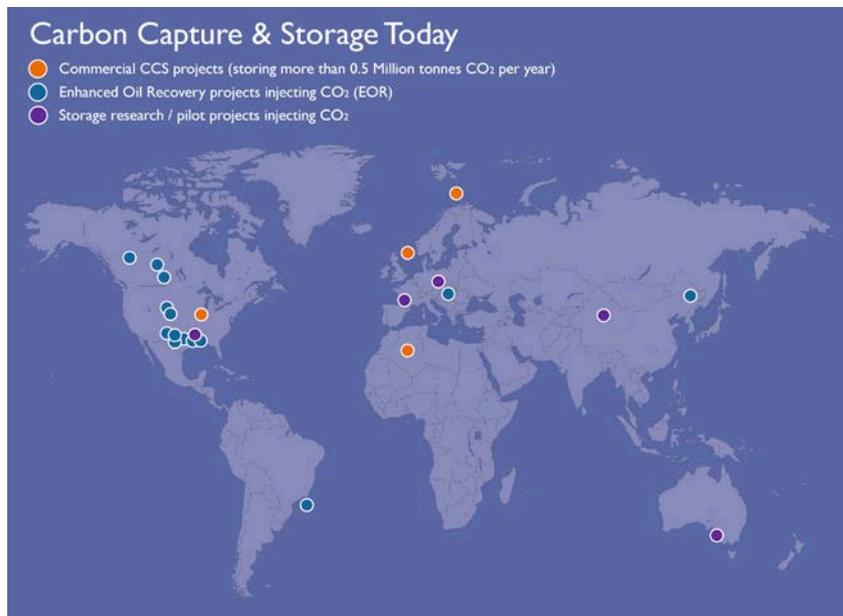
the original pressure with very high confidence that it will be securely trapped. In fact, large amounts of CO<sub>2</sub> are already injected into old onshore oil wells in the USA and Canada. Injecting the CO<sub>2</sub> maintains the reservoir pressure and reduces the stickiness of the oil allowing more of it to be extracted – a process known as enhanced oil recovery (EOR). While EOR has not been undertaken for the purpose of addressing climate change as it mostly uses CO<sub>2</sub> extracted from natural CO<sub>2</sub> reservoirs, it has given scientists and engineers a huge amount of knowledge about how CO<sub>2</sub> behaves underground that can be applied to CCS. Research suggests that depleted oil and gas wells have the capacity to store between around 675 billion and 900 billion tonnes of CO<sub>2</sub> – around 30 years worth of current global CO<sub>2</sub> emissions from power plants and industry.

Saline aquifers are the other main reservoirs where CO<sub>2</sub> can be stored. These are large expanses of underground rock containing very salty water. This water is unsuitable for drinking or for irrigation and so is of little use to humanity. If appropriate cap rocks are present above these saline aquifers, CO<sub>2</sub> can be injected into them. Unlike depleted oil and gas fields, injecting CO<sub>2</sub> will increase the original pressure on the cap rock. However, some of these saline aquifers are very large (many tens to hundreds of kilometres in extent), so that provided the permeability of the rock is high, any increase in pressure can be spread across a huge area of the capping rock. This means that a lot of CO<sub>2</sub> can be injected and only raise the pressure on the cap rock by a very small amount. Careful study and selection is required to ensure that the cap rocks can withstand this small pressure increase, but research and testing suggests that saline aquifers around the world have the potential to safely store huge quantities of CO<sub>2</sub>. Their total capacity is estimated to be between 1000 billion and 10,000 billion tonnes of CO<sub>2</sub> – 50 to 500 years worth of current global CO<sub>2</sub> emissions from power plants and industry.

### **Current CO<sub>2</sub> storage activity**

A number of projects are currently underway in which CO<sub>2</sub> is being injected into underground reservoirs for storage. These include EOR projects (some of which are now using CO<sub>2</sub> captured from industrial sources), two large commercial CCS projects offshore of Norway injecting millions of tonnes of CO<sub>2</sub> per year into saline aquifers deep beneath the seabed, and a number of smaller research projects located in many places around the world. Figure 3 shows the locations and types of these different projects in 2012. All of these projects are successfully injecting and storing CO<sub>2</sub> and along with research into natural CO<sub>2</sub> reservoirs, have given scientists and engineers a lot of opportunities to study and understand how CO<sub>2</sub> behaves underground. This knowledge can also be used to develop regulations for CO<sub>2</sub> storage that both enable CO<sub>2</sub> storage and therefore CCS to take place, but minimise the risks of possible leakage.

Figure 3: CO<sub>2</sub> storage activity in 2012. A small number of commercial CCS projects are injecting and storing large amounts of CO<sub>2</sub>, and EOR projects are also injecting CO<sub>2</sub> into old oil reservoirs to increase the amount of oil extracted. Smaller injections of CO<sub>2</sub> are also being undertaken at pilot and research projects around the world.



Source: Vivian Scott, © SCCS

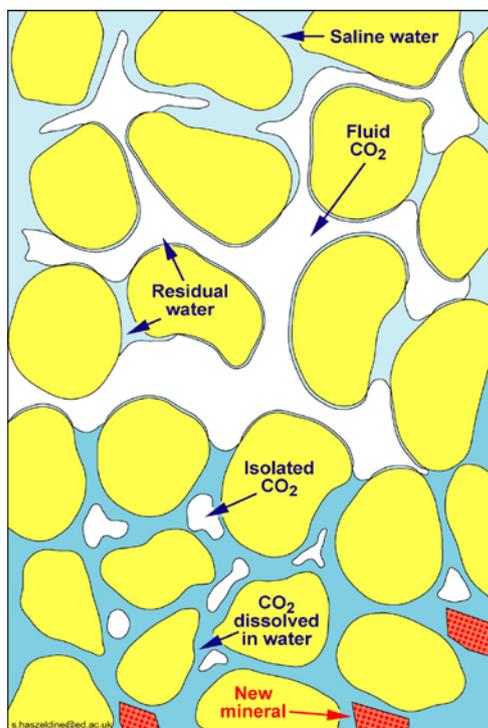
### Behaviour of CO<sub>2</sub> underground

While the physical capping of the reservoir by the cap rock is the main process by which the CO<sub>2</sub> is contained, there are a number of other processes that occur that, as time passes, increase the security of the storage by reducing the amount of free CO<sub>2</sub> (and so the pressure) in the reservoir.

When CO<sub>2</sub> is injected it initially forms a buoyant plume of free CO<sub>2</sub> in the reservoir rock, held in place by the capping rock. Once injection has finished, the plume can continue to move (upwards to the cap rock and sideways along it) but its size is gradually reduced by three processes. Firstly, as the plume moves through the rock lots of tiny individual amounts of the CO<sub>2</sub> can become “residually trapped”. This means that little bubbles of the CO<sub>2</sub> get held between the individual rock grains without enough buoyancy to move further. Second, the CO<sub>2</sub> can dissolve into water also present in the rock with the water-CO<sub>2</sub> solution taking up less space than the water and CO<sub>2</sub> separately. This solution is denser than water so slowly sinks through the storage rock. Lastly, the CO<sub>2</sub> can chemically react with the reservoir rock creating new minerals. This is a very slow process taking many thousands of years but essentially permanently removes the chemicals (carbon and oxygen) in the CO<sub>2</sub> for geological timescales (many millions of years). Figure 4 shows a diagram of these processes.

As a result of these processes, once a CO<sub>2</sub> storage site has been filled to an appropriate level and the injection wells sealed, the security with which the CO<sub>2</sub> is contained, and the confidence that it cannot escape, will increase as time passes.

Figure 4: Diagram showing a magnified cross section of CO<sub>2</sub> injected into a reservoir containing salty water – a saline aquifer. The free fluid CO<sub>2</sub> moves up through the reservoir leaving behind isolated trapped bubbles. Some of the CO<sub>2</sub> also dissolves into the water, and some over thousands of years reacts with the rock to form new minerals.



Source: Stuart Haszeldine, © SCCS

### Selecting CO<sub>2</sub> storage sites

All of this information can be used to identify specific sites in the rocks underground where safe and secure injection and storage of CO<sub>2</sub> could be undertaken. These sites need to have the right combination of reservoir rock overlain by capping rock. The reservoir rock needs to be appropriately porous (sufficient space for the CO<sub>2</sub>) and permeable (the CO<sub>2</sub> can move through the rock to fill up the pore spaces). The capping rock needs to be impermeable to CO<sub>2</sub> (the CO<sub>2</sub> can't move through it) up to a pressure that allows a sufficient quantity of CO<sub>2</sub> to be injected beneath it.

Once possible sites are identified, research is needed to check that all the key components of a safe and secure storage site are in place. This research will include studying the reservoir rock to identify the kind of fluid that it contains and the pressure that this fluid is under. Next, modelling is undertaken to assess what any increase in pressure might do – for instance might injecting CO<sub>2</sub> and so raising the pressure push the existing fluid in a particular direction. The integrity of the cap rock also needs to be investigated. Are there any existing fractures, are they already open or could an increase in pressure open them? Similarly, if the cap rock has previously been drilled through to extract oil or gas, the condition of these sealed wells needs to be checked. Much of this information may already exist for an old oil or gas well;

for saline aquifers, drilling a test well to take samples of the rock, and possibly performing a test injection of a small amount of CO<sub>2</sub>, might be required to gather the relevant data.

If the results of all this work indicate that the site is suitable for CO<sub>2</sub> storage, developers and regulators can agree upon a region called a “storage complex” which encompasses all the features relevant to the containment of the CO<sub>2</sub>. This complex will include the reservoir and cap rock layer or layers that are intended to hold the CO<sub>2</sub> in place. Once injection commences, the CO<sub>2</sub> should be closely monitored. Should it be seen to be behaving in an unexpected fashion and at risk of escaping from containment in the agreed complex, then measures (such as ceasing injection) can be undertaken to minimise the chance of CO<sub>2</sub> leakage.

### **Summary**

Reservoir rocks featuring lots of spaces between the rock grains (pores) can contain CO<sub>2</sub> in these tiny pores in a similar fashion to the way they contain oil and gas. To prevent the CO<sub>2</sub> escaping to the surface the reservoir rocks need to be overlain by capping rocks through which the CO<sub>2</sub> cannot move. This combination of reservoir rock and capping rock is found across much of the world, but to select specific places where CO<sub>2</sub> could be safely injected and stored the properties of the rock need to be well understood. Studying naturally occurring CO<sub>2</sub> reservoirs, injecting CO<sub>2</sub> into oil reservoirs to increase oil production and early CCS and CO<sub>2</sub> injection research projects have enabled scientists to learn about how rocks can securely contain CO<sub>2</sub>. This enables possible CO<sub>2</sub> storage sites to be identified, their suitability and capacity for storing CO<sub>2</sub> assessed and the chances of leakage minimised.

### **Glossary**

EOR: Enhanced Oil Recovery involves injecting CO<sub>2</sub> into oil reservoirs when they are nearing the end of production to allow extra oil to be extracted.

Free CO<sub>2</sub>: Pure CO<sub>2</sub> in a reservoir is often called free CO<sub>2</sub> to distinguish it from CO<sub>2</sub> dissolved in water in the reservoir.

Permeability: A measure of how well connected the spaces (pores) in between the individual rock grains are which represents how easily a fluid can travel through the rock by moving from one pore to the next.

Porosity: A measure of the proportion of the volume of a rock that is spaces (pores) between the individual rock grains. These spaces can contain fluids including water, oil, gas and CO<sub>2</sub>.

Residual trapping: The leaving behind of little pockets of fluid (CO<sub>2</sub>) in between rock grains as it moves through the rock. These little pockets do not have enough buoyancy to move on their own so are trapped. As an example, when a sponge is held under water it only partially fills up with water. This is because pockets of air are residually trapped in the sponge. Squeezing the sponge forces this air out allowing the sponge to absorb more water.

Storage complex: A region of underground rocks containing all the components of the CO<sub>2</sub> storage (reservoir rock and cap rock) that is agreed by a storage site developer and regulatory bodies. To fulfil their obligations a storage operator must show that the injected CO<sub>2</sub> remains fully contained in the storage complex.

### **Further Reading**

International Panel on Climate Change: Special Report on Carbon Dioxide Capture and Storage (Chapter 5) <http://www.ipcc-wg3.de/special-reports/special-report-on-carbon-dioxide-capture-and-storage>

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## **Briefing Note 9**

### **Possible impacts of carbon dioxide (CO<sub>2</sub>) leakage onshore**

This Briefing Note examines possible sources and effects of leakage of carbon dioxide (CO<sub>2</sub>) from onshore components of carbon dioxide capture and storage (CCS) projects. These include the CO<sub>2</sub> capture facility, CO<sub>2</sub> transport and, if located onshore, the injection facility and geological storage site. The possible impacts and dangers of CO<sub>2</sub> leakage are explored and the measures and experience that can be applied by operators and regulators to reduce risks introduced. The role of Environmental Impact Assessments (EIAs) in identifying potential risks and establishing appropriate operating procedures and incident responses is outlined.

#### **Possible sources of CO<sub>2</sub> leakage from CCS onshore**

CCS is proposed to reduce CO<sub>2</sub> emissions from large stationary sources of human-made CO<sub>2</sub> such as fossil fuel burning power plants, steel and cement factories and oil refineries. CCS involves three broad stages. First – capturing the CO<sub>2</sub> – either in a facility added to an existing source, or built as part of a new source. Second – transporting the CO<sub>2</sub> to the injection site, most usually by pipeline. Third – injecting the CO<sub>2</sub> into appropriate rocks deep underground for long-term storage. All of these stages present a possibility for CO<sub>2</sub> leakage, but all can also be managed to minimise both the chance of leakage occurring and the hazards that a leak might pose.

#### **Potential dangers and environmental impacts of CO<sub>2</sub>**

CO<sub>2</sub> is a very common chemical and is naturally present in air at a concentration of around 0.04%. CO<sub>2</sub> is produced by many processes including burning substances containing carbon (including fossil fuels and wood), and respiration (extracting energy from the chemicals in food) by animals, humans and plants. However, while not considered 'toxic', high concentrations of CO<sub>2</sub> are dangerous to living things. In humans, breathing air containing around 1-3% CO<sub>2</sub> leads to rapid breathing, tiredness, headaches and blurred vision, but with no lasting damage once normal conditions return. Higher concentrations (greater than 3% CO<sub>2</sub>) present a serious hazard. Unless exposure is only very brief a condition called hypercapnia where there is too much CO<sub>2</sub> in the blood can occur leading to unconsciousness and possible death if treatment such as moving the casualty away from the high CO<sub>2</sub> area and giving them oxygen-rich air is not quickly applied.

Carbon dioxide capture and storage (CCS) consists of three basic steps: (1) the selective capture of the CO<sub>2</sub> resulting from the burning of fossil fuels such as coal, oil and gas (and biomass); (2) the compression and transportation of the captured CO<sub>2</sub>; and, (3) the injection of the CO<sub>2</sub> into rock formations hundreds of meters below the Earth's surface where it can be securely stored for hundreds of thousands of years. CCS is a vital tool in reducing global carbon emissions as it is the only technology available which can 'decarbonise' burning fossil fuels to generate electricity and heat, as well as allowing major industrial sectors manufacturing steel, cement and many other products to be decarbonised.

Similar health effects to those found in humans also occur in many animals. High CO<sub>2</sub> concentrations can also be dangerous to plants. A low concentration of CO<sub>2</sub> (up to

around 4% of the total gases) is naturally present in the soil, but concentrations above 5% can limit plant growth by interfering with the chemical processes in roots. Sustained soil CO<sub>2</sub> concentrations above 20% can kill plants. Changes in soil CO<sub>2</sub> concentration can be monitored by inspecting the behavior of key “indicator species” – plants that react in a particular and easily identifiable way to any changes in soil CO<sub>2</sub> concentration.

Even if there is a source of concentrated CO<sub>2</sub> at or near the ground surface, it usually presents little danger to humans outside enclosed spaces as air movement mixes the CO<sub>2</sub> into the air. This mixing quickly reduces the CO<sub>2</sub> concentration to safe levels. However, CO<sub>2</sub> is denser (heavier) than the other gases in air, so if there is little air movement dangerous levels of CO<sub>2</sub> can accumulate around a concentrated CO<sub>2</sub> source, especially in landscape features lower than the surrounding area such as pits, troughs or deep valleys. Such circumstances can pose a serious hazard. However, the actual level of risk to human health from leaking CO<sub>2</sub> is very low. Scientists are able to use records of incidents and fatalities at naturally occurring CO<sub>2</sub> leaks (from naturally occurring CO<sub>2</sub> in underground rocks) to assess the likely levels of risk that could be posed by leaks from engineered CO<sub>2</sub> storage. The results found that even with little access restriction and warnings, the risk posed to the local population by natural CO<sub>2</sub> leaks was extremely small (1 in 100 million chance of fatality), compared with the risks of fatality from lightning strikes (1 in 100 thousand) or in a motoring accident (1 in 10 thousand). The risks posed by engineered CO<sub>2</sub> storage should be much less due to careful storage site selection and monitoring.

An additional possible concern related to deep underground storage of CO<sub>2</sub> is the potential for contamination of underground fresh water aquifers used for drinking and irrigating agriculture. Fresh water aquifers are generally located much closer to the surface (up to around 500m) than the deep rock formations (around 1000 - 3000m depth) considered for CO<sub>2</sub> storage which often contain unusable very salty and mineral rich water. Many layers of capping rock often lie between these fresh and saline aquifers preventing connection between them. While extremely unlikely, contamination could possibly occur either by CO<sub>2</sub> entering the fresh water (perhaps from an injection well), or salty water being displaced into fresh water by the injected CO<sub>2</sub>. Monitoring of water quality can be used to check that contamination is not occurring, and should it happen, measures to minimise its impact applied. As well as ceasing CO<sub>2</sub> injection, CO<sub>2</sub> could be removed by aerating the water and other water treatment methods can also be used if needed.

### **CO<sub>2</sub> capture and transport – leakage risks and prevention measures**

CO<sub>2</sub> capture and transport both occur on or near the land-surface. While a CO<sub>2</sub> leak from capture and transport would therefore have an immediate effect on the surrounding area, it would also be easy to detect, e.g. there would be an unexpected change in CO<sub>2</sub> pipeline pressure alerting the operators and enabling a rapid shut-off and immediate repair.

Several different methods for capturing CO<sub>2</sub> at the source facility are available, all of which are designed to produce a concentrated (over 95%) CO<sub>2</sub> output ready for

transport and storage. Such a concentration of CO<sub>2</sub>, often at high pressures and high temperatures, could present a serious hazard. However, CO<sub>2</sub> source facilities are large industrial sites, familiar with the appropriate containment and handling of hazardous substances such as high temperature steam, natural gas, petroleum and other chemical products. The addition of CO<sub>2</sub> capture will require some CO<sub>2</sub> specific health and safety measures and procedures, and operators and regulators are working closely on early CCS projects to develop suitable standards and practices to minimise CO<sub>2</sub> related risks.

Given the large volumes - millions of tonnes per year - of CO<sub>2</sub> that might be captured from large facilities applying CCS, pipelines are the most practical method for onshore CO<sub>2</sub> transportation. In a pipeline, CO<sub>2</sub> is usually compressed under high pressure to be moved as a dense gas or liquid. Leakage of CO<sub>2</sub> into the atmosphere from pipelines is a possibility, and might occur due to a material failure of the pipeline, caused by a valve or welding failure or by corrosion, or by an external force (accidental breaching). Release of CO<sub>2</sub> from a pipeline poses two hazards. First, as a substance under high pressure, while not flammable, a CO<sub>2</sub> leak could explode forcefully, and as it rapidly expands from a leak it can cool to very low temperatures posing a risk to anything in the immediate vicinity – high pressure natural gas pipelines present a similar risk. Second, as CO<sub>2</sub> is a heavy gas if an accidental release were to occur near a low-lying landscape feature and in still weather conditions, a hazardous CO<sub>2</sub> gas layer might form.

However, onshore CO<sub>2</sub> pipeline technology is well-established and has been used since the 1970s to supply CO<sub>2</sub> for use in enhanced oil recovery (EOR) to old oilfields in the USA and Canada. Like natural gas pipelines, regulations set standards for the materials and designs used and the operation and inspection procedures applied. Around six thousand kilometers of such pipeline is currently in operation, and no serious CO<sub>2</sub> leakage or accidents have occurred. Experience from the operation and regulation of natural gas pipelines – extensively used worldwide - can also be applied. Research has also been undertaken to explore CCS specific CO<sub>2</sub> pipeline requirements. This includes examining the effect of some of the possible trace chemicals (substances present in tiny amounts) in the captured CO<sub>2</sub> on the resistance of pipeline materials to corrosion, creating accident scenarios to gain direct experience of pipeline failure and developing models for CO<sub>2</sub> dispersion from a leak to allow for risk assessments of proposed pipeline routes.

### **CO<sub>2</sub> storage – leakage risks and prevention measures**

CO<sub>2</sub> storage is undertaken by injecting the CO<sub>2</sub> into rocks deep (usually over a kilometer down) underground. Appropriate storage sites consist of a reservoir rock into which the CO<sub>2</sub> can be injected to fill the tiny spaces between the individual rock grains, overlain by a layer, or layers of cap rocks – rocks through which CO<sub>2</sub> cannot pass which hold the CO<sub>2</sub> in place. Potential storage sites can be depleted oil or gas fields, deep saline aquifers (rocks containing very salty water), or in some cases coal seams that are too deep to be mined. Possible leakage routes could occur in places where the capping rock fails to contain the CO<sub>2</sub>. This might be a result of natural features such as gaps where the capping rock isn't present, or fractures (cracks) in

the capping rock. Alternatively, old oil and gas wells that cut through the capping rock might also present a possible leakage route. These are sealed with cement when the wells are closed but need to be checked to make sure the seal is able to contain CO<sub>2</sub>.

To minimise the risk of leakage from a CO<sub>2</sub> storage site many different measures can be taken – both in selecting the site and in monitoring the injected CO<sub>2</sub> once storage operations have begun. The selection and licensing of CO<sub>2</sub> storage sites should be properly regulated to ensure that chosen sites are appropriate for storage and that all potential leakage pathways have been examined. Selection processes include analysis of the properties of the storage and capping rocks, checking the status of any old sealed wells, and identifying if nearby rocks contain any fluids (e.g. fresh water) that are or might be used and should therefore be protected from contamination. A detailed model of the storage site is then made to predict the movement and behavior of the CO<sub>2</sub> in the injection site. This model enables regulators and the storage site developer to define a “storage complex” – a section of the underground rocks including the storage rock and capping rock which encompasses the whole area relevant to the CO<sub>2</sub> storage process.

Once this selection process has been completed and a license for injection and storage given the CO<sub>2</sub> can be monitored. Monitoring can be done both directly by instruments placed down the injection well or separate monitoring wells, and indirectly for example by using seismic – a technique that uses echo-sounding methods. This monitoring enables engineers to check that the CO<sub>2</sub> is behaving as expected. If the CO<sub>2</sub> is found to be behaving in a different way to that expected then further investigation can be undertaken, and if deemed necessary, corrective measures applied. These might include ceasing CO<sub>2</sub> injection and perhaps even withdrawing some of the already injected CO<sub>2</sub> to reduce the pressure. If a leak is suspected surface monitoring could also be undertaken and installed in areas that might be at risk – e.g. low lying landscape features. These systems could quickly alert public authorities to any possible risks to human health.

A growing number of both commercial and experimental injections of CO<sub>2</sub> into underground rocks have been undertaken and continue at sites around the world. These injections are being used to improve knowledge of the CO<sub>2</sub> storage process, and to assess and develop different monitoring methods. So far, at all the sites identified as suitable for CO<sub>2</sub> storage where CO<sub>2</sub> injection has taken place, no CO<sub>2</sub> has been found to be leaking from the designated storage complex.

An additional benefit of CO<sub>2</sub> storage in underground rocks is that as time passes the security of CO<sub>2</sub> storage increases. When the CO<sub>2</sub> is injected it first forms a buoyant plume of “free CO<sub>2</sub>” in the storage rock, with upward movement prevented by the CO<sub>2</sub> being unable to move through the capping rock. However, a number of processes take place that act to reduce the size of the CO<sub>2</sub> plume and so reduce the pressure it exerts on the cap rock. First, as the plume moves through the rock many tiny individual amounts of CO<sub>2</sub> become “residually trapped” – they get stuck between the individual grains without enough buoyancy to move. Second, the CO<sub>2</sub>

dissolves into water also present in the rock. This creates a water-CO<sub>2</sub> solution which takes up less space than the water and CO<sub>2</sub> separately. This solution is denser than the water on its own so sinks through the storage rock away from the plume. Both the residual trapping and dissolving of the CO<sub>2</sub> start almost immediately and continue to take place over long time scales. Last, the CO<sub>2</sub> can chemically react with the reservoir rock itself creating new minerals. This process is very slow taking many thousands of years but permanently fixes the chemical elements (carbon and oxygen) in the CO<sub>2</sub> for geological timescales (many, many millions of years).

Once injection of the desired amount of CO<sub>2</sub> into a storage site has been completed and the injection wells sealed, the storage site should initially be monitored closely to observe any continued movement of the CO<sub>2</sub>. Then as time passes, as a result of the processes described above slowly reducing the amount of free CO<sub>2</sub>, the confidence in the security of the site can increase. This reduces the chances of leakage and means that less frequent monitoring might be required.

### **Assessing the environmental risks – Environmental Impact Assessments**

To assess the risk posed by any new development, most jurisdictions require that an Environmental Impact Assessment (EIA) be carried out and approved prior to permission for the project being granted by the regulators. An Environmental Impact Assessment is defined by the International Association for Impact Assessment (IAIA) as: “the process of identifying, predicting, evaluating and mitigating the bio-physical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made.” An EIA is required for any CCS project to be granted approval for the capture, transport and underground storage of CO<sub>2</sub>. This EIA will need to establish a structured means for defining and evaluating the potential environmental impacts that may occur and the existence of appropriate measures to manage and reduce them. An EIA will evaluate the probability of leakage, agree how monitoring will occur and decide the action plan to be followed should a leak occur.

Experience in the methods used for fixing leaks has been gained from other activities such as natural gas pipeline transport. It is reasonable to expect that these techniques can be modified to work for CO<sub>2</sub> pipelines and experiments have and can be undertaken where necessary to check that emergency techniques work as expected. Methods for dealing with leakage from CO<sub>2</sub> storage sites have been considered but have not yet been used primarily because no such leaks have yet been detected.

The details of an EIA can differ between countries, but they are also always site and project specific. An EIA will frequently be placed in the public domain for a period of consultation before approval, offering the public the opportunity to comment and provide feedback on the environmental and other aspects of the proposed project. This can potentially result in a project being abandoned if legitimate and unanswerable concerns are raised, but in most cases addressing any concerns raised during consultation results in a better project in which the relations between developers and potentially affected parties are improved.

## Summary

CCS requires the handling of concentrated CO<sub>2</sub> on the surface at the capture facility and during transport, and during injection into deep rock formations for storage. Leakage is possible both during capture and transport, and from the storage site. However, experience and safety measures developed both from existing CO<sub>2</sub> capture, transport and storage operations and from similar processes like the natural gas industry can be applied both to minimise the chance of leakage, and enable leakage to be quickly identified and the risks to humans and the environment addressed. Environmental Impact Assessments allow developers, regulators and the public to assess the risks of a project, identify potential problems and establish prevention and repair methods to ensure projects are safely and properly operated.

## Glossary:

EOR: Enhanced Oil Recovery involves injecting CO<sub>2</sub> into oil reservoirs when they are nearing the end of production to allow extra oil to be extracted.

Free CO<sub>2</sub>: Pure CO<sub>2</sub> in a reservoir is often called free CO<sub>2</sub> to distinguish it from CO<sub>2</sub> dissolved in water in the reservoir.

Indicator species: A plant or animal that is monitored to assess levels of a chemical such as CO<sub>2</sub> in its environment as the plant or animal has an easily identifiable response to changes in the level of exposure to chemical.

Residual trapping: The leaving behind of little pockets of fluid such as CO<sub>2</sub> in between rock grains as it moves through the rock. These little pockets do not have enough buoyancy to move on their own so are trapped. As an example, when a sponge is held under water it only partially fills up with water. This is because pockets of air are residually trapped in the sponge. Squeezing the sponge forces this air out allowing the sponge to absorb more water.

Storage complex: A region of underground rocks containing all the components of the CO<sub>2</sub> storage (reservoir rock and cap rock) that is agreed by a storage site developer and regulatory bodies. To fulfil their obligations a storage operator must show that the injected CO<sub>2</sub> remains fully contained in the storage complex.

## Further Reading

International Panel on Climate Change: Special Report on Carbon Dioxide Capture and Storage (Chapters 3,4, 5) <http://www.ipcc-wg3.de/special-reports/special-report-on-carbon-dioxide-capture-and-storage>

International Association for Impact Assessment : What is an impact assessment.  
[http://www.iaia.org/publicdocuments/special-publications/What%20is%20IA\\_web.pdf](http://www.iaia.org/publicdocuments/special-publications/What%20is%20IA_web.pdf)

World Resource Institute (2008). CCS Guidelines: Guidelines for Carbon Dioxide Capture, Transport, and Storage. [http://pdf.wri.org/ccs\\_guidelines.pdf](http://pdf.wri.org/ccs_guidelines.pdf).

UK Health and Safety executive (2011). Assessment of the major hazard potential of carbon dioxide (CO<sub>2</sub>) <http://www.hse.gov.uk/pipelines/co2conveying.htm>

Roberts, J.J., Wood, R.A., Haszeldine, R.S. Assessing the health risks of natural CO<sub>2</sub> seeps in Italy. Proceedings of the National Academy of Sciences, 2011. <http://www.pnas.org/content/108/40/16545.full>

#### IEAGHG Reports

2006/02: Safe Storage of CO<sub>2</sub>

2007/01: Environmental Assessment for CO<sub>2</sub> Capture and Storage

2007/02: Role of Risk Assessment in Regulatory Frameworks for CCS

2007/03: Potential Impacts of Leaks from Onshore CO<sub>2</sub> Storage Projects on Terrestrial Ecosystems

2009/06: Safety in Carbon Dioxide Capture, Transport and Storage

2011/11: Potential Impacts on Groundwater Resources of Geological Storage

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## Briefing Note 10

### Possible impacts of carbon dioxide (CO<sub>2</sub>) leakage offshore

This Briefing Note examines the possible sources and effects of leakage of carbon dioxide (CO<sub>2</sub>) from offshore components of carbon dioxide capture and storage projects. While some sources from which CO<sub>2</sub> might be captured are offshore (e.g. natural gas platforms), most are onshore. As a result, for CO<sub>2</sub> to be stored in rocks beneath the seabed it requires transporting in the marine environment and offshore facilities for its injection. Measures and experience that can be applied by operators and regulators to reduce the risk of leakage in offshore situations are discussed and the impact of CO<sub>2</sub> leakage explored. The role of an Environmental Impact Assessment in identifying potential risks and establishing appropriate operating procedures and responses to incidents is also outlined.

#### Possible sources of CO<sub>2</sub> leakage offshore

For CO<sub>2</sub> storage in rocks beneath the seabed (offshore storage), captured CO<sub>2</sub> must first be transported to the storage site for injection. The most practical transport options for moving large volumes of CO<sub>2</sub> in the offshore environment are pipelines or ships. For transportation in pipelines or ships the CO<sub>2</sub> is compressed under high pressure – either as a dense gas or a liquid. As a result, if the pipeline or gas tank on the ship were to be ruptured, CO<sub>2</sub> would leak out until the source of CO<sub>2</sub> was stopped or the leak repaired.

Once the CO<sub>2</sub> has reached the location of the storage site it requires injection into the rock formation chosen for storage. If the CO<sub>2</sub> has arrived by ship it needs to be transferred to the injection facility, whereas a pipeline can be integrated into the facility. For injection the CO<sub>2</sub> also needs to be pressurised. As with pipeline and ships there is potential for CO<sub>2</sub> to leak during the injection if the equipment were to rupture or fail.

Lastly, CO<sub>2</sub> might escape from the storage site itself and possibly leak out at the seabed. While storage sites will be chosen to minimise this possibility the processes by which they could potentially leak need to be understood. CO<sub>2</sub> is buoyant in the subsurface so will move upwards through the rock unless held in place by a layer of rock through which the CO<sub>2</sub> cannot pass (known as the cap rock). However, if the cap rock is fractured (cracked), there could be possible passageways through for the CO<sub>2</sub>. Another possible escape route could be through old wells drilled to extract oil and gas. These are sealed with cement when the wells

Carbon dioxide capture and storage (CCS) consists of three basic steps: (1) the selective capture of the CO<sub>2</sub> resulting from the burning of fossil fuels such as coal, oil and gas (and biomass); (2) the compression and transportation of the captured CO<sub>2</sub>; and, (3) the injection of the CO<sub>2</sub> into rock formations hundreds of meters below the Earth's surface where it can be securely stored for hundreds of thousands of years. CCS is a vital tool in reducing global carbon emissions as it is the only technology available which can 'decarbonise' burning fossil fuels to generate electricity and heat, as well as allowing major industrial sectors manufacturing steel, cement and many other products to be decarbonised.

are closed, but present a possible escape route if the sealing was done incorrectly or has corroded. Lastly, the CO<sub>2</sub> could move laterally (sideways) through the rock in which it is stored to a place where the rock isn't adequately covered by a cap rock enabling the CO<sub>2</sub> to escape.

### **Measures to prevent offshore CO<sub>2</sub> leakage**

Regulation for CCS has to be designed to minimise the chances of leakage from any parts of the system, and to ensure that should a leak occur it is quickly detected, its possible effects understood, and the source of the leak repaired or prevented. At the same time, the regulation also has to allow sufficiently safe CCS to happen – regulators have to deliver rules that are practical to follow and not so expensive to apply that they prevent safe CCS from happening.

### **Offshore Pipeline**

There is considerable experience with laying and operating offshore pipeline for transporting hydrocarbons in the oil and gas industry. CO<sub>2</sub> pipelines are already used extensively onshore - around 6000km of CO<sub>2</sub> pipeline is currently in operation in the USA without incident. Offshore experience is more limited – the best example being that used at the Snøhvit gas processing and CCS facility in the Barents Sea (Norway) which has been operating without problems since 2008. In the offshore environment many practices have been developed to maximise pipeline safety. These include designing materials resistant to corrosion in the marine environment and establishment of pipeline corridors using trenching and burying of pipes to protect them from damage by other marine activities like commercial fishing. Pipeline inspections are routinely carried out to check for possible damage and corrosion. The pressures of the substances in the pipelines are closely monitored so that any leakage is quickly detected and the pipeline can be shut down for repair. None of these measures can completely rule out leakage, but they can greatly reduce the possibility and enable a rapid response should leakage occur.

### **Transporting CO<sub>2</sub> by ship**

Similar measures can be applied to CO<sub>2</sub> transport ships and associated facilities. A small amount of shipping of CO<sub>2</sub> already takes place (e.g. for use in the food packaging industry), and experience and regulation of moving very large volumes of natural gas by ship in the Liquefied Natural Gas (LNG) industry can also be applied. LNG ships use sophisticated double hull designs that prevent breaching of the gas containing compartments even if the ships run aground or are involved in collisions. Since the first voyages began in 1959, LNG ships have completed tens of thousands of voyages covering many millions of miles without any major accident and only a small number of minor incidents worldwide – none of which have involved large leakages of gas.

At offshore injection facilities, many of the same issues – corrosion and accidental damage - have to be considered. Here, the regulation applied to offshore hydrocarbon activities is a useful starting point. There is also the direct experience gained at the limited number of offshore facilities currently injecting CO<sub>2</sub> into rocks beneath the sea such as the commercial scale Snøhvit and Sleipner gas processing and CCS facilities in Norwegian waters, and the smaller scale K-12B platform in Dutch waters.

Measures can also be taken to minimise the risk of leakage from the storage site itself. First, the selection and licensing of CO<sub>2</sub> storage sites should be properly controlled to ensure that they are appropriate, and that no potential leakage pathways are overlooked. This includes detailed analysis of the storage and capping rocks (there are frequently many capping rock layers), and researching and if necessary checking the condition of any existing or sealed wells. Next, modelling can be undertaken to predict the behaviour of the CO<sub>2</sub> in the storage site. This allows regulators and storage site developers to agree on a “storage complex” – a region including the storage rock and capping rock and appropriate sideways and downwards extensions.

Once a site has been found to be suitable and injection commenced, monitoring of the CO<sub>2</sub> and the storage complex can be undertaken, both by instruments in the storage site (down the injection or separate observation wells) and also by remote methods like seismic (echo sounding) from ships. The information gathered can be compared with the models to check that the CO<sub>2</sub> is behaving as expected. If CO<sub>2</sub> is found to be behaving in an unexpected fashion or moving beyond the agreed storage complex then measures to address these issues can be applied. These would include ceasing the CO<sub>2</sub> injection and perhaps withdrawing some of the CO<sub>2</sub> if necessary. The storage complex is deep below the seabed, frequently below many other cap rock layers, so even if CO<sub>2</sub> escapes the complex it is still not likely to reach the seabed itself. However, seabed monitoring can also be undertaken to detect if some CO<sub>2</sub> has somehow escaped unnoticed. This can include inspecting for tell-tale “pockmark” features made by gas leaving seabed sediments, monitoring of the chemical composition of the water and observing the local ecosystem to see if it has reacted to any changes.

The offshore CO<sub>2</sub> injections already taking place have given industry and regulators useful experience in how to safely operate CO<sub>2</sub> storage beneath the seabed. To date (2012), the Sleipner and Snøhvit projects in Norwegian waters have stored over 15 million tonnes of CO<sub>2</sub> in rocks deep beneath the seabed without any leakage detected.

One of the benefits of CO<sub>2</sub> storage in underground rocks is that the security of CO<sub>2</sub> storage increases the longer the CO<sub>2</sub> is in place. When CO<sub>2</sub> is injected it initially forms a buoyant plume of “free CO<sub>2</sub>” in the reservoir (storage) rock, held in place by the capping rock. But once injection has finished, over time a number of processes occur that reduce the size of the plume and so the pressure it exerts on the cap rock. Firstly, as the plume moves through the rock lots of tiny individual amounts of the CO<sub>2</sub> can become “residually trapped” – that is that they get held between the individual grains without enough buoyancy to move further. Second, the CO<sub>2</sub> can dissolve into water also present in the rock with the water-CO<sub>2</sub> solution taking up less space than the water and CO<sub>2</sub> separately. This solution is denser than water so will sink through the storage rock. Both of these processes start almost immediately and continue to happen over long time scales. Lastly, the CO<sub>2</sub> can chemically react with the reservoir rock creating new minerals – this is a very slow process taking thousands of years but permanently fixes the chemical elements (carbon and oxygen) in the CO<sub>2</sub> for geological timescales (many, many millions of years).

As a result of these processes, once a CO<sub>2</sub> storage site has been filled to an appropriate level and the injection wells sealed, it should initially be monitored closely to observe any

continued movement of the CO<sub>2</sub>. Then as time passes and the processes described above reduce the amount of free CO<sub>2</sub>, confidence in the security of the site can increase so less frequent monitoring might be required.

### **Possible effects of CO<sub>2</sub> leakage in the marine environment**

In case CO<sub>2</sub> did leak, either from transport or storage facilities, it is important to understand the possible environmental and safety impacts. CO<sub>2</sub> is naturally present in air (humans, animals and plants produce CO<sub>2</sub> through respiration), but high concentrations are dangerous with the potential to asphyxiate. In normal outside conditions any CO<sub>2</sub> leaking into the air quickly mixes and disperses. However, as CO<sub>2</sub> is heavier than the other gases in air it can sink into still depressions (e.g. a low space in a ship) so detectors need to be in place to alert people working in possibly hazardous places. The CO<sub>2</sub> within pipelines and storage facilities is also at high pressure so while it is not flammable a leak could explode forcefully. As CO<sub>2</sub> expands from a leak it can cool to very cold temperatures possibly damaging metals and posing a danger to anyone nearby. Again, operators and regulators have to put in place appropriate health and safety measures to minimise the risk of injury from any accidental release.

Leakage into the sea either from a pipeline or from a storage site through the seabed has the potential to damage the local environment. CO<sub>2</sub> dissolves into water changing its chemical composition and making it more acid (decreasing its pH - the measure of acidity) with detrimental effects on some marine life. Exactly how acidic the sea water might become depends upon the local properties of the seawater environment. For example how much the water mixes, and how well the different chemicals naturally present in the water can buffer (resist) changes in the pH. The lowest possible pH in the North Sea appears to be about 6.5 - very slightly acidic (neutral is 7). Lower pH values (e.g. 4.5 – 6) comparable to the acidity of coffee or carbonated water are possible for instance in the Okinawa Trough (East China Sea) where naturally-occurring CO<sub>2</sub> seeps into the bottom of the ocean.

The absorption of human-made CO<sub>2</sub> from the atmosphere into the ocean is having this effect, lowering the pH at a global scale, threatening marine plants and animals like coral reefs and the creatures that live in them. Leakage from a localised source could damage local marine life, especially creatures that are unable to quickly move away. Research at natural sources of CO<sub>2</sub> entering the sea water from beneath the sea-bed and sites where CO<sub>2</sub> has been deliberately released, enables scientists to identify “indicator species”. These are organisms that react in a particular way to increased CO<sub>2</sub> levels and so their behavior (including presence, abundance or absence) can be used to detect possible leakage. A “baseline survey” which measures and records the environment beforehand is also useful to allow changes in plants, animals and other organisms to be easily seen. In the worst cases considerable local environmental damage could occur, but once the leak has been stopped it is expected that the local ecosystem will be able to quickly recover as (unlike many industrial chemicals) CO<sub>2</sub> is not toxic.

### **Assessing the environmental risks – Environmental Impact Assessments**

To assess the risk posed by any new development, most jurisdictions require an Environmental Impact Assessment (EIA) to be carried out and approved prior to permission for the project being granted by regulators. An Environmental Impact Assessment is defined

by the International Association for Impact Assessment (IAIA) as: “the process of identifying, predicting, evaluating and mitigating the bio-physical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made.” An EIA is required for any CCS project to be granted approval for capture, transport and underground storage of CO<sub>2</sub>. This EIA will need to establish a structured means for defining and evaluating the potential environmental impacts that may occur and the existence of appropriate measures to manage and reduce them. An EIA will evaluate the probability of leakage, agree how monitoring will occur and decide the action plan that will be put into place should a leak occur.

A broad range of monitoring techniques are available to monitor the storage reservoirs and detect CO<sub>2</sub> leaks. Many of these techniques are well established, while others continue to be developed. Experience in the methods used for fixing leaks has been gained from other activities such as natural gas pipeline transport. It is reasonable to expect that these techniques can be modified to work for CO<sub>2</sub> pipelines and experiments have and can be undertaken where necessary to check that techniques work as expected. Methods for dealing with leakage from CO<sub>2</sub> storage sites have been considered but have not yet been used primarily because no such leaks have yet been detected.

The details of an EIA can differ between countries and they are also site and project specific. An EIA will frequently be placed in the public domain for a period of consultation before approval, offering the public the opportunity to comment and provide feedback on the environmental and other aspects of the proposed project. This can potentially result in a project being abandoned if legitimate and unanswerable concerns are raised, but in most cases addressing concerns raised during consultation results in a better project in which the relations between the project developers and potentially affected parties are improved.

### **Summary**

CO<sub>2</sub> storage in rocks beneath the seabed requires handling of CO<sub>2</sub> in the marine environment. Leakage is possible both from transportation and injection facilities and the storage site itself. However, many measures and experience from existing offshore CCS projects and other offshore industries can be applied to minimise the chance of leakage and limit the risks both to humans and the marine environment. Environmental Impact Assessments allow developers, regulators and the public to assess the risks of a project, identify potential problems and establish prevention and repair methods to ensure projects are safely and properly operated.

### **Glossary:**

**Baseline survey:** A detailed survey of a local environment and its plant and animal inhabitants before any planned process has taken place. This allows any changes to be measured by comparing later surveys with the baseline survey.

**Cap rock:** A layer of rock lying on top of the reservoir rock which contains the CO<sub>2</sub>, oil or natural gas that is impermeable (cannot be passed through) to the substances in the reservoir. The cap rock prevents the CO<sub>2</sub>, oil or natural gas escaping from the reservoir.

Free CO<sub>2</sub>: Pure CO<sub>2</sub> in a reservoir is often called free CO<sub>2</sub> to distinguish it from CO<sub>2</sub> dissolved in water in the reservoir.

Indicator species: A plant or animal that is monitored to assess levels of a chemical such as CO<sub>2</sub> in its environment as the plant or animal has an easily identifiable response to changes in its level of exposure to the chemical.

Pockmark: A round depression in mud or sediment on the seafloor often caused by a bubble of gas escaping.

Residual trapping: The leaving behind of little pockets of a fluid such as CO<sub>2</sub> in between rock grains as it moves through the rock. These little pockets do not have enough buoyancy to move on their own so are trapped. As an example, when a sponge is held under water it only partially fills up with water. This is because pockets of air are residually trapped in the sponge. Squeezing the sponge forces this air out allowing the sponge to absorb more water.

Storage complex: A region of underground rocks containing all the components of the CO<sub>2</sub> storage (reservoir rock and cap rock) that is agreed by a storage site developer and regulatory bodies. To fulfil their obligations a storage operator must show that the injected CO<sub>2</sub> remains fully contained in the storage complex.

### **Further Reading**

International Panel on Climate Change: Special Report on Carbon Dioxide Capture and Storage (Chapters 3,4, 5) <http://www.ipcc-wg3.de/special-reports/special-report-on-carbon-dioxide-capture-and-storage>

ECO<sub>2</sub>: Sub-seabed CO<sub>2</sub> storage, impact on marine ecosystems, [www.eco2-project.eu](http://www.eco2-project.eu)

QICS (Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage) project – <http://www.bgs.ac.uk/qics/geoimpact.html>

International Association for Impact Assessment : What is an impact assessment.  
[http://www.iaia.org/publicdocuments/special-publications/What%20is%20IA\\_web.pdf](http://www.iaia.org/publicdocuments/special-publications/What%20is%20IA_web.pdf)

World Resource Institute (2008). CCS Guidelines: Guidelines for Carbon Dioxide Capture, Transport, and Storage. [http://pdf.wri.org/ccs\\_guidelines.pdf](http://pdf.wri.org/ccs_guidelines.pdf).

UK Health and Safety executive (2011). Assessment of the major hazard potential of carbon dioxide (CO<sub>2</sub>) <http://www.hse.gov.uk/pipelines/co2conveying.htm>

### **IEAGHG Reports**

2008/08: Assessment of Sub Sea Ecosystem Impacts

Authors: Vivian Scott, Anne-Maree Dowd and Simon Shackley



## Briefing Note 11

### Monitoring for the presence and movement of CO<sub>2</sub> in CO<sub>2</sub> capture and storage (CCS) projects

#### Introduction

Why and how can carbon dioxide (CO<sub>2</sub>), captured as part of CO<sub>2</sub> Capture and Storage (CCS) projects, be monitored in the geological storage site? Monitoring techniques, methods for addressing leakage and responsibilities for applying monitoring regimes and any necessary repairs will be explained in this Briefing Note..

#### What is monitoring and verification and why is it needed?

The storage stage in the carbon dioxide capture and storage process requires CO<sub>2</sub> to be safely stored in rocks deep underground (the subsurface) from where it will be unable to enter the Earth's atmosphere. Geological storage sites are selected by their capability to safely trap CO<sub>2</sub> within the subsurface rocks for many tens of thousands of years or longer. These storage sites may be comprised of depleted oil and/or gas (hydrocarbon) fields or rocks containing very salty water (deep saline aquifers) into which injected CO<sub>2</sub> will be safely stored. However, due to uncertainties in characterising the deep geological storage sites, the movement of CO<sub>2</sub> within these storage sites cannot be predicted with 100% certainty. For this reason storage site operators are required under regulation to confirm that the injected CO<sub>2</sub> is being confined and not escaping back to the atmosphere. To do this a range of monitoring and verification techniques can be used. By providing verification of storage these monitoring techniques create assurances that CO<sub>2</sub> storage is safe and that the CCS process is being effectively deployed as a greenhouse gas emission reduction strategy.

The objectives of monitoring and verification are to assess the following with respect to stored CO<sub>2</sub>:

- Verify quantities injected and stored
- Ensure the pressure in the storage unit is acceptable
- Ensure that the injection well is in operable condition
- Demonstrate that CO<sub>2</sub> remains trapped where intended
- Detect leakages early enough in the process for remediation to be effective
- Measure any leakage that might occur
- Monitor the effectiveness of any required remediation
- Confirm that any old and shut-in wells are not allowing leakage.

Carbon dioxide capture and storage (CCS) consists of three basic steps: (1) the selective capture of the CO<sub>2</sub> resulting from the burning of fossil fuels such as coal, oil and gas (and biomass); (2) the compression and transportation of the captured CO<sub>2</sub>; and, (3) the injection of the CO<sub>2</sub> into rock formations hundreds of meters below the Earth's surface where it can be securely stored for hundreds of thousands of years. CCS is a vital tool in reducing global carbon emissions as it is the only technology available which can 'decarbonise' burning fossil fuels to generate electricity and heat, as well as allowing major industrial sectors manufacturing steel, cement and many other products to be decarbonised.

## How do we monitor and verify the geological storage of CO<sub>2</sub>?

When CO<sub>2</sub> is injected into porous geological formations either onshore or offshore its distribution and migration can be monitored using a number of techniques. Although geological storage monitoring is relatively new, most of the monitoring techniques needed are already in existence and have been used for other applications.

When CO<sub>2</sub> is injected at depths greater than around 800m it has the density (thickness) of oil but behaves like a gas. Because of industry experience in predicting the distribution and movement of oil and gas in underground rock formations, many techniques to monitor CO<sub>2</sub> like substances have been utilised for many years. Techniques for monitoring the surface and near surface above the storage site have also already been developed for many kinds of environmental monitoring and can be directly used for CO<sub>2</sub>. Details of current CO<sub>2</sub> monitoring techniques in deep geological rock formations and at the surface are as follows:

### a) Monitoring the subsurface distribution of CO<sub>2</sub>

Monitoring techniques are very site specific and will depend on the geology of the storage site, the regulatory requirements and (to some extent) the budget of a CO<sub>2</sub> storage project. Most can be applied both onshore and offshore, though offshore activity is usually more costly due to added complexity of working in the offshore environment. Summarised below are some of the most common techniques used today, though many others are also in active development.

- *Pressure Monitoring:* The measurement of reservoir pressure is one of the primary techniques used. Data on reservoir pressure is collected using 'downhole pressure sensors'. This technique relies on the assumption that injecting CO<sub>2</sub> will raise the pressure within the rock formation. This data is useful for identifying the first signs of pressure build-up and movement of CO<sub>2</sub>.
- *Seismic Monitoring:* This technique is commonly used in the oil and gas industry and has been applied effectively at the Sleipner CO<sub>2</sub> storage project offshore of Norway, which stores CO<sub>2</sub> in the porous rocks deep under the North Sea. In this process seismic (sound) waves generated at a moving source (a ship or a truck) travel down into the subsurface. The waves are reflected back depending on the nature of the rock and the fluids within, and are picked up again at a receiver on the surface. This technique can pick up small volumes of free phase (not dissolved) CO<sub>2</sub> at a resolution of down to around 5% of the reservoir fluids. In order to track the movement of CO<sub>2</sub> in and around the storage site, a baseline seismic survey must be taken before injection followed by a repeat survey usually at intervals of around two years. This technique can be used both on and offshore, but is among the more expensive monitoring methods to undertake.
- *Microseismic:* This technique relies on similar processes to those used in earthquake seismic monitoring. It is used to detect any unusual events occurring underground which may indicate movement in the rock that seals the storage reservoir. This technique is useful for confirming that the caprock above the storage site has not been damaged by CO<sub>2</sub> injection.
- *Satellite Imaging:* Satellite imaging can be used to detect any movement of the ground surface in an upward direction, which may arise due to the injection of CO<sub>2</sub> in the subsurface below. In the In Salah CCS project in the Algerian desert 8-10mm of

surface uplift has been detected due to the CO<sub>2</sub> injection. Although this method has been proven effective in this specific case, satellite imaging can only be completed onshore where there is little vegetation or infrastructure.

- *Well Logging*: Wireline well tests which involve lowering various types of sensor capable of measuring properties like temperature into existing or new wells can assess both rock and fluid properties by taking multiple measurements along the length of the well. Again this technique has been utilised for many years in the oil and gas industry and can be used to calculate the concentration of CO<sub>2</sub> in the rock formation within the storage site.
- *Injection well integrity*: Established techniques currently in use in the oil and gas industry can also be used to monitor the integrity of CCS injection wells. Pressure based procedures are commonly used to test the mechanical integrity of the injection well and ensure no leakages are occurring. 'Wireline logs' (Figure One) can be used to assess the condition of cement around the well casing. Downhole instruments used to measure temperature and noises to detect well failures in natural gas storage projects can be readily adapted for CO<sub>2</sub> storage projects.

#### **b) Monitoring environmental impacts at the surface and near surface**

The environment above the storage site can be monitored to detect if there is any effect of the CO<sub>2</sub> storage on for instance underground water supplies, air quality and/or plant and animal life. Assessing the properties of the environment before CO<sub>2</sub> storage commences establishes a baseline dataset, to which regular monitoring measurements can be compared to enable detection of any increase in CO<sub>2</sub> that might be migrating from a storage site. The methods differ depending on the location of the storage site – for instance onshore, offshore, beneath aquifers supplying fresh water supply (groundwater), or under agricultural or forested terrain. Some of the more common methods are detailed below.

- *Groundwater quality monitoring*: Groundwater can sometimes contain naturally occurring CO<sub>2</sub> (e.g. fizzy mineral water), but chemical analyses of water samples can be used to determine the origins of any CO<sub>2</sub>. Tracers (tiny amounts of easily detected harmless chemicals that don't naturally occur in the local environment) could also be added to the injected CO<sub>2</sub> enabling detection of any environmental contamination from a CO<sub>2</sub> storage site.
- *Atmospheric monitoring*: Scientists use various types of chemical sensor to monitor CO<sub>2</sub> levels in the air (Figure One) and soil. These techniques can be applied to allow for detection of increased CO<sub>2</sub> levels that might be caused by CO<sub>2</sub> leaking from a storage site.
- *Ecosystems monitoring*: Plant and animal life both onshore and on the seabed are sensitive to chemical changes such as increased CO<sub>2</sub>. This can be seen at places where naturally occurring CO<sub>2</sub> leaks to the surface or seabed. As a result, the behaviour of plants and animals can be monitored as a method for detecting CO<sub>2</sub> leakage. For instance, the diversity of species in the local environment might change, or the rate at which certain plants or animals grow might change. Scientists are currently undertaking experiments to learn more about how different species respond to increased CO<sub>2</sub> levels in their environment.



*This flux tower being installed at a geologic storage site measures the concentration of gases in the atmosphere. Such devices can detect increases in CO<sub>2</sub> Image source CO2CRC*

*Wireline logs are made by lowering instruments down the well to measure various properties of the rocks along its length. Image source: Copyrighted material, Schlumberger (used by permission)*

*Figure 1: Monitoring technologies for detecting CO<sub>2</sub>*

## **Leakage**

### **a) Potential leaks**

Geologic storage sites should be chosen and operated to avoid leaks. In the unlikely event of a leak, however, methods are generally available to fix the problem. Responsibilities for those activities are being set out in the legal frameworks that are evolving for CCS in many jurisdictions.

In many cases, CO<sub>2</sub> is likely to be tightly held within the storage formation. CO<sub>2</sub> that is kept in place primarily by 'structural trapping' (i.e. by the physical barrier of cap rock and other rock features), however, has the potential to move out of the storage formation. For example, leakage pathways may be created by reactivating old faults or, if injection pressures are raised above certain levels, by creating new ones. The most likely route for CO<sub>2</sub> leakage is where a well has been drilled into the geological formation (a wellbore); this is particularly relevant to depleted oil and gas fields, or in areas where a lot of exploration for oil and gas has previously taken place. Wellbores can become a source of leakage if they are not constructed or sealed properly or if the seal which closes them degrades over time.

### **b) Methods to fix leaks**

Should movement of CO<sub>2</sub> from the storage reservoir and complex occur during or after injection, methods are generally available to fix the leak. Most of these methods have long been used to fix leaks from other types of wells. A substantial base of experience has been gained over many years in rectifying leakage from natural gas storage projects, subterranean liquid waste disposal projects, and groundwater and soil contamination from other sources. These techniques can also be used for CO<sub>2</sub>, with the advantage that, unlike those other materials, CO<sub>2</sub> is not explosive or flammable, nor is it toxic, though it can be dangerous at high concentrations if it is able to accumulate undetected in land depressions, e.g. at the

bottom of valleys or pits, hence the need for monitoring. It is reasonable to expect that these techniques would work for CO<sub>2</sub>. They have not yet been used for this purpose, however, primarily because it has not been necessary to fix leaks at existing geologic storage projects.

Leaks can generally be expected to be eliminated by reducing injection or storage reservoir pressures or by adjusting pressures in different parts of the reservoir. Stopping injection at the current site and resuming it at a more suitable site may also eliminate leaks.

In most cases, it is likely that CO<sub>2</sub> leaks into the soil, atmosphere or groundwater could be safely dissipated at the surface – the CO<sub>2</sub> would not reach levels anywhere near dangerous concentrations as it would quickly mix with the other gases in the air. However, any such leakage would undermine the purpose of the CO<sub>2</sub> storage so would need to be stopped, and leakage into any enclosed spaces (e.g. cellars) or low lying areas (valleys or pits) where CO<sub>2</sub>, being heavier than air, could accumulate would need to be very carefully monitored to alert the operator and regulator to possibly dangerous (above 3%) CO<sub>2</sub> concentrations.

Old oil and gas wells that have been sealed and shut-in may present the most significant risk of leakage from CO<sub>2</sub> storage. These are usually sealed with heavy mud or cement but the quality of the seals needs checking and if necessary re-sealing. If the injection well itself leaks, it can be repaired by replacing parts of the well or injecting cement to seal the leaks. If necessary, the well can be properly sealed and shut-in. This is a standard and long-established technique for sealing leaking wells. Many countries have established procedures for shutting-in of oil, natural gas and other mineral extraction wells that can be applied to CO<sub>2</sub> injection.

Due to the trapping mechanisms utilised by geologic storage, and the dispersion of the injected CO<sub>2</sub>, any movements from the storage formation are likely to be slow, allowing time to make repairs before any serious damage is done. Appropriate monitoring techniques are needed to ensure that any unintended movement of the CO<sub>2</sub> is caught early so that repair procedures can be implemented.

### **Who is responsible?**

In a geologic storage project, some party or parties must be responsible for effective planning, safe and secure operation, detecting and fixing any unwanted movement of CO<sub>2</sub> that might occur, and repairing any adverse impacts. Who those parties are depends on the project operator and the applicable legal system, which varies by jurisdiction. CCS is a new type of activity and legal frameworks for it are evolving. In countries where extensive oil and gas production activities take place (in particular, Enhanced Oil Recovery (EOR) or acid gas injection), the legal framework may be relatively well advanced due to the similarity of CCS to those activities. In other jurisdictions, less of the legal framework may be in place.

Storage in geologic formations under the ocean is governed by various international treaties, most notably the London Convention, which covers every ocean. In addition, other treaties govern specific ocean regions. The London Convention and its 1996 Protocol (known as the London Protocol) in particular, govern marine pollution and ocean dumping.

The governments that are parties to the London Protocol agreed in 2006 to allow injection of CO<sub>2</sub> in sub-seabed geologic formations.

The project operator will usually have the primary responsibility for effectively planning the project, obtaining the necessary permits, operating the injection facilities safely and closing the facilities properly when the injection period is over. Monitoring and remediation responsibilities may vary, especially post-injection. Parties with post-injection responsibility may include the operator, governments, a third party brought in under contract, or some combination, all subject to the prevailing legal framework. This may also change over time.

#### *Case Study- Europe*

In 2009 the European Commission (responsible for proposing legislation) published the CCS Directive on geological storage of carbon dioxide. This directive set out a number of rules that operators of storage sites must comply with. The directive states that “after a storage site has been closed, the operator should remain responsible for maintenance, monitoring and control, reporting and corrective measures”. After 20 years, if CO<sub>2</sub> has been proven to be completely and permanently stored, the responsibility of monitoring and, if necessary, managing the storage site may be transferred to the government. However the operator must provide the financial support to cover the monitoring costs of that storage site for a further period of 30 years. The selection of the correct monitoring technique that can verify that CO<sub>2</sub> has been safely stored is therefore essential.

#### **Monitoring and verification - current issues**

*Post injection monitoring-* Once CO<sub>2</sub> injection has stopped and wells have been sealed some monitoring may continue to detect any CO<sub>2</sub> migration that might occur afterward. As discussed above, efforts are underway to develop protocols for long-term monitoring and address issues such as the type of monitoring that needs to occur and for how long the monitoring needs to continue.

*Cost of monitoring-* Although techniques such as 4D seismic have proven to be effective, they are relatively expensive to undertake. This expense may limit the number of projects they can be applied to. Work is underway to develop the most cost effective monitoring and verification techniques that are capable of proving secure storage and satisfying regulation while keeping the costs of CO<sub>2</sub> storage reasonable.

#### **Summary**

CO<sub>2</sub> storage in deep underground rocks can be monitored to check for leakage using a variety of techniques well-established in the oil and gas and other sectors. These include measurements in the storage site itself using instruments lowered into injection or observation wells, monitoring of the storage site from the surface using seismic (sound wave reflection) methods, and monitoring of the surface environment. Some of these methods work equally well on or offshore, while others are specific to certain conditions. The costs of different methods also vary and so have to be considered in the overall cost of CO<sub>2</sub> storage. Research is underway to refine existing monitoring methods and develop new ones – early CO<sub>2</sub> storage projects will play a major part in this. Regulators and operators have to agree appropriate monitoring practice that, while not being prohibitively costly, ensures timely detection of any leakage to enable preventative intervention.

## Further Reading

### Further Reading

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### IEAGHG Reports

2005/05: Monitoring Workshop – Inaugural Meeting

2006/09: 2<sup>nd</sup> Meeting of the Monitoring Network

2007/05: 3<sup>rd</sup> Monitoring Network Meeting Report

2008/16: 4<sup>th</sup> Monitoring Network Meeting

2009/10: CCS Site Selection and Characterisation Criteria

2009/11: 5<sup>th</sup> Meeting of the Monitoring Network

2010/14: 6<sup>th</sup> Meeting of the Monitoring Network

2011/08: Feasibility of Monitoring Tools

2011/14: The 7<sup>th</sup> IEAGHG Monitoring Network Meeting

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## Briefing Note 12

### What are the legal issues surrounding carbon dioxide capture and storage?

Underground carbon dioxide (CO<sub>2</sub>) storage is likely to require new national laws to be developed as well as modifications to existing national and international legal frameworks. Legal efforts to govern and support the development of CCS projects initially focused upon the removal of unwitting legal barriers, particularly with regards to CO<sub>2</sub> storage in international waters. Subsequent efforts have focused upon the design of dedicated legal and policy frameworks to facilitate capture, transport and storage of CO<sub>2</sub>, and have specified the legal entities and periods for long-term liability as well as operators' financial requirements.

#### Introduction

Existing laws that govern underground CO<sub>2</sub> storage vary a great deal across legal jurisdictions (regions, countries and states) and in some cases new laws and entire legal frameworks have been dedicated to regulating the development of future CCS projects. This is still very much a work-in-progress and is occurring at different paces across the world. Examples from several nations will be mentioned to illustrate particular points, however a single comprehensive legal framework governing CCS operations within one jurisdiction will not be discussed in detail.

### What are the main legal issues surrounding the storage of CO<sub>2</sub> in rock formations below ground?

#### Is CO<sub>2</sub> a waste or commodity?

A key issue has concerned whether CO<sub>2</sub> should be defined as a waste or as a commodity. If CO<sub>2</sub> is classed as a waste, it is subject to more stringent regulations concerning storage, transport and disposal. This question has been partially resolved in the EU by excluding permanently stored CO<sub>2</sub> from the list of wastes and from the scope of EU waste legislation. In the USA, the Environmental Protection Agency (EPA) has also proposed to exclude CO<sub>2</sub> from legislation governing hazardous wastes, provided that permanent storage complies with rules for a new class of CO<sub>2</sub> injection wells. Storage in geological formations located in international waters has also been permitted with the amendment of international dumping laws.

Carbon dioxide capture and storage (CCS) consists of three basic steps: (1) the selective capture of the CO<sub>2</sub> resulting from the burning of fossil fuels such as coal, oil and gas (and biomass); (2) the compression and transportation of the captured CO<sub>2</sub>; and, (3) the injection of the CO<sub>2</sub> into rock formations hundreds of meters below the Earth's surface where it can be securely stored for hundreds of thousands of years. CCS is a vital tool in reducing global carbon emissions as it is the only technology available which can 'decarbonise' burning fossil fuels to generate electricity and heat, as well as allowing major industrial sectors manufacturing steel, cement and many other products to be decarbonised.

However, uncertainty remains with respect to the legality of transporting CO<sub>2</sub> across legal boundaries (whether by pipeline or ship) under international conventions where CO<sub>2</sub> may still be defined as a hazardous waste under some circumstances.

#### Permanence of CO<sub>2</sub> storage and potential leakage

The key legal issue arising from CO<sub>2</sub> storage relates to storage permanence and the consequences of potential leakage. Leakage of CO<sub>2</sub> from a geological storage complex ('non-permanence') could result in damage to the environment, human health and physical property. It could also result in wider economic losses from price effects on land. Leakage will also have implications for climate change, as carbon reduction efforts would be compromised by any CO<sub>2</sub> released into the atmosphere. Provisions to ensure permanence and to regulate the consequences of leakage are at the core of CCS legislation. Adequate site characterisation and selection, risk assessment, risk management and monitoring are therefore crucial elements of regulatory frameworks.

Comprehensive short- and long-term liability frameworks are essential to ensure that the consequences of non-permanence are adequately repaired and compensated for. Liability frameworks are being developed in several jurisdictions around the world, many of which include financial security provisions and specify the exact responsibilities of governments and companies undertaking CCS projects, in the event that damages occur. Such issues are generally handled under liability provisions, which involve assessments of negative impacts resulting from e.g. operational accidents that involve humans, miscalculations that result in leakage of CO<sub>2</sub> from a geological storage complex, or seismic activity that results in CO<sub>2</sub> leaking into geological features that contain drinking water resources. Liability will differ in the case of an active storage operation and one that has been closed and handed over to a state authority for long-term monitoring.

#### **Who owns the rocks into which CO<sub>2</sub> is injected?**

The approach to ownership depends on the legal jurisdiction and often upon whether injection is taking place into a formation containing minerals – which would include oil, gas and coal. In this case, there are many existing laws and CO<sub>2</sub> injection would, in the first instance, follow these. According to the English legal approach (e.g. UK, Canada) the owner of a mineral interest has ownership over the geological formation. Even after extraction of minerals ceases, the mineral rights are maintained by the original operator. In many European countries, the state owns the geological formations that lie below the surface (sometimes called the 'sub-surface') not only on-shore but also off-shore. In Germany, the individual states, *Länder*, own the sub-surface.

Under US law, the owner of the surface tends to own the geological formation. The experience with using CO<sub>2</sub> to increase oil production by injecting it into oil fields – a process known as Enhanced Oil Recovery (EOR) – has driven the legal approach to CO<sub>2</sub> injection activities in North America. However, when CO<sub>2</sub> is to be injected into a

rock formation in the US that is known to contain drinking water, laws regulating water extraction are followed. In other words, CO<sub>2</sub> injection and storage regulations are generally governed by the type of sub-surface resources that are available for extraction.

Some countries have already modified their national laws regarding ownership of the sub-surface in order to enable CCS. For example, both the UK and the province of Alberta in Canada have passed laws giving the government ownership over the pore-spaces in the rock (including offshore in the UK). The UK Government does not claim ownership over the rock itself or of minerals within the rock, but has instead claimed ownership over the spaces within the rock (the pore-space) in which CO<sub>2</sub> would be stored.

### **Storage of CO<sub>2</sub> under the seabed**

The laws surrounding storage below ground on land are different from those governing storage below the seabed. In some parts of the world, off-shore storage is emerging as the preferred option, e.g. in northern Europe. The 'territorial seas' (up to 12 nautical miles from a legal jurisdiction's shoreline) are subject to the laws of the country to whom they belong. A number of international conventions regulate human use of international waters beyond this limit that are still considered to be within a country's Exclusive Economic Zone, or 200 miles beyond the border of the territorial sea. Beyond this zone, for reasons of environmental protection, the disposal of wastes into the sea or under the seabed is strictly prohibited under international law.

The London Convention (1972) and the London Protocol (1996) are globally applicable conventions which regulate disposal of wastes and other materials to the sea and sub-sea. This used to imply that CO<sub>2</sub> storage under the seabed was forbidden. However, the London Protocol was modified in 2006 in order to permit CO<sub>2</sub> storage provided environmental impacts are properly assessed. Storage of CO<sub>2</sub> in the ocean water column itself was strictly prohibited at the time because of the high uncertainty related to possible environmental impacts.

In 2009, a further modification was made to the London Protocol to permit the movement of CO<sub>2</sub> across national boundaries, so that a CO<sub>2</sub> pipeline network can potentially be constructed between countries. However, only a few countries have so far ratified this amendment and it will only come into force to enable the transboundary transportation of CO<sub>2</sub> after a sufficient number of members ratify it.

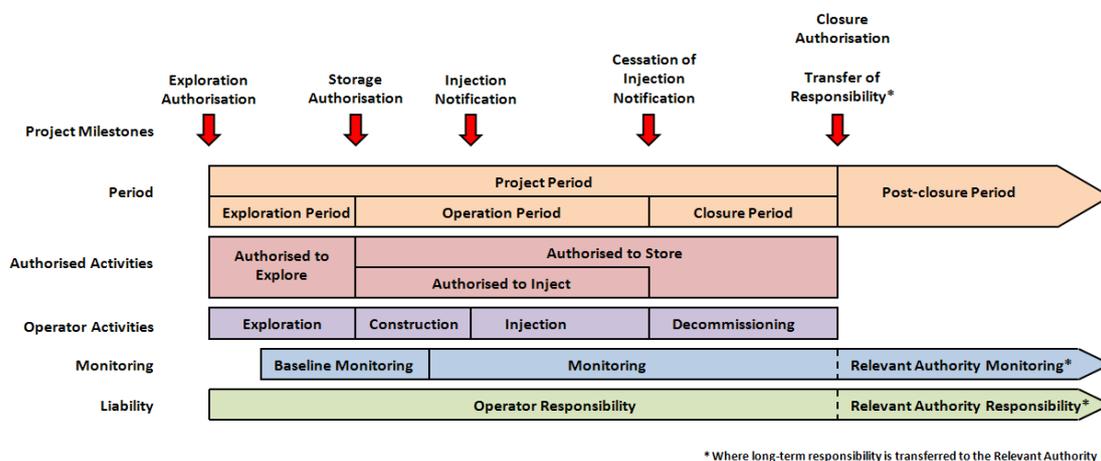
Additional laws protecting international waters are also applicable in some regions, such as the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR). Such conventions may introduce additional requirements and assessments before CO<sub>2</sub> storage can be accepted in a particular region.

### **New laws to cover CO<sub>2</sub> storage**

A number of countries and regions – in Europe, North America and Australia – have now passed laws, which allow CCS to become operational - provided that important

safety measures are in place. The key stages in regulating a CO<sub>2</sub> storage project are illustrated in Figure 1. This shows that there are four key stages: exploration (seeking and characterising a potential geological formation suitable for CO<sub>2</sub> storage); operation (during which CO<sub>2</sub> is injected); closure (when injection ceases and the injection well is permanently sealed); and post-closure (when monitoring continues for several years). In many countries, an exploration license will be required separately from an operational license. In nearly all of these jurisdictions, the operator is the party responsible and therefore liable for the capture, transport and storage stages during the operational period. After operations cease, financial requirements are usually placed on the responsible party who will then be liable for any costs arising during a post-operational period, usually between 15 and 50 years. Beyond this point, a national authority is designated as the responsible party under all legal frameworks.

Figure One: The Stages of a CCS Project



Source: IEA (2010), *Carbon Capture and Storage: Model Regulatory Framework*, OECD/IEA, Paris

## Europe

The European Union passed a Directive on CCS in 2009. The provisions of a European Directive have to be implemented into the national laws of the 27 countries, which comprise the European Union. The Directive mainly governs onshore and offshore CO<sub>2</sub> storage – initial exploration of rock formations, injection tests, long-term operations, monitoring, and the post-closure period – while a few provisions cover capture and transport. With the passage of the CCS Directive, critical legal barriers and possible obstacles to CCS operations contained in other Directives were addressed. For instance, CO<sub>2</sub> might otherwise have been regulated as an industrial pollutant under the Environmental Liability Directive, making transport of large volumes across state boundaries more complicated.

Under the new CCS Directive, any operators wishing to undertake storage in rock formations need to apply for and obtain a permit. They must show that they have made a careful site selection; that a wide range of risks has been assessed prior to injection; that the risks assessed are regularly updated with new information; and

that a comprehensive monitoring plan is in place to manage this process. If any CO<sub>2</sub> should leak out of the geological storage complex (which includes all the layers of rock, salt and mud that act as barriers to the movement of CO<sub>2</sub> out of the rock formation) and into the atmosphere or ocean, the operator is required to purchase an equivalent amount of CO<sub>2</sub> emission allowances from the so-called EU Emissions Trading Scheme (EU-ETS). The EU-ETS is the EU's CO<sub>2</sub> allowance market that currently applies to over 12,000 industrial installations with a substantial heat or power usage. These operators are required to purchase sufficient allowances at the market price to cover their annual CO<sub>2</sub> emissions. A revision to the EU-ETS in 2008 enabled CO<sub>2</sub> storage operators to make their CO<sub>2</sub> emission allowances - equivalent to the quantity of permanently stored CO<sub>2</sub> - available within the EU carbon market, as a way of offsetting CO<sub>2</sub> emissions elsewhere against CO<sub>2</sub> stored permanently underground.

Once operations at a storage site have ceased, the Directive requires that the operator monitor the site. Should there be any evidence of CO<sub>2</sub> leaking from a site during this post-closure period, the operator must address the leakage and pay for any leaked CO<sub>2</sub> through the EU-ETS. This requirement will go on for a minimum of twenty years. Provided the storage site is considered safe, a designated national authority (usually a country's environment agency) will then take over responsibility for managing the site. The operator will pay for the costs of monitoring the site (and fixing any problems that arise) for thirty years after it has been handed over to the national authority. A number of financial instruments have been proposed as evidence of sufficient funds to cover any liabilities that arise during this period. However, the exact amount, payment schedule, and whether operators will be required to pool their funds as is generally the case with environmental liability legislation in the EU, has yet to be decided.

All EU Member States were obliged to adopt national legislation implementing the CCS Directive by June 2011. At the time of writing (February 2013), at least 10 Member States have yet to comply. Until they do, industrial CCS operations will not be permitted in these countries.

### Australia

In Australia, onshore and offshore CO<sub>2</sub> storage is governed by a mixture of federal and state legislation. This builds upon existing petroleum legislation but also includes project-specific legislation. Different approaches to long-term liability between the states have arisen (either transferring liability to a government authority or having it remain with the operator).

### North America

CO<sub>2</sub> injection and storage in deep aquifers in the USA is ultimately regulated by the federal Environmental Protection Agency (EPA), and falls under the so-called Safe Drinking Water Act. This act covers the safe extraction and consumption of drinking water from below ground and storage of CO<sub>2</sub> has therefore been viewed as

incidental to this objective. As in Europe, the USA has decided not to regulate storage under existing provisions – which are generally aimed at safeguarding drinking water from radioactive and chemical wastes – and therefore introduced a new type of injection well (Class VI) specifically for CCS operations. This move also aims to de-classify CO<sub>2</sub> as a hazardous waste. In the case of CO<sub>2</sub> injection into formations containing oil, the existing legal provisions controlling EOR are followed. Since EOR operations have not conventionally been used for the purpose of long-term CO<sub>2</sub> storage, some revisions of the existing laws are probably required, e.g. to ensure that adequate measurement and monitoring of the injected CO<sub>2</sub> is undertaken. Individual states in the USA have also introduced their own laws to regulate CO<sub>2</sub> storage and this has resulted in a patchwork of, sometimes, overlapping legislative initiatives. For instance, while the federal EPA has established a 50-year ‘long-term stewardship period’, and has yet to define financial requirements, some states have introduced a shorter operator liability period, as well as well-defined financial requirements to permit site transfer to a state authority.

In the Canadian province of Alberta, upon certified site closure, ownership of stored CO<sub>2</sub> is vested in the state, which assumes all long-term liabilities (provided all regulations have been correctly followed by the operator). A financial contribution by the operator to a post-closure stewardship fund is also required to enable the province’s government to cover the costs associated with the transfer (liability as well as monitoring and management of facilities). The Canadian province of Saskatchewan has also introduced legislation to regulate CO<sub>2</sub> transport and storage.

### Other Parts of the World

Governments, industry operators and researchers in other countries have started the process of evaluating the legal framework surrounding CCS projects, including in South Africa, South Korea, China, Malaysia, UAE, Qatar, Japan, Brazil, Indonesia and India. The speed at which a legal framework will emerge is likely to depend on project development, both at the national level and internationally. In Japan, for example, plans for a trial CO<sub>2</sub> injection into a rock formation below the seabed are stimulating the development of the legal framework covering such injection.

### Unresolved Issues

Several other issues arising from CO<sub>2</sub> storage with possible legal implications have been raised by researchers and industry and have yet to be resolved through legislation. These include but are not limited to:

- pressure effects on nearby fossil fuel extraction operations as a result of CO<sub>2</sub> injection;
- pressure effects resulting in possible seismic activity far beyond the CO<sub>2</sub> injection point;
- the possible impact of CO<sub>2</sub> injection on the displacement of oxygen-depleted brine water, which is forced out of the rock and could work its way into sea water;

- insurance schemes for CCS operations with substantial operational liabilities.

### **New laws to cover CO<sub>2</sub> capture**

Generally, existing legal arrangements covering power plants can be applied to power plants with CO<sub>2</sub> capture. There are, however, some issues that need further legal development.

### Carbon Capture Readiness

As well as covering CO<sub>2</sub> storage, the EU Directive on CCS also establishes what is called a 'carbon capture readiness requirement' for all new combustion plants with a rated electrical output of at least 300 Megawatts. This means that consent to build new power plants burning coal, gas or wood is subject to an assessment of the technical and economic feasibility of retrofitting CCS in the future, when the technology is proven. If such assessment is satisfactory, sufficient space must be left available at the site for CO<sub>2</sub> capture and compression equipment (and pipelines for onward transport of the CO<sub>2</sub>) to be installed.

### CO<sub>2</sub> Emissions Performance Standard (EPS)

In some countries and states a 'CO<sub>2</sub> emissions performance standard' (EPS) has been established in law. An EPS limits the amount of CO<sub>2</sub> that may be emitted from a power plant per unit of electricity generation. In the USA, Japan and the EU, EPSs for sulphur dioxide and nitrous oxides have been operational since the 1970s and 1980s. The first EPS for CO<sub>2</sub> was introduced in California in 2007 where the allowable average emissions are just below 500g CO<sub>2</sub> per kilowatt hour (kWh) of electricity. This level is higher than the average emissions rate of a natural gas-fired power plant (a so-called 'combined cycle gas turbine' (CCGT) plant). This means that while a new gas-fired power plant can be built and operated in California without CO<sub>2</sub> capture, a new coal-fired power plant cannot (since it has much higher CO<sub>2</sub> emissions of about 750g per kWh of electricity). A new coal-fired power plant would therefore need to have at least some CO<sub>2</sub> capture and storage equipment installed and functioning before it could operate. Similar legislation has since been introduced in the states of Oregon, Washington, and Montana and the EPA is now planning to pass a federal limit, also just below 500g CO<sub>2</sub> per kWh. Other countries and states are also considering introducing a CO<sub>2</sub> EPS, e.g. the UK and the Canadian province of Alberta.

### **Transport**

Existing pipeline transport of CO<sub>2</sub> in the USA and Norway has been undertaken under existing legal controls in those countries. In many other countries and regions the legal situation is less clear. For example, there are no explicit regulations within the EU that regulate the transport of CO<sub>2</sub> via pipeline. This means that Member States may pass standards separately from one another, further complicating the legal situation for transboundary CO<sub>2</sub> transport, which still remains to be clarified under related international conventions.

As a general rule, regulation of CO<sub>2</sub> transport can draw on experience of piping hydrocarbons. This holds true for both point-to-point pipelines and more complex 'hub-and-spoke' pipeline arrangements with shared use of the infrastructure. Minor modifications in existing laws for CCS are likely to be required. In the UK, for example, the Pipeline Safety Regulations are being revised to incorporate safety standards for CO<sub>2</sub> pipelines. New comprehensive standards are under development by organisations such as Det Norske Veritas (DNV).

### **Further Reading**

IEA (2011) CCS Legal & Regulatory Review

For two years running the IEA has published an updated document on the state of legal developments across a number of jurisdictions.

IEA (2010), Carbon Capture and Storage: Model Regulatory Framework

The IEA has analysed several legal issues and best practices discussed here, across a number of jurisdictions, with a view towards supporting development of a bespoke legal and regulatory framework. However, it is important to note that individual jurisdictions will likely modify such tailor-made frameworks to fit their interests and concerns.

IEA GHG 2006/02	Safe Storage of CO <sub>2</sub>
IEA GHG 2006/03	Permitting Issues for CO <sub>2</sub> Capture and Geological Storage
IEA GHG 2011/11	Potential Impacts on Groundwater Resources of Geological Storage

University College London's Carbon Capture Legal Programme (now maintained by the Global CCS Institute):

<http://www.globalccsinstitute.com/networks/cclp>

The CCLP site has a comprehensive list of regularly updated 'legal resources' with coverage of CCS related bills and legislation from around the world.

Authors: Ben Evar and Simon Shackley

## Briefing note 13

### What does the public think about carbon dioxide capture and storage?

#### Introduction

Carbon dioxide capture and storage (CCS) is a technology with the potential to be an essential part of the solution to mitigate climate change. In order to develop the technology and deploy it in time to reduce greenhouse gases to a level that avoids dangerous effects of climate change, many more CCS facilities will need to be constructed. It has been estimated that 100 large projects will be required by 2020 and 3,400 large projects by 2050. This massive scaling-up of activity brings with it technological challenges.

The public plays an equally important role in ensuring the widespread deployment of CCS. Public opposition to nuclear energy and wind energy has been well documented and has limited the deployment of these technologies. Until now, the pace of CCS has been slow, due in part to public opposition to the technology in countries including the Netherlands, Germany and the USA. A small number of proposed projects and facilities have been cancelled or have gone ahead in a much reduced form due to local public opposition.

There is thus increasing recognition that public understanding and perceptions of CCS will directly affect the deployment of the technology.

#### What is the public?

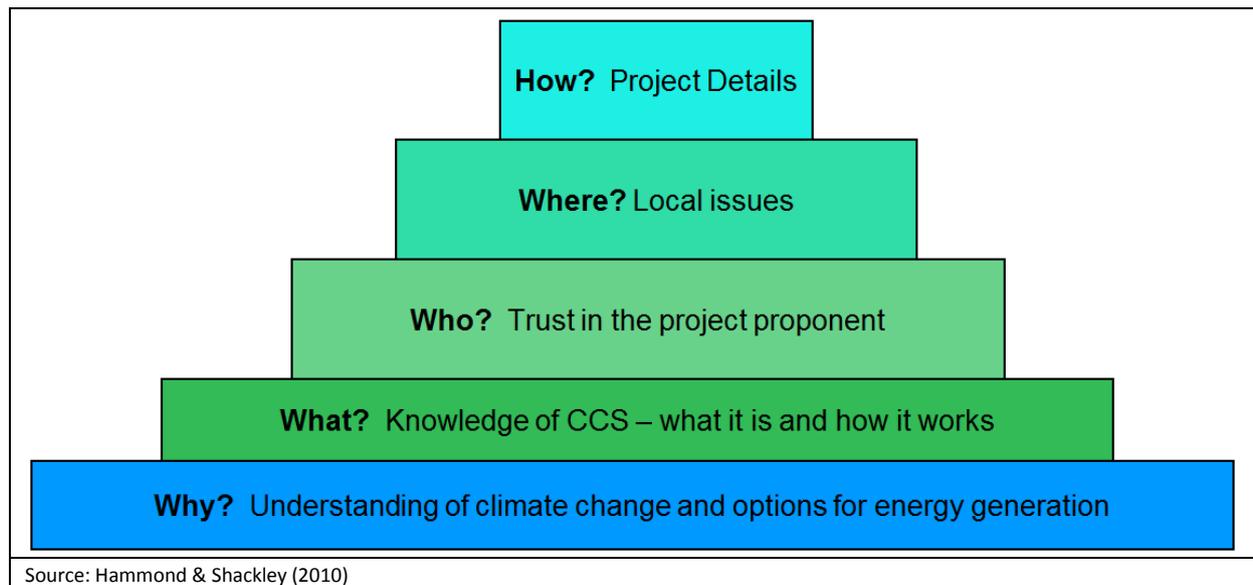
Every person in society is a member of the public. However, the public is made up of lots of different groups, all of which vary according to location, culture, education, income and historical background. In other words, it is important to understand that the public is not a single entity, and to recognise these differences when thinking about how “the public” views CCS. Different people may well have different views on CCS depending on their life circumstances and history. Of course, people’s views and opinions can themselves change over time as the political, economic and social background evolves.

Carbon dioxide capture and storage (CCS) consists of three basic steps: (1) the selective capture of the CO<sub>2</sub> resulting from the burning of fossil fuels such as coal, oil and gas (and biomass); (2) the compression and transportation of the captured CO<sub>2</sub>; and, (3) the injection of the CO<sub>2</sub> into rock formations hundreds of meters below the Earth's surface where it can be securely stored for hundreds of thousands of years. CCS is a vital tool in reducing global carbon emissions as it is the only technology available which can 'decarbonise' burning fossil fuels to generate electricity and heat, as well as allowing major industrial sectors manufacturing steel, cement and many other products to be decarbonised.

#### The public and CCS

There are five major questions that the public generally ask in relation to CCS (Figure 1). Not every person will require an answer to every question in order to form their opinion on CCS, but it is likely that all questions will be asked. It is therefore necessary for CCS advocates to be able to have a discussion about every step of this pyramid with the public.

Figure 1: Steps towards public acceptance of CCS projects



### Understanding and knowledge

A large number of studies have been undertaken which endeavour to measure public understanding and perceptions of CCS. This work reveals that in general the public has limited knowledge of CCS, and limited understanding of both the climate change and energy context that supports the need for CCS. This is not surprising as CCS is a new emerging technology that has yet to be fully deployed anywhere in the world.

There are a lot of misconceptions among the public with regards to carbon dioxide (CO<sub>2</sub>) and CCS. For instance, some people incorrectly believe that CO<sub>2</sub> is flammable and toxic, while others confuse CO<sub>2</sub> with ozone, and climate change with the hole in the ozone layer. People also frequently wonder if the risks they have heard about in negative media reports about other energy technologies like nuclear power and hydraulic fracturing (also known as “fracking”) for gas pertain to CCS as well.

Furthermore, studies have shown that some sections of the public do not accept the scientific consensus around human-induced climate change and are sceptical about the impact of humankind on the climate. Subsequently, as CCS is mostly promoted as a way of achieving deep cuts in carbon emissions to avoid the worst impacts of climate change, these people do not see a need for CCS.

It is therefore vital to clearly explain the context and rationale for CCS as well as how the technology works (Figure 2).

*Figure 2: Members of the public learn about climate change at an event in Edinburgh, UK*



Source: © Simon Shackley, University of Edinburgh

### Trust

The trust that the public has, or does not have, in industry, government and science to deliver a CCS project is very important. The technical and scientific detail and uncertainty surrounding a new technological innovation like CCS often makes it very hard for the public to understand fully. As such, the public needs to feel that the people that do claim to understand the science and technology can be relied on to make safe, fair and ethical decisions on behalf of society as a whole. The perceived trustworthiness, accountability and competence of both individuals and the organisations (companies, government departments, agencies, environmental groups, universities, and so on) will therefore have a large influence upon public perceptions.

This is not to imply that potential hazards and risks of environmental and health and safety impacts are not of concern to the public. It does suggest, however, that the sense of empowerment enjoyed by a community – that is, the degree to which it has a “voice” which is heard by the powerful (“those in charge”) – has a strong influence over its willingness to embrace unknown technologies.

Trust can be felt “in” an individual, organisation or a process (i.e. trust in their honesty, integrity or impartiality) and towards their ability “to do” (i.e. trust in their competence). Both forms of trust are necessary to ensure public acceptance of CCS.

In particular, the public must trust the institutions involved in CCS to:

- deliver truthful information and a safe project;
- operate a transparent and fair decision-making process;

- be accountable should things go wrong; and,
- treat local people fairly in the distribution of costs and benefits, be they environmental, social or economic.

Trust is arrived at through a history of “good behaviour” which includes honesty and putting the public interest before those of profit and self-interest; as well as perceptions of fairness and accountability. There is evidence to suggest that communities who feel they have been treated unfairly in the past are less likely to accept new developments like CCS in their area. Trust also contributes to other factors, most notably the credibility of information and evidence provided by the person presenting it. The quality of information provided can be of limited consequence if the public does not trust the person or institution delivering it. Trust, fairness and accountability should things go wrong are all important, connected variables.

The relationships that exist between the proponents of a CCS project (the developer or government agency) and the individuals or communities are thus key to public opinion. Evidence suggests that the public often place more trust in academia and non-governmental organisations (NGOs) than in government and industry. This is often explained by the implied motivations of the respective groups, with industry’s stake in the successful deployment of CCS, while NGOs are perceived as caring about addressing climate change and academia is seen as a reputable source of scientific fact.

#### Local issues

The benefits of CCS are widely distributed (globally for climate change mitigation) but the costs in terms of risks can be perceived as being concentrated over a small area. Those who live close to the development may feel that they have to bear the brunt of the environmental and social costs. Public opinion is therefore especially important in communities local to proposed CCS projects. Locations and communities differ greatly, even within a small geographic area, and the “social fit” of a project in its local context can be an important indicator of potential public acceptance or opposition.

Factors that will influence local feeling include: local relationships (historic and contemporary) with the fossil fuel and energy industries; the suitability of the project to the character of a place (e.g. rural idyll or industrial town); reactions to other recent infrastructural developments; and the fit with the needs of the local economy (including potential new jobs and any compensation which might be part-and-parcel of a development).

Resistance to a project could be high when the development is perceived to threaten the local area. Hence, if a new industrial-type development is planned in a rural area, some resistance could be anticipated, though in an area of very low population density infrastructural development is sometimes welcomed. Conversely, support could be more forthcoming in an area with a strong industrial heritage, perhaps especially with the power generation, coal, gas and oil sectors.

Likewise, local relationships to the proponents of the particular project could be a major determining factor. For instance, the public may turn against the project if it is supported by

an unpopular local or regional political figure. On the other hand, public support may increase if the development is led by a company or institution with a long history of being a good and trusted employer in the area (Figure 3). It is worth noting that while one or two projects may be accepted in an area, “development fatigue” may set in and a third or fourth project considered to be one too many. If a community feels they have borne an unfair proportion of recent developments, there may come a point at which opposition emerges, even if it was not evident initially.

#### Benefits & risks

Finally, public perceptions of CCS will be informed by an analysis of the perceived benefits and risks of the technology and proposed projects. If a project is perceived to bring with it local benefits then it is likely to be viewed favourably. In contrast, if a project is perceived to carry many risks (be they economic, environmental or technological) then it may be looked upon negatively.

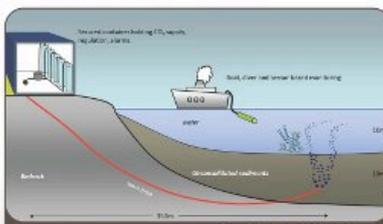
Local benefits are often viewed in economic terms. If the project will bring jobs and investment to an area then there could be support for CCS. The prestige of having cutting-edge technology can also be a draw for communities. On the other hand, if a community feels that they are shouldering all of the risks associated with the project and receiving none of the benefits, they are likely to oppose the project.

Figure 3: Public information poster for the QICS experiment in Oban, Scotland, which was met with broad public support



# World first experiment

## This spring and summer Tralee Bay Holiday Park hosts a cutting-edge scientific experiment that investigates how geological carbon storage may affect the marine environment.



**Experimental design of the QICS project:**

The Ardmuckich Bay CO<sub>2</sub> release study is led by scientists from SAMS (Scottish Association for Marine Science), who are partners of the larger QICS project (Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage). QICS is a four-year scientific research project involving UK partners and collaborating institutions from Japan and coordinated by Plymouth Marine Laboratory. The QICS project is funded by the Research Councils of the UK and further supported by the Scottish Government. Its purpose is to improve understanding of the sensitivities of the UK marine environment to a potential leak from a CCS system and to develop appropriate technologies to monitor the marine environment for leakage. The project, which commenced in June 2010, will provide information for regulators, industry, NGOs and the public alike.



SAMS divers will visit the release site as part of regular monitoring.

**QA What are we doing?**

We are carrying out an experiment to investigate what happens if there is a carbon dioxide (CO<sub>2</sub>) leak from a carbon capture and storage (CCS) reservoir into the marine environment. We are introducing small amounts of CO<sub>2</sub> into the sediment in a carefully controlled way, in order to measure how it moves through sediments and whether it affects marine life, and to be prepared for any unintentional leaks in the future. The results of this experiment will be of use to many future large scale CCS projects throughout the world. This is the first time such an experiment has been carried out – it is unique.

**QA Why do we need to know this?**

We know that climate change is real and is caused by increasing amounts of atmospheric CO<sub>2</sub> from industrial processes being added to the atmosphere, as a result of some human activities which use fossil fuels. We need to find ways of reducing their use through other energy sources, and by finding ways to capture CO<sub>2</sub> before it reaches the atmosphere. Carbon capture and storage (CCS), where CO<sub>2</sub> is collected at source, transported through pipelines to a suitable site and then stored deep underground in geological strata, is one such method that has much support worldwide.

**QA How do we know that it works?**

There are already several CCS projects in operation around the world, including the Statoil run Sleipner site in the North Sea. This has been storing 1 million tonnes of CO<sub>2</sub> each year for the last decade and pumping it back into an empty oil well.

**QA What's going to happen in Ardmuckich Bay?**

In order to best mimic a potential CCS leak we need to release CO<sub>2</sub> below the seabed. Drilling a borehole from land and inserting a stainless steel pipe (20mm in diameter) allows us to inject CO<sub>2</sub> directly into the sediment, without disturbing the sedimentary structures above. A specialist drilling company (Allen Watson Ltd), were engaged to drill through solid rock to a spot 10 metres below the seabed about 350 metres offshore – the release point. The release begins in mid-May this year and CO<sub>2</sub> will be released at a rate equal to a few hundred people's daily exhalation, for a 30 day period and then turned off. Monitoring will continue for a further 90 days to study the recovery of the environment.

**QA What will the experiment tell us?**

We know that CO<sub>2</sub> is a natural component of seawater and is a very important factor in determining the suitability of seawater for life. The amount of CO<sub>2</sub> controls the acidity or alkalinity (pH) of seawater as well as the concentration of compounds called bicarbonate and carbonate which are used by many sea creatures to form their shells

**QA Why in Ardmuckich Bay?**

The bay has suitable sediment types, typical sea life, underlying rocks suitable for drilling and good access from nearby land. Additionally it is close to the Scottish Association for Marine Science (SAMS) who are overseeing this part of the project and providing the boats and dive team that will carry out a lot of the monitoring and observation work. After the site was selected we consulted widely including with The Crown Estate and Marine Scotland, who grant permissions for such activities, as well as with Scottish Natural Heritage, Scottish Environmental Protection Agency and local landowners. The local community will be kept informed of developments as the experiment progresses and we welcome further questions about the project.

**QA What will the experiment do to the Bay?**

We expect small, temporary impacts on marine life in the restricted area where the experiment is taking place, which is likely to be around 10m in diameter. Most species will simply move away if they feel any discomfort, which is part of what we are going to observe, but it's the microbes that really interest us and that we will be monitoring closely. We are certain that there will be no long term effects on the wildlife of the bay, so the quality of fishing will not be affected.

**QA Is it dangerous?**

In high concentrations (e.g. in confined spaces) CO<sub>2</sub> can be dangerous, but the experiment here in the bay is using small amounts, under carefully controlled conditions. The only reason we are asking recreational users to keep away from the marked area of the experimental site is to avoid disturbing the monitoring equipment moored to the seabed.

**QA What happens when the experiment is finished?**

At the conclusion of the experiment all equipment will be removed from both the land site and from the seabed, leaving only the landward opening of the narrow pipe beneath a small and secure manhole cover.

**We would like to thank you for your cooperation in helping to make this experiment a success.**

# Thank you!

The site will be visited regularly by QICS scientists, who will be happy to answer any further questions you may have.

More information can be found on these websites:  
[www.smi.ac.uk/henrik-stahl/qics](http://www.smi.ac.uk/henrik-stahl/qics)  
[www.bgs.ac.uk/qics/home.html](http://www.bgs.ac.uk/qics/home.html)

The experiment progress blog is available at:  
[www.facebook.com/groups/13657263117394/](http://www.facebook.com/groups/13657263117394/)

The local lead scientist at the Scottish Association for Marine Science (SAMS) is:  
**Dr Henrik Stahl**  
 E: henrik.stahl@sams.ac.uk  
 T: 01631 559 000

Project lead scientist is:  
**Dr Jerry Blackford**  
 E: jrb@pml.ac.uk



Source: © SAMS and PML, QICS project

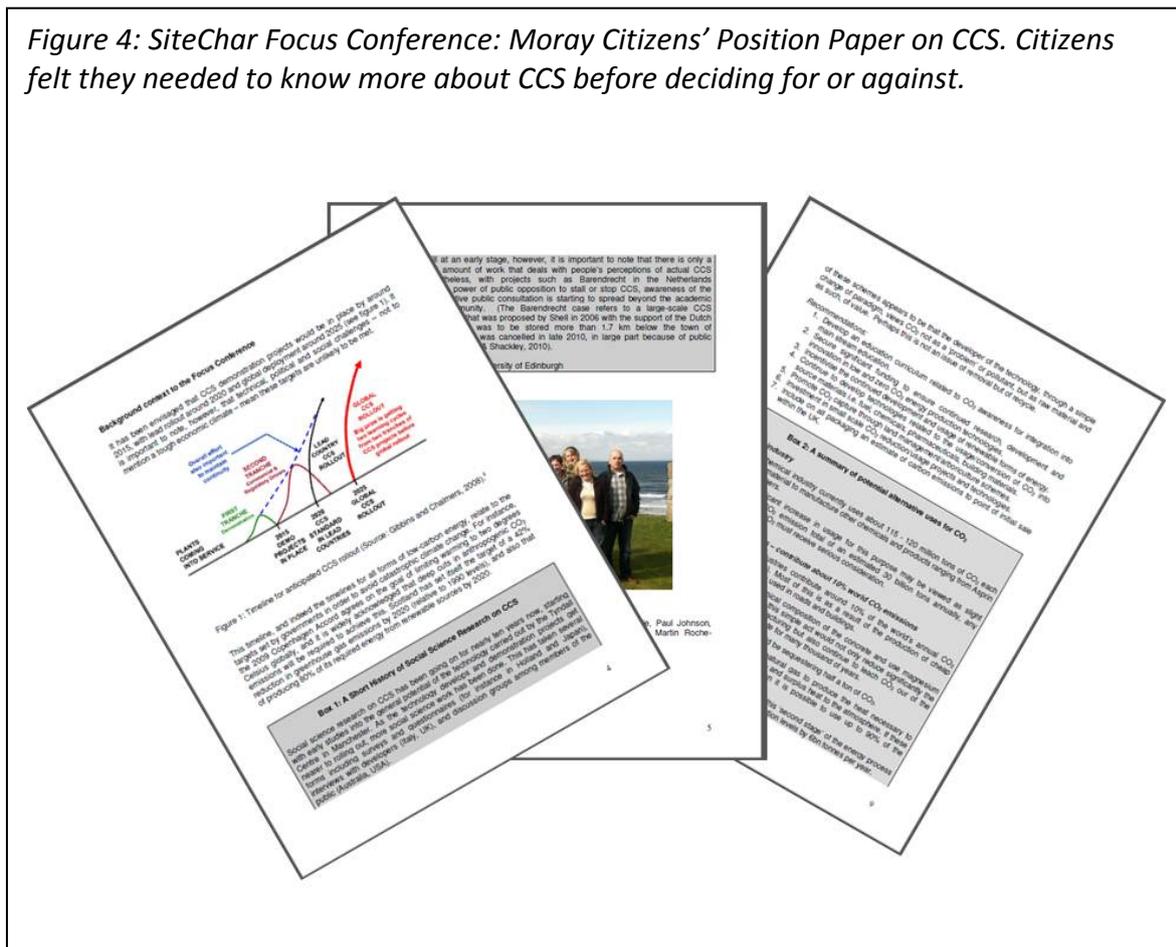
## Public Support

The findings of international research into public opinion of CCS can be crudely summarised as “reluctant acceptance” of the technology rather than “enthusiastic support”. These opinions have, however, been demonstrated to be constantly changing and context-dependent. This is partly because respondents generally know very little about CCS and therefore cannot give an informed answer on something they know little about. It is also

because people’s opinions about CCS as a general concept are often different to their perceptions when faced with the development of an actual CCS project near to them.

Studies using a range of methods in some countries (e.g. Australia and Canada) tend to show that public perceptions turn somewhat more positive as people are provided with more technical information when accompanied with explanations from expert stakeholders. In other countries (e.g. Scotland and the Netherlands), the pattern is not so clear, with some research supporting the above, but other research suggesting that the provision of more information led to somewhat lower acceptance of CCS. Allowing people to interact informally with experts and creating an atmosphere where members of the public feel free to ask anything, no matter how irrational it may seem to them, has also been shown to have positive effects on public perception. Situating CCS in the relevant context by thoroughly explaining the link with climate change and the available policy options for carbon abatement, appears in some (but again not all) research to shift perceptions in a positive direction. For example, in a context where renewable energy deployment has been very successful, CCS might not be regarded as favourably as in a context where other low-carbon energy options are less well progressed (Figure 4). Whenever members of the public participate in in-depth discussions on CCS, the resulting perceptions are more informed, but will, by definition, not then be representative of ‘public opinion’ at large.

*Figure 4: SiteChar Focus Conference: Moray Citizens’ Position Paper on CCS. Citizens felt they needed to know more about CCS before deciding for or against.*



Further analysis of this research reveals the most common concerns that the public can have about CCS. These are summarised in Table 1.

*Table 1: Common public concerns*

<b>Issue</b>	<b>Concerns</b>
Leakage of CO <sub>2</sub> from geological storage sites and pipelines	<p>The public are often concerned about the safety of storage. This may in part stem from a lack of understanding of how the CO<sub>2</sub> will be stored in rock formations, and a lack of trust in those operating CCS projects. Recent high-profile events such as the Fukushima nuclear incident in Japan and “fracking” episodes in the USA and UK can also lead the public to question how much we really know about the ground under us, and industry’s ability to operate safely.</p> <p>Concern over the risks of leakage in terms of explosions, health and safety impacts on local populations, and the impacts on ground water, plants, animals and ecosystems are often cited as reasons against CCS.</p> <p>A further concern is that any CO<sub>2</sub> leakage defeats the purpose of CCS, which is to prevent CO<sub>2</sub> from entering the atmosphere.</p>
Feasibility & Costs	<p>CCS technology is expensive and it is not clear who is going to pay for it. Consumers are wary that the bill will fall to them. Part of these costs is for substantial infrastructure which does not exist today, and there is concern that the technology is not ready yet. There is also concern as to whether there is enough storage capacity.</p>
Trust and Confidence	<p>The motivations of industry and politicians involved in CCS are often not trusted, with particular misgivings about industry being allowed to profit from this. The perception that companies’ profits are rising despite higher energy prices serves only to reinforce these misgivings. Trust in companies, governments and scientists who state that CCS is safe is often lacking. There is also a question over long-term liability and responsibility for the storage of CO<sub>2</sub>.</p>
Local Issues	<p>Issues such as the impacts on water consumption/availability, visual disturbances, land-use rights, decommissioning and monitoring can be important to communities.</p>
Avoids tackling the ‘real issue’	<p>There is a concern among some sections of the public that CCS allows the unsustainable use of fossil fuels to continue into the future. At the same time CCS could deter investment in, and policy attention directed towards, renewable energy development, energy efficiency and reducing energy demand, which many people see as key to a genuinely sustainable future energy system.</p>
Moral issues	<p>Are we “playing God”? Novel technologies like CCS are sometimes viewed as interfering with nature. Storing CO<sub>2</sub> in the ground can also be seen as leaving an unwanted legacy for future generations.</p>
A use for CO <sub>2</sub> ?	<p>The idea of treating CO<sub>2</sub> as a waste product and storing it permanently</p>

	underground can concern some people who would prefer it to be made use of in such a way that it comes to have a value.
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## **Public engagement**

It is necessary to engage with the public on CCS in order to enable people to make better informed judgements about the technology. Engagement is the process of having an informed, two-way discussion as to whether a CCS project is appropriate in a particular locality and context, and is concerned with making better decisions and legitimising the decision-making process.

Right at the start of the CCS site selection process, the environmental and technical characteristics of potential sites will be thoroughly explored. However, just as limitations in infrastructure or geology can make a project in a particular area unviable, so too can a social context that is unlikely to be supportive of CCS. It is therefore crucial to build a good understanding of the social characteristics of potential CCS sites right at the start of the development, in order to gauge likely support and identify possible areas of concern. This process is known as social site characterisation.

Social site characterisation has been carried out in recent years in many countries including Australia, USA, Poland and the UK. It aims to develop a full and thorough understanding of the social characteristics of the area in which a CCS project will operate. The kinds of things that social site characterisation looks at include: the history of fossil fuels and/or extractive industry in the area; the economic and employment situation; who the key stakeholders are and what motivates them; the demographic and social profile of the communities local to the development; what the key issues in the area are; and which individuals and/or organisations the public and local communities trust to convey messages to them.

Social site characterisation can be done in a number of ways depending on what the researchers want to find out. For example, existing data and statistics can be collated, local residents could be surveyed, key stakeholders and community leaders could be interviewed, a discussion group or a 'town meeting' could be held to find out how local people and stakeholders feel about low carbon energy. The results of the social site characterisation then feed back into the engagement strategy, helping to identify key stakeholders that need to be consulted and listened-to, for example regarding the kinds of messages that need to be communicated.

Nonetheless, successful public engagement is not a guarantee that every project will go ahead. Projects may be rejected by the public even if they are technically viable, so establishing if this is likely to be the case early on would greatly speed up the search for a suitable project site. However, if the reasons for a CCS project are sound, the plans carefully laid, and social conditions favourable, a good engagement strategy should greatly increase the chances of acceptance. In contrast, CCS project development which lacks effective public communications and engagement could suffer from public opposition.

## **Summary**

Public perceptions of CCS are crucial as the public has the power to both facilitate and to block the deployment of CCS projects. At present, public understanding of CCS is characterised by misconceptions and lack of knowledge of the technology and its rationale. Public engagement and education should be pursued to overcome this and allow for more informed decision-making on the part of the public. Developers must also be careful to listen to what the public actually thinks about CCS and act accordingly, rather than attempting to second guess what the public's concerns might be.

### **Further Reading**

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Wade S and Greenberg S (2011) *Social Site Characterisation: From Concept to Application* AJW: Washington DC.

Authors: Leslie Mabon, Rhys Howell and Simon Shackley





	and Geological Storage								
2006/04	International Oxy-Combustion Network for CO <sub>2</sub> Capture: Report on Inaugural Workshop								
2006/05	Launch Meeting of the Risk Assessment Network								





















