Evaluating technology options to mitigate greenhouse gas emissions

ieaghgoverviews 2013

Published by:

IEA Greenhouse Gas R&D Programme
Pure Offices
Cheltenham Office Park
Hatherley Lane
Cheltenham
Glos.
GL51 6SH

Printed by: CLK Media

Disclaimer

The overviews reported in this publication were prepared as an account of work sponsored by the IEA Greenhouse Gas R & D Programme. The views and opinions of the authors expressed herein do not necessarily reflect those of IEA Greenhouse Gas R&D Programme, its members, the International Energy Agency, nor any employee or persons acting on behalf of any of them. In addition, none of these make any warranty, expressed or implied, assumes any liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, products or process disclosed or represents that its use would not infringe privately owned rights, including any party's intellectual property rights. Reference herein to any commercial product, process, service or trade name, trade mark or manufacturer does not necessarily constitute or imply an endorsement, recommendation or any favouring of such products.

Date Published: 2014
Review compiled and designed by Becky Kemp.

Contents

Background

The IEA Greenhouse Gas R&D Programme (IEAGHG) hold a primary remit to act as an informed source of impartial information on greenhouse gas mitigation options, and this is achieved by the instigation and management of research studies and technological evaluations, and the establishment and maintenance of a growing series of international research networks. The reports from these studies and networks form the core of information available to IEAGHG members on an ongoing basis.

Each technical study will include a short overview prepared by the respective IEAGHG staff member responsible for the management of the study, and each network report incorporates a short executive summary, briefly summising the topics discussed at the meeting, and any significant conclusions or developments.

This book follows up on the success of the second Overview Book produced at the end of 2011. It draws together the overviews and executive summaries written by IEAGHG over the course of 2012, segregating the overviews into their respective category, as directed in the contents, in order to allow IEAGHG members and other readers to quickly identify the reports by subject area, or area of interest at a glance.

This book also serves as a quick reference guide for IEAGHG staff and members to quickly and efficiently pick out previous reports that may be useful or relevant to current activities and studies.

2013-04 UNDERSTANDING THE TECHNO-ECONOMICS OF DEPLOYING CO_2 CAPTURE TECHNOLOGIES IN AN INTEGRATED STEEL MILL

Key Messages

The global steel industry has made significant investment in reducing CO_2 emissions mostly by raising their energy efficiency. However, to achieve a reduction of the direct CO_2 emissions per tonne of steel produced from BF-BOF route by greater than 50%, CO_2 capture and storage is required.

Development of breakthrough technology such as oxy-blast furnace (OBF) is currently on-going within the steel industry but will require large scale demonstration to validate engineering design and optimisation of the process. This study presented one of the several options that could be employed for a steel mill with OBF and CO_2 Capture.

Deployment of post-combustion capture technology, capturing CO_2 from various sources of flue gases within the integrated steel mill is technically possible and could be readily retrofitted to an existing steel mill. However, this study has demonstrated that this option could have significant costs implications on steel production which could affect the commercial viability of the steel plants fitted with CCS.

The steel industry is a globally competitive industry and hence they will be reluctant to introduce cost disadvantages like adding CCS without some global agreement on emissions reduction.

Background

The iron and steel industry is one of the largest industrial sources of CO_2. Globally, it accounts for about 6% of anthropogenic CO_2 emissions (approx. 1.2 Gt CO_2/year). Currently, two main processes dominate global steel production:

- the integrated steel mill in which steel is made by reducing iron ore in a blast furnace and subsequent processing in a primary steelmaking plant (BF-BOF Route); and
- the mini-mill in which steel is made by melting scrap steel or scrap substitutes in an electric arc furnace (EAF Route).

In 2011, around 1.5 billion tonnes of crude steel are produced worldwide. Roughly, ~69% of the steel produced are from BF-BOF steelmaking route; and ~29% of the steel produced are from recycled scrap using EAF steelmaking route. Currently, China is responsible for nearly 45% of the steel produced worldwide. Alternative iron and steel making processes based on direct or smelting reduction technologies - such as COREX, FINEX, DRI, Midrex and many others - are also used to produce steel in various sites worldwide. Several of these technologies are commercially proven; however, they only account for a small share of steel produced globally. It is expected that steel production via BF-BOF and EAF routes would still dominate steel production in several decades to come.

To reduce CO_2 emissions from steel mills, one of the leading options being considered by iron and steel stakeholders is CCS. Development of this technology for application in iron and steel production is still on-going (i.e. ULCOS project, World's Steel CO_2 Breakthrough Programme, etc…).

This project, by IEAGHG in collaboration with Swerea MEFOS AB was developed with co-funding support from Swedish Energy Agency, SSAB, LKAB and Swerea MEFOS member companies. The project was initiated in January 2010. This was managed by a Steering Committee whose members include representatives from the funding partners. Swerea MEFOS AB led and coordinated this project. Corus Consulting PLC (now TATA Steel Consulting) undertook the cost evaluation and financial modelling; SINTEF Materials and Chemistry undertook the evaluation of post-combustion capture CO_2 modelling.

Study Description

Objectives of the Study

The primary goal of this project is to establish a methodology to evaluate the cost of steel production when deploying CO_2 capture technology in an integrated steel mill. The objectives of this study were:

- To specify a "REFERENCE" steel mill typical to Western European configuration; and assess the techno-economic performance of the integrated steel mill without and with CO_2 capture.

- To evaluate the techno-economic performance, the breakdown of the CO_2 emissions; and estimating the CO_2 avoidance cost of the following cases:
    - o Case 1: An integrated steel mill typical to Western Europe as the base case.
    - o Case 2: Post-Combustion CO_2 capture using conventional MEA at two different levels of CO_2 capture rate (End of Pipe Cases or EOP)
    - o Case 3: An Oxygen Blown Blast Furnace (OBF) with top gas recycle and the use of MDEA/Pz as solvent for CO_2 capture

Scope of the Study

The scope of the study was to:

- Provide a description of the integrated steel mill,
- Evaluate the performance and economics of steel production without and with CO_2 capture,
- Develop the financial cost model that could be used in future studies and capable of incorporating various site specific conditions of the steel mill,
- Identify key areas of development that could be recommended for future studies.

Study Basis

The technical and economic assessments were based on a new build integrated steel mill situated in the coastal region of Western Europe producing 4 MTPY of HRC using processes that are typical to any average steel mill. The Reference Steel Mill (without CO_2 capture) consists of 12 different major processes and various auxiliaries. Figure 1 schematically presents the battery limit of the steel mill without CO_2 capture representing various input and output of raw materials, product, by-products and waste products.

For an integrated steel mill with CO_2 capture, this study evaluated two possible capture options namely:

1. Steel mill with Post-Combustion Capture using standard MEA solvent for capturing CO_2 from the flue gases of various combustion processes;
2. Steel mill equipped with OBF and using MDEA/Pz solvent for capture of CO_2 from the top gas.

Both technology options for CO_2 capture are considered either as existing technologies that could be deployed in an integrated steel mill with moderate risk; or technologies that are currently being developed and could be deployed in the near future.

Table 1 summarises the battery limit of the integrated steel mill without and with CO_2. This table also presents an overview to the modification made to the integrated steel as compared to the REFERENCE case when CO_2 capture plants were installed.

The cost of HRC production and CO_2 capture were estimated assuming a 10% annual discount rate in constant money values, a 25 year economics plant life, a fixed price input for various raw materials, energy and reductant, fluxes and other consumables. A full list of the economic criteria used in the study is given in the main reports.

Results and Discussion

Steel Production

Steel is predominantly produced from reduction of iron ore or melting of recycled scrap. Hot Rolled Coil (HRC) is one of the several standard products that could be produced from a steel mill. The production of HRC based on integrated steelmaking routes involves various processes which include:

- Raw materials preparation (sinter, coke and lime production),
- Iron making process (hot metal production and desulphurisation),
- Steelmaking process (basic oxygen steelmaking process, ladle metallurgical refining),
- Casting (continuous slab casting),

- Reheating and Rolling (finishing mill).

To support the iron and steel production processes, power plant and air separation units are generally included as part of the integrated steel mill. Typically, surplus off-gases from the steel mill are used by the power or cogeneration plant as fuel to produce electricity or steam (in several cases, hot water is also produced for district heating). The main purpose of the air separation unit is to deliver large amount of oxygen needed by both iron making and steelmaking processes. Other industrial gases such as nitrogen and argon are also used as utility gases for these processes.

CO_2 Capture Technologies for an Integrated Steel Mill – An Overview

CO_2 emissions from an integrated steel mill come from various sources. For the REFERENCE steel mill without CO_2 capture, the top 5 sources of CO_2 emissions are from the flue gases of the hot stoves, power plant, sinter plant, coke ovens' underfired heaters and lime kilns. This consists of ~90% of the total direct CO_2 emissions of the steel mill. The addition of CO_2 capture plant to an integrated steel mill could practically reduce CO_2 emission by 50 to 60%. However, this would consequently increase the steel mill's overall energy consumption (steam, electricity or fuel gases).The study evaluated three different scenarios for deployment of CO_2 capture technologies in a conceptual integrated steel mill.

Two scenarios involved the deployment of post-combustion capture technology using MEA as solvent achieving two level of CO_2 avoidance. For Case 2A (EOP-L1), this involved the capture of CO_2 from flue gases of the hot stoves (Unit 300) and the steam generation plant (Unit 2000). For Case 2B (EOP-L2), additional CO_2 could be captured from flue gases of the coke ovens' underfired heaters (Unit 100) and the lime kilns (Unit 1000).

The third scenario (Case 3) involved the deployment of oxygen blown blast furnace or OBF. CO_2 in the top gas produced by the OBF are captured using MDEA/Pz solvent. The majority of the top gas is recycled back to the shaft of the OBF which should reduce coke consumption of the OBF, compared to the conventional blast furnace.

Post-Combustion Capture Technology

The choice of post-combustion capture technologies (i.e. use of chemical

absorption technology capturing CO_2 from different flue gases within the steel mill) means that there will be no major modifications to the core iron and steel production. The main modification to the steel mill will involve only the addition of:

- Flue gas processing (i.e. deeper SOx and NOx removal, direct contact coolers)
- CO_2 capture plant
  - o absorber and stripper columns,
  - o heat exchangers,
  - o reboiler and
  - o condensers
- CO_2 compressors and dehydration unit

Additionally, to meet the increase energy demand of the CO_2 capture plant, the steel mill would require the expansion of their power plant and steam generation plant to provide additional steam and electricity generation capacity.

Oxy- Blast Furnace (OBF) and CO_2 Capture

The oxy-blast furnace involves the replacement of hot blast with pure oxygen and recycled top gas or OBF process gas (OBF-PG). This process comes with several versions. ULCOS[1] has developed this technology and evaluated three different versions. This is illustrated in the figure overleaf.

In general, the OBF technology involves the removal of CO_2 from the top gas to produce the OBFPG. Part of the OBF-PG (with option to pre-heat or not) are mixed with oxygen and injected at the tuyeres of the blast furnace; whilst another part of the OBF-PG are preheated and injected into the middle shaft of the blast furnace. Another version of this process involves the preheating and recycling of the all the OBF-PG together with cold oxygen into the tuyeres of the furnace.

OBF together with CO_2 capture has several advantages to reduce CO_2 emissions which include:

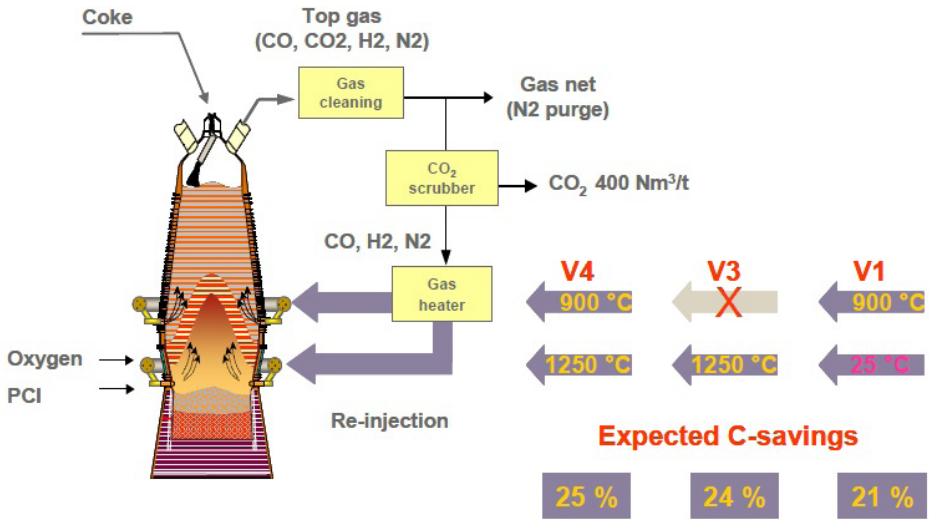
- The top gas with CO_2 removed could be recycled to the blast furnace

[1] ULCOS stands for the Ultra Low CO_2 Steel, it is an EC funded projects of some 20 partners from the steel and associated organisations that have been working on topics related to CO_2 reduction, including CCS in the steel industry since 2010.

which should lower the coke consumption and also reduce direct CO_2 emissions of the coke plant.

- A higher concentration of CO_2 in top gas and smaller volume of gas to be processed (as compared to flue gases) could be expected. This should lower the energy requirements of the CO_2 capture plant.
- Higher pressure of the OBF Top Gas (and higher partial pressure of CO_2) as compared to flue gases should make it feasible to employ several other CO_2 capture technology options. This include but not limited to:
    - o Chemical absorption using solvent such as MDEA/Pz, AMP, etc… which are suitable for high partial pressure of CO_2.
    - o PSA or VPSA
    - o Cryogenic separation.

ULCOS has selected the use of OBFv4 and PSA together with cryogenic separation for their Florange Demonstration Project[2]. It should be noted that the selected OBF version of ULCOS is totally different from the version of OBF presented in study this study which is nearly similar to OBFv1 and it



Different Versions of Oxy-Blast Furnace Configuration Evaluated by ULCOS

[2] Florange Project was submitted to the EC for NER300 application. However, due to technical and commercial reason, their application to the NER300 has not been successful.

varies only to the technology used to capture of CO_2. In this study, the use MDEA/Pz solvent has been selected but it should be noted that this is not recommended as the best available technology; but is used only to serve as an example to evaluate the cost of capturing CO_2 from an integrated steel mill.

Performance of the Integrated Steel Mill with CO_2 Capture – Summary of Results

The overall energy consumption of the steel mill without and with CO_2 capture is summarised in Table 2. From the results, the following could be summarised.

REFERENCE Steel Mill (Case 1)

- For Case 1, REFERNECE Steel Mill (Base Case), would require a net energy input of ~21.27 GJ/t HRC. Around 96% of the energy input (net) to the steel mill is provided by the coking coal and PCI coal. Natural gas is only used by the captive power plant to supplement the energy requirements of the steel mill.
- Also, for the REFERENCE Steel Mill, it was demonstrated that the overall energy consumption could be reduced by improving the efficiency of the power plant that provides the electricity to the steel mill. This is illustrated in various step-off cases showing a reduction of at least 0.85 GJ/t HRC could be possibly achieved (for Case 1B, 1C and 1D).
- It could also be noted that several improvements could still be deployed to increase the energy efficiency of the iron and steel making processes[3]. However, these energy saving measures could be very site specific and mostly dependent on payback period of the CAPEX needed to deploy these technologies.

Steel Mill with Post-Combustion CO_2 Capture (Case 2)

- For Cases 2A and 2B, the overall energy consumption of ~24.64 GJ/t HRC (Case 2A) and ~25.94 GJ/t HRC (Case 2B) were reported respectively. Compared to the REFERENCE Steel Mill (Case 1), the additional energy requirements for both Case 2A and Case 2B are mainly due to the increase

[3] This has been demonstrated from the comments and data provided by ULCOS (as reported in ANNEX 3 of the Report Overview).

in natural gas consumption by the steam generation plant (Unit 2000) and the power plant (Unit 1200).

- Natural gas consumption of the steel mill with CO_2 capture have increased from 0.85 GJ/t HRC (REFERENCE Case) to 4.21 GJ/t HRC (Case 2A) and 5.52 GJ/t HRC (Case 2B). Bulk of the increase is mainly due to the natural gas consumption of the captive power plant providing all of the electricity required by the steel mill. This constitutes to about ~86.5% and ~71.2% of the total natural gas consumed by the steel mill for Case 2A and Case 2B respectively; and the balance of which are consumed by the steam generation plant.
- Electricity demand of the steel mill with CO_2 capture have increased from 400.1 kWh/t HRC (REFERENCE Case) to 572.6 kWh/t HRC (Case 2A) and 621.7 kWh/t HRC (Case 2B). For both cases, the bulk of the increase in electricity demand is mainly due to the electricity demand of the CO_2 capture plant including compression (delivering the CO_2 at 110 bar_a).

Steel Mill with OBF and MDEA CO_2 Capture (Case 3)

- The deployment of OBF has resulted in major modifications to the design and operation of the iron making processes. This includes changes to the coke and sinter production. One of the key changes is the reduced coke consumption of the OBF compared to that of the conventional blast furnace by ~25%. Additionally, the productivity of the blast furnace is expected to increase. Consequently, this reduces the required hearth diameter of the blast furnace from 11 m (for REFERENCE Case) to 8.5 m (for OBF Steel Mill). A more detailed description to the different changes to the steel mill design and operation has been presented in the main report (Vol. 3 Section C).
- For the steel mill with OBF and MDEA/Pz CO_2 capture, the overall energy consumption of ~21.82 GJ/t HRC has been reported. This is an increase of ~0.55 GJ/t HRC compared to the overall energy consumption of the REFERENCE Steel Mill (21.27 GJ/t HRC).
- It could be noted that there is an increase in natural gas consumption from 0.85 GJ/t HRC (REFERENCE Case) to 5.05 GJ/t HRC (Case 3). On the other hand, the reduction in coke consumption of the blast furnace has led to a reduction of coking coal required by the steel mill from 16.29

GJ/t HRC (REFERENCE Case) to 12.43 GJ/t HRC (Case 3). Consequently, the reduction in coking coal consumption has also reduced the coking by-products exported from the steel mill from 0.90 GJ/t HRC (REFERENCE Case) to 0.69 GJ/t HRC (Case 3).

- The bulk of the natural gas consumption is primarily due to the consumption of the power plant (72% of the total), steam generation plant (13%) and the OBF-PG heaters (15%).
- The installation of the OBF, CO_2 capture and recycling of the processed top gas to the blast furnace would involve major changes on how off-gases from the hot metal production are distributed and used within the steel mill. This is illustrated in Table 3 which summarises the gross and net fuel input to the hot metal production.
- The electricity demand of the steel mill with OBF and MDEA CO_2 capture has also increased to 573.4 kWh/t HRC (Case 3) from 400.1 kWh/t HRC (REFERENCE Case). Bulk of the increase is due to the changes to the electricity required by the iron making processes. Table 4 presents the breakdown of the electricity demand for the hot metal production without and with CO_2 capture.
- Improvement to the steam production for the steel mill with OBF and MDEA CO_2 capture were evaluated. Two different step-off cases (Case 3A and 3B) were examined. Both cases involved the use of CHP plant. Case 3A delivers the low pressure steam to the CO_2 capture plant based on a cycle with no steam reheat; whilst Case 3B provide the steam using a cycle with steam reheat. It could be summarised that consumption of natural gas by the steel mill with OBF and MDEA CO_2 capture has been reduced to 4.81GJ/t HRC (for Case 3A) and 4.65 GJ/t HRC (for Case 3B) respectively as compared to the 5.05 GJ/t HRC of natural gas consumed by the OBF Base Case (Case 3).

Overall CO_2 Emissions of the Steel Mill Without and With CO_2 Capture

The breakdown of the CO_2 emissions from the integrated steel mill without and with CO_2 capture is presented in Table 5.

- The CO_2 avoided of 50.1% and 60.3% were reported from the steel mills with post-combustion capture using MEA for Case 2A (EOP-L1) and for

Case 2B (EOP-L2) respectively; whilst CO_2 avoided of 46.5% was reported for the steel mill with OBF/MDEA CO_2 capture (Case 3).

- For the steel mill with OBF/MDEA CO_2 capture, achieving CO_2 avoidance of 46.5% would only need to capture 860 kg CO_2/t HRC; whilst for steel mill with post-combustion capture (Case 2A or EOP-L1), achieving a CO_2 avoidance of 50.1% would need to capture 1243 kg CO_2/t HRC. The lower CO_2 capture rate required for steel mill with OBF/MDEA CO_2 capture (Case 3) is mainly contributed by the lower CO_2 emissions of the coke plant (Unit 300) due to the reduced coke consumption of the OBF as compared to the conventional BF of the REFERENCE Case.
- Additionally, this study also illustrated that by increasing the CO_2 avoidance from 50.1% to 60.3% for steel mills with post-combustion capture using MEA solvent (i.e. EOP-L1 vs. EOP-L2 Cases) would consequently result to an increase in the overall energy consumption of the steel mill of 24.64 and 25.94 GJ/t HRC respectively. Using the overall energy consumption for the REFERENCE Case (i.e. 21.27 GJ/t HRC) as basis, this corresponds to an increase in energy consumption of 3.37 GJ/t HRC to 4.67 GJ/t HRC.

Levelised Cost of Steel Production (Breakeven Price of the HRC Ex-Works)

The breakeven price of the HRC from the Integrated Steel Mill without and with CO_2 capture was evaluated. The total investment cost including recurring CAPEX (Table 6), the annual O&M cost (Table 7), and annual revenues from by-product sales (Table 8). The breakeven price of the HRC reported in this study should represent the levelised cost of HRC delivered at the gate of the steel mill.

The CO_2 avoidance cost is calculated from the difference of the breakeven price of the HRC produced for both steel mills without and with CO_2 capture and divided by the differences of their direct CO_2 emissions (Table 9). It should be noted that CO_2 avoidance cost reported in this study doesn't include the cost of CO_2 transport and storage.

From this study, the following key results could be summarised:

- The study provided a breakdown of the cash flow analysis of the different major processes of the steel mill without and with CO_2 capture. This also provides detailed information regarding the breakdown of the cost of

direct CO_2 emissions per major processes of the steel mill. It should be noted that the cost model developed for this study could be adapted for future studies and could also incorporate several site specific conditions to evaluate the cost of CO_2 capture from an integrated steel mill.

- The breakeven price of the HRC produced from the RSM without CO_2 capture (Case 1) producing 4 MTPY was estimated at US$ 575.23/t HRC. Figure 2 presents the breakdown of the cost of HRC production. It could be noted that nearly 60% of the cost of steel produced consists of the different raw materials (i.e. iron ore burden, ferro-alloys, scrap and fluxes), fuel and reductant. The CAPEX only contribute to around 21% of the total cost. It could be concluded that the cost of steel produced (ex-works) could be strongly influenced by the different market drivers mainly the cost of iron ore, coking coal and energy (i.e. for this study, this is represented by the cost of natural gas consumed).
- The breakeven price of the HRC produced from the Steel Mill with post combustion CO_2 capture using MEA producing 4 MTPY was estimated at US$ 652.44/t HRC and US$ 677.70/t HRC for Case 2A (EOP-L1) and Case 2B (EOP-L2) respectively. The breakdown of this price is presented in Figures 3 and 4. As compared to the breakeven price of the HRC from the REFERENCE Case, this represents an increase of ~US$ 77.20 and ~US$ 102.50 per tonnes of HRC for Case 2A and 2B respectively.
- The breakeven price of the HRC produced from a Steel Mill with OBF and MDEA CO_2 capture (Case 3) producing 4 MTPY was estimated at US$ 630.22/t HRC. The breakdown of this price is presented in Figure 5. This represents an increase of ~US$ 55.00/t HRC as compared to the breakeven price of the HRC produced from REFERNECE Steel Mill.
- The estimated cost of CO_2 avoidance for HRC produced from steel mill with post-combustion capture are US$ 74/t CO_2 and achieving 50% CO_2 avoided (Case 2A) and US$81/t CO_2 and achieving 60% CO_2 avoided (Case 2B). On the other hand, the cost of CO_2 avoidance for the HRC produced from steel mill with OBF and MDEA/Pz CO_2 capture are significantly lower at US$57/t CO_2 and achieving 47% CO_2 avoided.

For all cases, it could be noted that the high cost of CO_2 avoidance is mainly due to the following:

1. Additional cost of natural gas consumed by the steel mill (as compared to the REFERENCE Case)
2. Additional total investment cost for the CO_2 capture plant, power plant and steam generation plant.

Both of these factors contribute to about 80 to 83% of the total price increase of the HRC.

The magnitude of the price increase for the HRC produced from the steel mill with OBF/MDEA CO_2 capture is lower as compared to the price increase for the steel produced from steel mill with postcombustion CO_2 capture using MEA (i.e. Case 2A – end of pipe case). Consequently, this also results to lower CO_2 avoidance cost for Case 3. This is attributed to the savings achieved from the reduced coke consumption of the OBF.

Sensitivity of CO_2 Avoidance Cost to the Price of Coking Coal and Natural Gas

This study has demonstrated that CO_2 avoidance costs for the HRC produced from the steel mill with CO_2 capture are strongly linked to the price of coking coal and natural gas and to sensitivity of the total investment cost.

Figure 6 presents the sensitivity of the CO_2 avoidance cost to the coking coal price for Case 2A and Case 3. This figure shows that the CO_2 avoidance cost for HRC produced from steel mill with Post- Combustion Capture is not sensitive to the coking coal price. However, this is not true to Case 3. An increase in the coking coal price should reduce the CO_2 avoidance cost for the HRC produced from steel mill with OBF and MDEA CO_2 capture could be observed.

For Case 2A, due to the fact that coke consumption has remained the same compared to the REFERENCE Steel Mill, it should not affect the cost of CO_2 avoidance for the range of coking coal price evaluated in this study. On the other hand, for Case 3, this result could only demonstrate the integrated nature of the steel mill. Due to the reduced coke consumption by the OBF, this should also reduce the coke production required. Consequently, this should also reduce the direct CO_2 emissions of the steel mill. Therefore, a higher coking coal price (which is the main raw material of the coke plant) should only reflect the magnitude of the cost reduction (which represents a cost saving) that could be achieved by the steel mill with OBF as compared to

the REFERENCE Case, consequently lowering the CO_2 avoidance cost.

Figure 7 presents the sensitivity of the CO_2 avoidance cost to the natural gas price for Case 2A and Case 3. This figure should help illustrate the interaction between the coking coal price and natural gas price. At coking coal price of 1P (i.e. hard coking coal at $220 and semi-soft coking coal at $160 per tonne), it is necessary to have natural gas price of ~$25/GJ to achieve the parity level of CO_2 avoidance cost for Case 2A and Case 3. This should hold true for coking coal price at 0.5P and 1.5P, it is necessary to have natural gas price of ~$18/GJ and ~$34/GJ to achieve the same effect on the CO_2 avoidance cost for both Case 2A and Case 3 respectively. It could be concluded that to make post-combustion capture option to be competitive as compared to the steel mill with OBF case, it is essential to achieve lower energy demand by the CO_2 capture plant.

Variability of the CO_2 Avoidance Cost

The variability of the CO_2 avoidance cost demonstrates the complexity of evaluating the cost of steel production from a steel mill without and with CO_2 capture. It should be noted that the reported CO_2 avoidance cost is very specific to the assumptions made in a study. This is illustrated by the range of CO_2 avoidance cost reported ($48 to 66 per tonne CO_2 avoided) from the different step-off cases evaluated for the REFERENCE Steel Mill (Case 1) and steel mill with OBF/MDEA CO_2 capture.

It could be noted that the variability is caused by the site specific conditions such as the definition of the battery limit, iron burden distribution, the level of external scrap input, and the efficiency of the processes delivering the electricity and steam could influence the overall energy performance of the integrated steel mill and its direct CO_2 emissions. Likewise, any changes to the iron and steel production due to its site specific conditions should also impact the cost of steel production. Consequently, this make any CO_2 avoidance cost reported from various studies not easily comparable.

Expert Reviewers' Comment

The draft study report was reviewed by several external experts including representatives from industrial gas companies, steel industry including members of the ULCOS, and experts on postcombustion CO_2 capture

technology. Not unexpectedly for a first of a kind study such as this, substantial numbers of comments were received.

Several experts from industrial gas companies have reviewed and raised various issues regarding the operation of the blast furnace and oxygen production. Most of these issues were clarified and if possible also incorporated in the final version of the report.

An example of this issue commented upon by the expert from the industrial gas companies is the possible discrepancy between the raceway adiabatic flame temperature (RAFT) of the blast furnace of the REFERENCE Case at 2056°C as compared to the OBF Case at 2140°C which makes it not comparable and could possibly favour the performance of the OBF case. This issue was clarified with Swerea MEFOS; and was addressed in the report.

Another example is on the different scenarios that could be possible for the operation of both low and high purity oxygen production. The central point of discussion involves the sale of Argon. In this study, the reduced high purity oxygen production for OBF case has led to reduced Argon sales reducing revenues by $20M/y. It was suggested that optimisation should be done to determine balance between production of low and high purity oxygen with respect to assumed price of Ar and energy requirements of both ASUs.

Members of the ULCOS consortium have been helpful in highlighting the importance of various factors that could impact the performance and cost of deploying CO_2 capture in an integrated steel mill. They have been critical with the selection of technology and provided their data for comparison. They have noted that the choice of the RSM presented in this study is an average steel mill which could be improved substantially. This comment was taken board and included in the recommendation that future study should include several other state of the art technologies that could be viably incorporated to achieve higher efficiency steel production.

Additionally, the ULCOS consortium has been critical with regard to the reported performance (i.e. steam demand of the reboiler) of the MDEA/Pz solvent. They believe that results presented are overly optimistic at 2.3 GJ/t CO_2. In this regard, IEAGHG consulted CSIRO (Australia) to provide an independent opinion regarding the results reported in this study. A detailed evaluation by CSIRO determined that the values reported for the reboiler

duty are considered reasonable. From CSIRO's assessment and calculation, it was noted that reboiler duty could range between 2.5 and 2.7 GJ/t CO_2 depending on how the process is optimised. It was in their opinion that the value of 2.3 GJ/t CO_2 reported by SINTEF in this study has been optimised based on conventional configuration which are typically found in a natural gas treatment plant and value reported could be achievable for the given operating pressure. Furthermore, they have concluded that the lower value of 2.1 -2.2 GJ/t CO_2 could be achieved by using the split flow configuration which has been demonstrated to reduce energy consumption in pilot plant operated by CSIRO.

Major Conclusions

The global steel industry has made significant investment in reducing CO_2 emissions mostly by raised energy efficiency. However, to achieve a reduction of CO_2 emissions greater than 50%, CO_2 capture is required. Development of breakthrough technology such as OBF is currently on-going. This will require large scale demonstration to validate engineering design and optimisation of the process. This study presented one of the several options that could be employed for a steel mill with OBF and CO_2 Capture.

Deployment of post-combustion capture technology, capturing CO_2 from various sources of flue gases within an integrated steel mill is technically possible. This could be readily retrofitted. However, this study has demonstrated that this option could have significant costs implications on steel production.

The following outcomes of this study could be summarised:

- Four different conceptual Steel Mills without and with CO_2 capture situated in the coastal region of Western Europe producing 4 MTPY standard grade Hot Rolled Coil were defined in significant detail. This report presented the following information:
    - o Details of the Boundary limit
    - o The Overall mass balance of the different major processes
    - o Details of the gas network
    - o Details of the electricity network
    - o Breakdown of the CO_2 Emissions of the different major processes

- The deployment of post-combustion CO_2 capture from various flue gas sources within the boundary limit of an integrated steel mill would not require major modification to the iron and steel production processes. However, it would require significant considerations to meet the increasing demand of steam and electricity by the CO_2 capture plant
- This study has shown that the addition of post-combustion capture using MEA as solvent has increased the overall energy consumption of the steel mill (as compared to REFERENCE Case) by 3.37 GJ/t HRC and 4.67 GJ/t HRC achieving 50 and 60% CO_2 avoided respectively.
- On the other hand, for a steel mill with OBF and MDEA CO_2 capture, this study has demonstrated an increase in the overall energy consumption of the steel mill (as compared to the REFERENCE Case) by 0.55 GJ/t HRC achieving 47% CO_2 avoided; which is significantly lower than the steel mill with post-combustion capture cases.
- This study has established a clear methodology to evaluate the cost of deploying the CO_2 capture plant in an integrated steel mill; it should be noted that cost of steel production could be very site specific.
- The estimated cost of CO_2 avoided for HRC produced from steel mill with post-combustion capture is US$74/t CO_2 achieving 50% CO_2 avoided (Case 2A) and US$81/t CO_2 for steel mill achieving 60% CO_2 avoided (Case 2B).
- The estimated cost of CO_2 avoided for HRC produced from steel mill with OBF and MDEA/Pz CO_2 capture are US$57/t CO_2 emissions avoided. This steel mill has achieved 47% CO_2 avoided.
- For all cases for steel mill with CO_2 capture, it could be concluded that significant portion (80 to 83%) of the increase in the breakeven price of the HRC is attributed to the additional total investment cost and increase in natural gas consumption.
- It could be concluded that breakeven price of the HRC produced from steel mill with OBF and MDEA CO_2 capture (US$ 630/t HRC for Case 3) is significant lower as compared the breakeven price of the HRC produced from steel mill with post-combustion CO_2 capture (US$ 650/t HRC for Case 2A). This is mainly due to the reduce coke consumption of the OBF.

Recommendations

After careful assessment and consideration of various comments from expert reviewers, the following are recommended as future studies:

It is essential to assess in more detail and incorporate other potential improvements to the cost and performance of the REFERENCE Steel Mill. This includes (but is not limited to) the evaluation of additional cases as described below:

- Removing one of the constraining extra-ordinary assumptions used in this study involving the principle of energy import and export from the steel mill. It should be noted that this assumptions has been employ to simplify the accounting of CO_2 emissions and cost. The removal of this assumption should consequently allow any surplus energy generated by the steel mill to be sold externally in the form of low grade heat or electricity. This should increase the energy utilisation efficiency of the steel mill. On the other hand, in case of any deficit, options to buy electricity from the grid could be evaluated, thus providing a more realistic scenario for European steel mill scenario.
- Improvement to the blast furnace operation by increasing oxygen enrichment and PCI coal injection, thereby reducing coke consumption.
- Incorporation of Top Gas Recycle Turbine (TRT) technology to increase electricity supply to the steel mill.
- Incorporation of hot stove oxygen enrichment technology. This should reduce consumption of other medium to high calorific value off-gases, therefore maximising the use of BFG during the heating cycle of the hot stoves.
- Incorporation of various waste heat recovery measures from the different processes of the steel mill. This could also include deployment of coke dry quenching, heat recovery from various flue gases of reheating furnaces, sinter plant (via flue gas recycling) and coke oven underfire heaters.

It is also recommended to evaluate other CO_2 capture options. This includes but is not limited to:

- Evaluation of other versions of ULCOS BF. This should demonstrate the sensitivity of the CO_2 avoidance cost to the different reduction level of coke consumption of the blast furnace. Furthermore, this should also evaluate other CO_2 capture technologies such as the use of PSA/VPSA or cryogenic separation.
- Assessment of other chemical absorption technologies capturing CO_2 from top gas of conventional blast furnaces. This represents part of the activities undertaken by the Japanese (Course 50) and South Korean (POSCO/RIST) R&D programmes; this activity should also include an assessment of the use of novel waste heat recovery (i.e. heat recovery from slag).
- Assessment of other novel CO_2 capture options. This includes: Air Products' BF plus technology, Linde's or LanzaTech's technology involving alcohol production from off-gases, and Praxair's technology involving hydrogen injection to the blast furnace.
- Assessment of integrated steel mill with DRI production unit and in combination with CO_2 capture. This option should open up several other opportunities for additional coke consumption reduction and at the same time achieving higher level CO_2 avoidance.

It is further recommended that other potential improvements to the operation of the Air Separation Unit to meet larger oxygen demand for the OBF based steel mill or AP's BF plus technology. This study could involve the evaluation of the following:

- Assessment of dual or split purity oxygen production.
- Optimisation of liquid argon production. Sensitivity to the assumed price of argon and energy demand of the ASU should be evaluated.

Please see report 2013-04 for full set of diagrams and figures from the recommendations for this study.

2013-05 POST-COMBUSTION CO_2 CAPTURE SCALE-UP STUDY

Introduction

Several government and international organisations have set 2020 as a target for commercial deployment of CCS. In order to keep this target, it is clear that the initial CCS demonstration projects and full scale CO_2 capture plants will have to be based on currently available technologies. These commitments and agreed targets give an important role for the solvent based post-combustion capture technology, which is considered to be the most mature of all the capture technologies available today. This technology provides a retrofit possibility and is already available on relatively small industrial scale; this makes it one of the most viable options for large scale CCS deployment.

However, the conventional solvent based post-combustion CO_2 capture technology are facing a number of challenges, which need to be addressed before full scale deployment. Major challenges are related to the high energy requirement, high capture cost and the uncertainties of the environmental impact from the capture technology and very important the challenge related to the scale. Therefore, IEAGHG has commissioned this study to define the different technical challenges associated to the conventional post-combustion capture technology with a special focus on those risks related to scale-up and full scale operational requirements.

Approach

This study was awarded to Black & Veatch, USA, on the basis of competitive tender. This study assess the technical challenges associated with full-scale design and operation of conventional post-combustion capture technologies for supercritical pulverized coal (SCPC) and natural gas fired combined cycle (NGCC) power plant. In this study technical and operational risks, performance gaps, technical challenges and sensitivity to several process variables are evaluated. Finally, a suggested scale-up strategy was developed with a focus on specific areas for development in future.

To accomplish the project objectives, Black & Veatch developed a full scale conceptual design of a 900 megawatt (MW) supercritical pulverized coal (SCPC) and an 800 MW natural gas fired combined cycle (NGCC) power plant without and with a solvent based CO_2 post combustion capture process, in order to serve as a basis for discussion of the issues associated with the scale-

up. A low sulphur Australian coal was used for SCPC case. The design of the selected power plant was based on conservative supercritical conditions and hence a conservative assessment of flows and equipment sizes. Black & Veatch has reviewed the post-combustion CO_2 capture technologies currently available and amine-based absorption process was selected as the most developed technology for both power plants. In this study a CO_2 capture efficiency of 90% was selected.

NOx reduction in the flue gas was achieved by Selective Catalytic Reduction (SCR) technology for both SCPC and NGCC power plants with 80-84% NOx removal efficiency. In the SCPC power plant SCR is located between the economizer outlet and the air preheater inlet whereas in the NGCC power plant SCR is situated in the exhaust gas path and is integral with the HRSG. An oxidation catalyst was selected for carbon monoxide (CO) reduction in NGCC power plant which is located upstream of SCR. Mercury reduction in the SCPC power plant was achieved by Powdered Activated Carbon (PAC) injection upstream of the particulate matter reduction. Particulates were removed from the SCPC power plant exhaust stream by Pulse Jet Fabric Filter (PJFF) as this technology is able to meet low particulate emissions for a wide range of fuel and operations. The particulate removal efficiency was specified as 99.9%. Major equipment lists for SCPC and NGCC with CO_2 capture cases (Case 2 and 4) are presented in Figure 1 and 2 respectively.

A Wet Flue Gas Desulphurisation (WFGD) with Limestone Forced Oxidation (LSFO) was selected for the SCPC power plant with SO_2 removal efficiency of 97.5%. A low level of SO_2 is required in the flue gas for amine based CO_2 capture systems. Since LSFO WFGD would likely not be able to achieve the low level required, a CO_2 polishing scrubber was selected for the SCPC power plant with CO_2 capture (Case 2). The SO_2 concentration in the flue gas for SCPC CO_2 capture process (Case 2) was assumed to be 10ppm.

The flue gas entering the CO_2 Capture process had CO_2 concentrations of 11.8mole% and 4.1mole% for SCPC and NGCC power plant cases respectively. The oxygen concentration in flue gas was 5mole% and 12mole% for SCPC and NGCC power plants respectively. Flue gas flow rate was 3989tonne/h and 4362tonne/h for SCPC (Case 2) and NGCC (Case 4) CO_2 capture cases respectively.

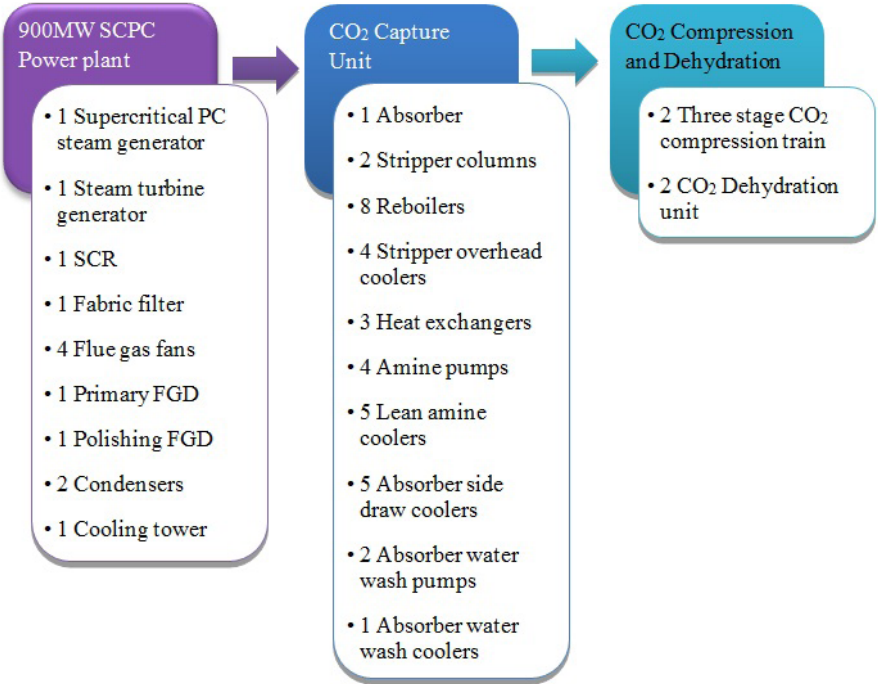


Figure 1, Major equipment list of 900MW SCPC with 90% CO_2 capture case (Case 2).

The CO_2 recovery process consists of 3 main sections: CO_2 absorption, solvent stripping, and CO_2 compression. The CO_2 absorber is a rectangular concrete column with stainless steel internals that divide the column into six parallel sections. Each parallel section of the CO_2 absorber has a cross section of approximately 7 meter (m) by 7 m. In the SCPC CO_2 case (Case 2) the absorber has three main vertical segments: the CO_2 absorption segment, the overhead cooling segment, and the water wash segment. Whereas in the NGCC CO_2 capture case (Case 4) the absorber has four main vertical segments: the quench cooler segment, the CO_2 absorption segment, the overhead cooling segment, and the water wash segment. A demister is used at the exit of the overhead segment of the absorber column to remove water droplets that may have been entrained with the flue gas for both Cases 2&4. The clean flue gas is vented to the atmosphere through a stack at the top of the absorption column. Table 1 gives the summary of electricity generation and CO_2 capture process specific utility requirements for SCPC and NGCC power plants.

The rich solvent from the bottom of the CO_2 absorber is sent to two parallel stripper columns by a rich solution pump through three plate and frame rich/lean solvent heat exchangers for the SCPC case (Case 2) and two plate and frame rich/lean solvent heat exchangers for the NGCC case (Case 4). The strippers used were cylindrical packed columns with the main shells made of carbon steel where the rich solvent is heated to liberate the CO_2. There are two stripper with eight reboilers for SCPC CO_2 capture Case 2, whereas for NGCC CO_2 capture Case 4, single stripper column with four reboiler at the bottom of the stripper was used.

	UNIT	CASE 1	CASE 2	CASE 3	CASE 4
Reference Case Description		Supercritical Pulverized Coal Rankine Cycle		2-on-1 G-Class Gas Turbine Combined Cycle	
Fuel Type		Low Sulfur Australian Coal	Low Sulfur Australian Coal	Natural Gas	Natural Gas
Net Plant Thermal efficiency	%	40.4	28.3	58.0	49.6
CO_2 Capture	%	No	90	No	90
ELECTRICAL OUTPUT					
STG	MW	-	-	280.4	223.7
Gas Turbine Generators	MW	-	-	529.5	529.5
Total Gross Output	MW	900.1	756.6	809.9	753.2
Auxiliary Electric Load					
Power Block	MW	35.5	35.1	19.6	22.1
Flue Gas Fans	MW	17.2	44.0	N/A	26.1
Air Quality Systems	MW	5.8	8.5	-	-
CO_2 Capture	MW	N/A	5.2	N/A	3.6
CO_2 Compression	MW	N/A	75.0	N/A	25.5
Total Auxiliary Electric Load	MW	58.5	167.8	19.6	77.3
Net Plant Output	MW	841.6	588.8	790.3	675.9
Energy Penalty	%	N/A	-30.0	N/A	-14.5
CO_2 for Transport	t/h	N/A	629	N/A	250
CO_2 to Atmosphere	t/h	702	73	276	28

PLANT UTILITY CONSUMPTION					
Makeup Water					
Cooling Tower	m^3/h	9,600	12,500	4,400	6,400
Cycle Makeup	m^3/h	25.9	26.1	7.7	8.1
Advanced Amine Solvent(1)	kg/h	N/A	283	N/A	210
CO_2 Dehydration Adsorbent(2)	kg/h	N/A	16	N/A	7
PLANT WASTE PRODUCTION					
Wastewater					
Cooling Tower Blowdown	m^3/h	1,900	2,300	880	1,300
CO_2 Capture Wastewater(3)	m^3/h	N/A	(Note 3)	N/A	(Note 3)
Amine Waste	kg/h	N/A	146	N/A	108

Notes:
1 Amine degradation includes degradation from oxygen and sulfur, but excludes NO_X.
2 Bed replacement every 3 to 5 years.
3 Minimal wastewater discharge. Water condensed from flue gas and CO_2 streams are used for cooling tower makeup.

Table 1, Electrical generation and utility requirements summary for SCPC and NGCC cases

Water is separated from the CO_2 stream in a knockout drum and CO_2 is relatively free of water vapour with a pressure of 1.7bara. This CO_2 stream is send to a three stage compressor and the dehydration unit. The final CO_2 stream has a purity of greater than 99.5% at 110bara and 38°C. While compression from 1.72 to 110 bara can be reached by three stages, this pushes the desirable limits, four or more stages of compression could also be used.

The cooling requirements for the CO_2 capture cases for SCPC and NGCC (cases 2 & 4) are approximately 20 and 40 percent higher respectively when compared to their non CO_2 capture cases 1 & 3. This study assumes that the use of a closed circulating cooling water systems utilizing wet mechanical-draft cooling towers for heat rejection from the condensers and other plant cooling systems.

In this work the focus is on the evaluation of the technical and operational issues related to the scale-up of post combustion capture technology for SCPC and NGCC power plants. Main operational issues associated with flexibility identified in this work were not investigated in further detail as IEAGHG study 2012-06, Operating Flexibility of Power Plants with CCS evaluates this issue much in detail.

Results and discussion

CO_2 post combustion capture design cases for SCPC and NGCC were reviewed to identify the major issues that will likely be faced when moving from the current pilot scale demonstration plants to constructing and operating large commercial scale units. In general, there appear not to be any major risks which have not been addressed either in power generation or elsewhere in the heavy industrial sector. Integration of the each component of the CO_2 capture facility at large scale and incorporation into existing power plant designs may represent the largest challenge. The following section discusses the main issues related to the scale up for post combustion capture process which have emerged in this study.

New Insights

Size and construction of absorber and stripper unit

In this study for the reference cases (2 & 4), single rectangular concrete absorber structures with multiple parallel sections were selected. Such a design should be technically feasible for design and construction. The construction of such a large concrete structure will not be simple, but the same techniques used to build large stacks can be used. More precision would be required to get internal dimensions and feeds connections for the absorber, but still its construction would not pose inordinate challenges to a competent construction company. The absorber required for large-scale CO_2 capture is the single largest technical challenge for designing and constructing a full scale CO_2 capture facility.

The size of strippers for SCPC and NGCC cases (2 & 4) studied are quite large for typical amine stripping technology require 2x7.2m and 1x7.0m columns respectively and approximately 23 meters length for both cases. However this size vessel is not outside what is considered to be normal and practical for construction. Similar to the absorber, liquid and vapour distribution in the stripper is important, but certainly within the range of existing, proven technology. The main challenge associated with the strippers is the transportation to the capture site due its large size. This issue is very site specific and may not pose a challenge where there is water access. In other locations local stick build fabrication may be necessary.

Plant Stiffening Requirements

Addition of CO_2 capture equipment to large-scale power plants results in a larger pressure drop associated with the CO_2 capture equipment compared to that across conventional air quality control (AQC) equipment. Also the natural stack draft will be reduced. This can be overcome by the use of fans with significantly higher head. To protect against the increased under and over pressures which can occur additional stiffening for boiler, ductwork and flue gas equipment will be required.

Applying stiffening of this type is an expensive and time intensive process when considered for a retrofit case. It may be possible to reduce the extent of stiffening needed by use of optimized control systems to limit pressure excursions during upset conditions. However, stiffening of the steam generator, flue gas equipment, and flue gas ducts should not pose a significant technical challenge to the design and construction of the new power plant but will result in some changes to standard design.

Flue Gas Bypass

During start-up, shutdown, and other upset conditions there is likely to be increased acid gas concentrations in the flue gas, primarily NO_2 and SO_2. This could result in the formation of excessive amounts of nitrous amines and Heat Stable Salts (HSS) in amine based solvents. For this reason a bypass around the CO_2 capture process is considered desirable. This would also allow the power plant to continue operating when the CO_2 capture process is unavailable for planned or unplanned maintenance activities.

Construction and operation of a flue gas bypass arrangement is not considered to be a technical risk at the scales presented. However the addition of a bypass system around the absorber, diverter dampers and transition piece is complicated. Especially when it is desired to access and service absorber column in the power plant operation. Special consideration should be given to the transition of the operation in and out of bypass mode to establish normal operating pressure loss in the absorber column. Moreover, coordination of the flue gas and boiler draft pressure during transition should be properly coordinated by flue gas fans and bypass damper controls.

Gas Turbine Back Pressure

In this study for NGCC with CO_2 capture (reference case 4) currently available gas turbine and HRSG product offerings are incorporated. Flue gas exhausted from each gas turbine and HRSG is at 3.7kPa(g) and atmospheric pressure respectively and at 97°C. Flue gas booster fans and structured packing flue gas coolers are required to boost the pressure to approximately 13.8kPa(g) and reduce the temperature to approximately 32.2°C appropriate for the CO_2 capture process.

In the situation when flue gas is exhausted from gas turbine at approximately 18 kPa(g) and cooled further in the HRSG this could eliminate the need for separate flue gas booster fans and will result in a smaller footprint, a less complex flue gas path and possibly a slight improvement in the overall power plant efficiency. These changes would require research and development to produce gas turbines designed for a higher backpressure. Even though a relatively minor change is costly and could add considerably to unit costs, especially if the market for such machines were small.

Flue Gas Fan Size

In order to overcome the pressure drop associated with AQC system and absorber, four axial induced draft (ID) fans with two fans placed in a series and each series operated in a parallel (2-by-2 arrangement) were used for the SCPC Case 2. For the NGCC Case 4, only two axial fans were selected. Incorporating fans to handle higher flows and pressure differentials will result in fewer units and thus results in a less expensive and more compact solution. It was found that the additional flue gas draft fans are not a technical challenge to the scale-up of CO_2 capture process. Nor is the development of larger head units, although the same considerations of market size apply as that for the modified gas turbines. If the number of units which can be sold is small the development cost would not be justified.

Emission Issues

Emission concentrations associated with the power plants with CO_2 capture are not particularly related to the scale of the plant, but there are some significant issues related to environmental regulations for these types of plants. The potential emissions from these plants are unique to the amine-

based post-combustion capture plants and include Amines, Nitrosamines, Nitramines and potentially hazardous sludge/liquids produced from amine based solvent reclaiming process. Regulations are still in process of formulation in many countries and the environmental effect of the airborne contaminants is not defined, so further research is required on the long-term health effects of Amines, Nitrosamines, and Nitramines. Moreover emission limitations for such process need to be established. In IEAGHG study 2012/07 on 'Gaseous emission from amine based post combustion CO_2 capture process and methods for deep removal' shows that the application of an additional acid wash on top of the absorber is one effective way of eliminating emissions of the lighter components. The study considers that addition of further amine emission reduction equipment like demister, after the main absorber can easily be incorporated in the absorber design. However development of the technology required for any further reduction in emissions would require "bleeding edge" advances.

The quantity of wastes will be larger for large scale plants when compared to that of the small-scale plants as for Case 2 and 4, 146 and 108 kg/h respectively amine waste was generated. Therefore, sustainable amine waste disposal techniques should be further developed and it may no longer be possible to rely solely on solvent suppliers or waste disposal companies to handle the increased waste quantities. IEAGHG has commissioned study on 'Reclaimer waste disposal from amine based CO_2 post Combustion capture plants' in which different sustainable disposal techniques for amine waste will be investigated.

Plume visibility may be an issue because of the much lower release temperature. Addition of a superheater to the vent stream is an option. Available heat from the air quality control system can be used for such a superheater. However, such an arrangement will add further complexity and a small efficiency penalty due to the increase in pressure drop.

Steam System, Turbine, Condenser

Saturated steam required by the CO_2 stripper reboilers to achieve 90% CO2 capture was 821t/h and 330t/h for SCPC and NGCC cases (Case 2&4) respectively and at 4.5 bara, which is a considerable amount. In SCPC Case 2 the required steam is extracted from the cross-over piping and de-

superheated to saturation before being sent to the amine stripping process whereas in a fully optimized design non-condensing turbines would be used to recover some of the energy lost to let down the steam to the required process conditions. These could be coupled to the CO_2 compressors. In NGCC Case 4, a quarter of the steam is taken from HRSG and the rest is taken from the LP turbine. While the conditions are quite suitable still the low flow rate of the steam from the HRSG is found to be inadequate to meet the requirement of the CO_2 capture plant.

The major original equipment manufacturers (OEMs) of large steam turbines are able to modify their standard steam turbine design to accommodate a CO_2 capture process. The combined cycle heat recovery steam generator (HRSG) and steam turbine do not require any major modifications from the standard industry design for this application, although there are opportunities for optimization of the steam extraction points and condensate return. IEAGHG study 2011-02 on 'Retrofitting CO_2 capture to existing power plants' concluded that the choice of CO_2 capture retrofit related to steam extraction is wider and other factors such as the size and age of the existing power plant may be more important in determining the steam extraction potential.

Secondary Issues

Post combustion capture will have some secondary issues when considering scale up which are still noteworthy. The following are some of these:

- **Increase in Cooling Water**

The cooling requirements for the CO_2 capture reference cases, compared to the non-capture reference cases, are approximately 20% higher for the SCPC case (Case 2) and approximately 40% higher for the NGCC case (Case 4). However cooling system design is very site specific and the economics related to cooling system is very much dependent on the price of the available water, as this was one of the main outcomes from IEAGHG study 2010/05 on 'Water Usage and Loss Analysis of Bituminous Coal Fired Power Plants with CO_2 Capture'. Therefore, in the dry location where water is scarce alternative cooling systems like air cooling will become more economical.

- **Flue Gas Desulphurizations**

In this study WFGD and a polishing scrubber system were used to reduce SO_2 to the level necessary to minimize amine based solvent degradation for

SCPC reference case (Case 2). However in future integration of primary and polishing flue gas desulfurization (FGD) stages into a single SO_2 absorber system would reduce the footprint of the flue gas cleaning.

Other points

- CO_2 Compression issues are mainly related to the availability of the plant and its start-up requirements. IEAGHG study 2010/07 on Rotating equipment for Carbon dioxide Capture and Storage concluded that integration of heat of compression into the power plant is essential to maximise the efficiency. Therefore, waste heat from the inter-stage heat exchangers can be used to achieve potential optimization.
- CO_2 drying requirement for suitable CO_2 compositions for its transportation by pipeline or ship is achievable by solid adsorbent technology.
- The size of the heat exchangers required for large scale power plant CO_2 capture will be quite large compared to the commercially available heat exchangers and multiple units will be needed.
- The CO_2 capture process controls could be integrated with the main power plant distributed control system or a separate system could be utilized with a communication interface.

Size Breakpoints

No significant size breakpoints were found for post combustion capture technology scale up. The main issues identified from this study are as follows:

- Above 1000-1200MW the construction of a single absorber may no longer be reasonable because of the increasing number of compartments.
- Above 1000MW a second stripper would be required for a NGCC plant with capture
- Above 1200MW a third stripper would be required for a SCPC plant with capture
- CO2 compressors are limited to around 75,000kW; so this could become a limitation if single trains were used for SCPC plants of more than the reference case size. However for reliability reasons two 50% trains were selected and available compressor size is not likely to be a break point issue.

Future Evaluation

Analysis of the CO_2 post combustion capture technology on the basis of technical risk, operational risk, gaps, challenges and design sensitivities was performed. From this evaluation some important areas for future research and development were identified and are presented in Table 2 for post combustion CO_2 capture process large scale application.

FUTURE RESEARCH & DEVELOPMENT	
PROCESS UNIT	
NGCC power plant	• Evaluation of the design change in gas turbine with an increased exhaust pressure up to 18kPa (g). • Evaluation of the design changes in HRSG based on gas turbine increased pressure.
Steam extraction	• Evaluation of non-condensing turbine use for additional energy generation for CO_2 compression in SCPC power plant. • Evaluation of the dispatch model for LP turbine, generator, downstream electrical equipment and heat rejection system.
Flue gas bypass	• Evaluation of the cost, safety and permit issues for CO_2 stack discharge for extended period of time for large scale post combustion CO_2 capture system.
Cooling system	• Evaluation of large scale CO_2 post combustion capture process cooling water system for low water available site.
Water / Wastewater impacts	• Evaluation of site specific water usage and waste water impacts for large scale CO_2 post combustion capture process.
Fans	• Development of axial fans with an increased head/flow capacity. • Evaluation of the optimal draft fan arrangement for specific project based on the technical design requirements for CO_2 capture process requirement and WFGD with polishing scrubber systems.
Flue gas cleanup	• Evaluation and optimization of the integrated primary and polishing FGD stages into single SO_2 absorber system.
Absorber	• Investigate effect of rectangular shape absorber on its hydrodynamics.
Stripper	• Development of the site specific transportation strategy for stripper columns.
	• Evaluation of the heat recovery from CO_2 compressor by heating condensate or feedwater into the intercoolers and aftercoolers of the CO_2 compressor.

CO_2 compressor	• Evaluation of the heat recovery from CO_2 compressor by heating condensate or feedwater into the intercoolers and aftercoolers of the CO_2 compressor. • Feasibility investigation of the power plant Rankine cycle and main steam turbine generator design integrated with direct steam turbine drive of CO_2 compressors.
CO_2 Drying	• Investigation of glycol solubility in supercritical CO_2 and glycol loss in the CO_2 glycol drying process.
Process Control System	• Evaluation of the CO_2 capture plant control system integration to the main power plant DCS system. • Evaluation of the optimized control system for CO_2 capture plant during power plant upset conditions.
PROCESS ISSUES	
Environmental	• Evaluation of the required technology for amine emission reduction and amine waste disposal.
Capture plant Startup and Shutdown	• Operational requirement during startup and shutting down of highly integrated power plant with CO_2 capture.
Operational Flexibility	• Evaluation of the operation flexibility for large scale CO_2 post combustion capture plant application in power plants.

Table 2, Future research and development required for large scale CO_2 post combustion capture for coal and natural gas based power plants.

Strategy for Commercialization

Application of the CCS technology is influenced by factors like environmental policy, research support and economics. Policy incentives that could be provided for CCS technology developers can include bonus carbon allowances for power that use CO_2 capture, tax credits, obligations for power that utilizes CO_2 capture, or a feed-in tariff would give a clear incentive for the use of CCS technology. In the near future use of CO_2 for enhanced oil recovery (EOR) might be one of the most attractive business option and hence can act as a strong economic driver for several future CCS projects. Therefore, while the post combustion capture technology commercialization will be driven principally by policy and market there are still some important technological improvements required as shown in Figure 4.

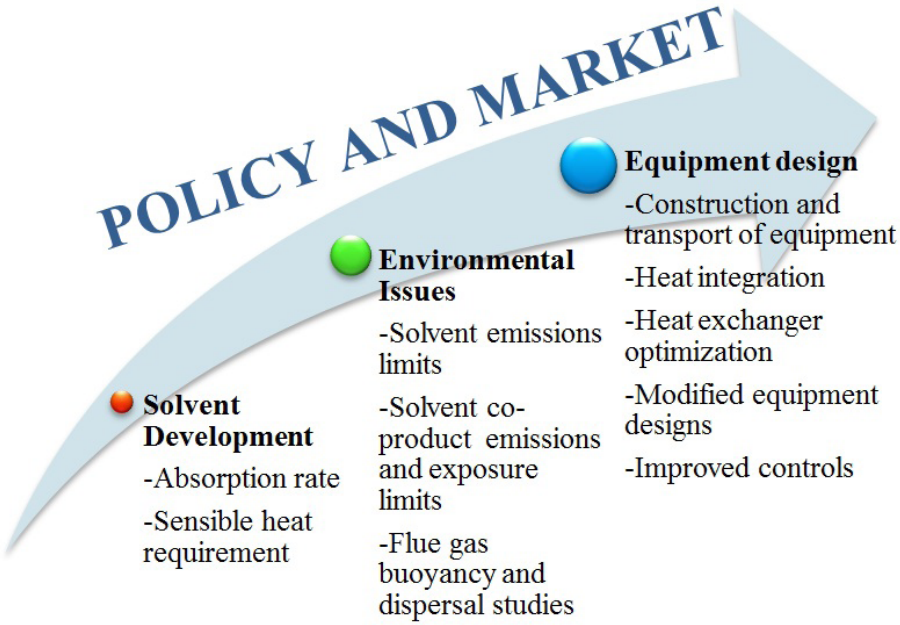


Figure 4, Strategy for scale-up of post combustion capture technology.

The most challenging part will be to reduce the cost of amine based solvent post combustion capture technology. Process integration and improved amine based solvents formulations may be able to reduce the energy requirement from the capture unit. Hence the main focus should be on improving the amine based solvents CO_2 absorption rate, absorption capacity and reduction in sensible heat requirement. The development of a large scale CO_2 capture unit evaluated in this work does not create a set of novel challenges from an equipment design viewpoint. Large-scale stripping of impurities in gas by liquid solvents in large vessels has been accomplished in the petrochemical industry for decades. Therefore, in CO_2 post combustion capture processes, issues related to appropriate liquid/gas distribution, maintaining required residence time and handling large quantities of solvent should not create major problems during operation. However, focusing on improving specific areas in equipment design should be beneficial as shown in Figure 4.

Large scale post combustion capture units present special concern for the environment and this area should be more thoroughly investigated prior to widespread commercialization. Many of these concerns involve the permissible exposure level for the solvents and impurities that are entrained in the treated flue gas emissions. Figures 4 shows the environmental issues to be focused on for safe application of post combustion capture process.

Expert Reviewer's Comments

Most reviewers felt that the key message from the report is that there are no major issue related to the scale-up of post combustion capture technology and that the required skills exists to build the process. They were largely happy with this conclusion .

One reviewer commented that the true issue in "Scale Up" is dealing with the uncertainties associated with going from current experience base to understanding what may happen in a commercial application. In his view point, this study is a quantitative assessment of specific uncertainties which underpins a "go/no-go" decision on commercial development. If the uncertainties are considered as a barrier, then further R&D should be indicated in this study. This suggestion was incorporated in the report and also an overview list for future R&D areas is presented in Table 2.

Another reviewer commented that it would be helpful if for each element of the post combustion capture technology chain an assessment and classification was made of whether what is being proposed is commonplace, "leading" edge, or "bleeding" edge. This was incorporated in the report in section 5. Another reviewer recommended that more should be said about the technical challenges and limitations related to the absorber size. This section of the report was expanded.

Conclusions

A summary of the process unit and operational issues related to post combustion capture unit scale up for SCPC and NGCC power plant cases (Case 2 and 4) are presented in Table 3.

Table 3 shows a summary of challenges related to different process units and operational issues for scale up of post combustion capture technology. Standard +; Moderate ++; Complex +++.

BARRIER	TECHNICAL BREAKTHROUGH	COMPLEXITY OF DEVELOPMENT	COST
PROCESS UNIT			
Steam Generation	+	+	+
Steam Extraction	+	+	+
Flue gas bypass	+	+	+
Cooling	+	+	+
ID Fans	+	+	+
Absorber	+	+	+
Heat exchanger	+	++	+
Stripper	+	++	+
CO_2 Compression	+	+	+
CO_2 Drying	+	+	+
PROCESS ISSUES			
Amine Emission	+	+	+
Capture plant Startup & Shutdown	+	+	+
Retrofit	+	+	+
Advanced Control System	+	+	+

Table 3, Summary of challenges related to different process units and operational issues for scale up of post combustion capture technology.

This evaluation is based on the main barriers:- technical breakthrough, complexity of development and cost. In this evaluation process units and operational issues were evaluated at three different level Standard +; Moderate ++; Complex +++. Also the cells are highlighted in traffic sign colors of Green, Yellow and Red representing the level of further research and development required in that particular area. The evaluation presented above in Table 3 shows that there are no major scale-up issues related to the CO_2 post combustion capture application in coal and gas based power plants. Although there are some areas of further research and development required in the technology development for units like steam extraction, cooling system, absorber, stripper, CO_2 compression and issues like environmental, retrofit and advanced control system. Whereas, construction of stripper and heat exchanger can be an issue which is site specific. Moreover stiffening will

be required for process units like boiler, ductwork, and flue gas equipment to overcome pressure increase by large size ID fans.

Recommendations to Executive Committee

Several areas where engineering and equipment development is required have been identified in this study. This study has mainly concentrated on the designs of the major equipment required for the CO_2 capture system. A major challenge for designing a system, especially when considering the eventual disposal of the captured CO_2, would be the design of the instrumentation and controls for this system. Although scale up of CO_2 capture process is possible without significant development, cost and performance, still these areas could be improved further by additional R&D. The IEAGHG programme should encourage equipment developers and suppliers to address issues identified in this study. This could be best done by improved interaction of different parties working in the engineering community. IEAGHG is not in a position to undertake the necessary development but could provide some guidance to those who are.

- Amine emission issue is significant environmental concern and disposal of amine based waste generated by large scale should be investigated in more depth.
- Important operational issues like cycling, part-load, intermittent operation, start-up, shut-down issues need to be looked more in detail at large scale.
- CO_2 large scale venting or depressurizing HP pipeline issues related to safety and permits should be further evaluated.
- Gaps and technical challenges should be evaluated further to include other elements that may constrain the operation flexibility of the power plants with CCS. In particular, evaluation of the possibility of operation of these plants in the mid and peak merit market, following a specific weekly demand curve should be performed. Attention should also be focused on identifying the capacity limits and ramping capabilities of equipment like the stripper and reboiler. To make frequent and fast start-ups/shut-downs will be difficult due to the time required to pre-heat the regeneration column. Therefore, ways to overcome these limitations should be investigated further.

2013-19 Deployment of CCS in the Cement Industry

Key Messages

- Established techniques can be used to reduce CO_2 emissions from cement production, including increased energy efficiency, use of alternative raw materials and fuels and reducing the clinker:cement ratio. However, CCS will be needed to achieve deep emission reductions.
- The preferred techniques for capturing CO_2 in cement plants are oxyfuel and post combustion capture. Pre-combustion capture is at a disadvantage because it is unable to capture the large amount of CO_2 produced by carbonate decomposition.
- Oxyfuel technology is in general expected to have a lower energy consumption and costs than post combustion capture using liquid solvent scrubbing.
- Some pilot plant projects for post combustion capture at cement plants are underway but oxyfuel technology for cement plants is still at the laboratory stage of development.
- A survey of the cement industry showed that most of the respondents think that CCS is relevant to them and they are aware of research projects, and half are involved in CCS activities. More than half of the respondents would contribute financially to CCS research but only a third would be willing to contribute to pilot or demonstration plants due to high costs.
- With the current legal and economic conditions CCS would impair the competiveness of cement production, which will inhibit development and application of CCS in the cement sector.

Background to the Study

The cement industry is a major source of industrial greenhouse gas emissions and accounts for around 5 % of global anthropogenic greenhouse gas emissions. The cement industry has been reducing its energy consumption and greenhouse gas emissions per tonne of cement through a variety of different techniques aimed at reducing costs and satisfying other environmental targets. These techniques have already been exploited to a significant extent and they will only be able to partly contribute to the emission reductions required to meet global climate change goals. The

remaining fraction of the reduction will require the application of CCS.

IEAGHG published a techno-economic study on capture of CO_2 in the cement industry in 2008[1]. Since that time the level of interest in the application of CCS to cement production has increased but there is still relatively little practical development work being carried out. The main objective of this study is to review greenhouse gas emissions in the cement industry and provide a survey of the state of development and barriers to the deployment of CCS in this industry.

This study was undertaken for IEAGHG by the European Cement Research Academy (ECRA) in Germany, at the request of and with financial support from the Global CCS Institute (GCCSI).

Scope of Work

The study focuses on the following tasks:

1. Review current practice in energy efficiency improvement and fuel and clinker substitution practices in relation to reduction of CO_2 emissions in the cement sector.
2. Engage with key stakeholders with the aim of identifying the key barriers to the demonstration of CCS in the cement sector.
3. Review the current state of development of potential CCS technologies evaluated for the cement industry, particularly oxyfuel and post-combustion capture and review current CCS activities initiated and led by the cement industry.
4. Review policy and government initiatives to support the application of CCS to the cement sector.

Findings of the Study

State-of-the-art practice towards CO_2 reduction in the cement industry

Cement is a blend consisting mainly of 'clinker', along with various additives. In the state of the art clinker production process shown in Figure 1 raw meal consisting mainly of carbonate mineral, usually limestone, is pre-heated against hot flue gas in a series of cyclone preheaters. It is then fed to

[1] CO_2 capture in the cement industry, IEAGHG report 2008/3, July 2008.

a precalciner when it is heated with fuel, resulting in the decomposition of most of the carbonate into calcium oxide and CO_2. The solid product from the precalciner is then fed to a rotary kiln where it is further heated by combustion of fuel and the calcium oxide reacts with silica and other minerals to produce the clinker product. The clinker is cooled, fed to a grinder and blended with other additives to produce cement.

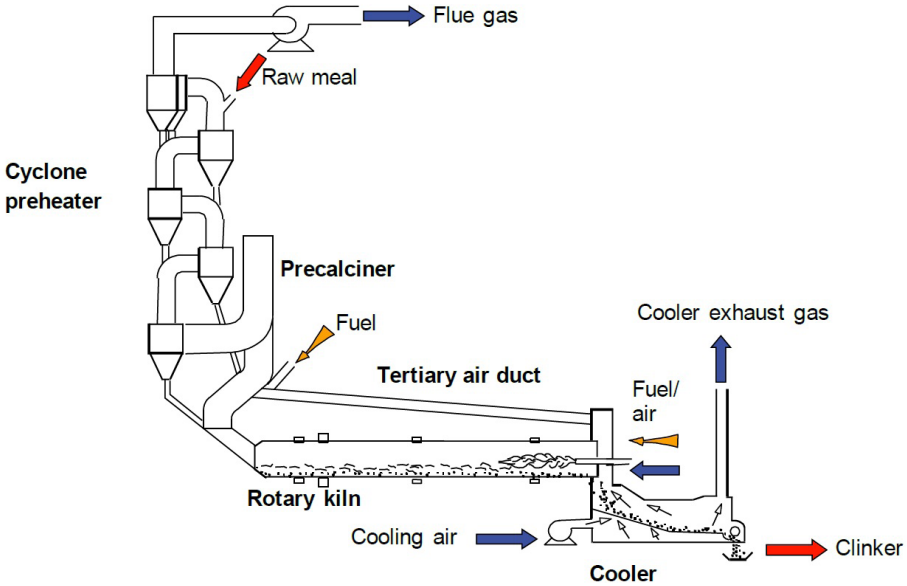


Figure 1 Cement clinker production plant

More than half of the CO_2 emissions from cement production are 'process related', i.e. from decomposition of carbonate mineral, and the rest are from fuel combustion. Apart from CCS, the main practices that can be used by the cement industry to reduce CO_2 emissions are:

- Increased energy efficiency
- Utilisation of alternative fuels
- Application of alternative raw materials
- A lower clinker:cement ratio

Increased energy efficiency

Just 64 % of the world's cement production is delivered by facilities which are equipped with precalciner technology and are working as described as state of the art practice. While a large number of cement plants with up-to-date technologies have been built in the last two decades, mainly in emerging countries, there is still a significant number of shaft, wet and semi-dry kilns as well as obsolescent grinding equipment in operation worldwide. Therefore, technical optimization of production processes offers a certain but limited improvement potential with respect to the energy demand.

In 2010 the thermal energy demand for cement clinker production was 3,580 MJ/t clinker[2] and the worldwide average electric energy demand for cement manufacturing was 108 kWh/t cement. According to ECRA's assessment the specific fuel demand can be reduced to a level of 3,300 to 3,400 MJ/t clinker in 2030 and to 3,200 to 3,300 MJ/t clinker in 2050, i.e. around a 10% reduction by 2050. A fundamental change in the actual cement production technologies causing a significant reduction in the specific energy consumption is unlikely.

Utilisation of alternative fuels

Utilisation of alternative fuels, mainly derived from waste streams such as waste oil, tyres, plastics, mixed industrial waste, animal meal, sewage sludge, wood waste and grain rejects can reduce net CO_2 emissions due to their lower carbon content as well as their biogenic fraction. The overall CO_2 emissions of a cement kiln plant are not necessarily decreased and the thermal energy demand of the process may rise but biomass is carbon neutral when part of an ecological cycle with photosynthesis and recycle via combustion. Measures such as oxygen enrichment and gasification could partly compensate for the increased thermal energy demand but at the expense of higher electrical energy demand. In general, a lot of know-how is required in order to adapt the process to the differing properties of alternative fuels. This know-how exists in some world regions or companies but it is lacking in others. The importance of alternative fuels is growing globally due to other environmental advantages and positive economics. There are some investment costs, mainly for storage and handling and in some cases pretreatment but operational costs are lower due to lower prices of alternative waste fuels compared to

[2] Worldwide weighted average, according to the World Business Council for Sustainable Development.

regular fuels such as coal. In summary, the application of alternative fuels and other fuel switching offers the potential to contribute to the target CO_2 reduction requirement in 2050 by 24 % compared to the base case.

Application of alternative raw materials

The application of alternative raw materials can help towards the limitation of the process related as well as fuel related CO_2 emissions. CO_2 emissions can be reduced by using decarbonated materials because the CO_2 emissions have already been charged to the earlier processes that created them. Examples of alternative materials are wastes from recycled concrete or fibre cements and other materials such as blast furnace slag and fly ash. The limitations to this technique are mainly the availability of the alternative materials and the need to correct the composition of the raw material mixture to maintain product quality and kiln operation, which is only possible to a certain extent. Due to the limited availability of these materials, it is more reasonable to use them as clinker substitute in the cement because this enables higher emissions reduction potentials to be achieved.

A lower clinker:cement ratio

Cement is a blend of clinker, i.e. the material produced by a cement kiln, and other additives. A lower clinker-to-cement-ratio results in less energy demand for clinker production as well as less process CO_2 emissions due to the decarbonation of the limestone. The most important clinker replacing constituents are fly ash, slag, limestone and pozzolanas (a type of mineral of volcanic origin). It has to be taken into account, that the blended cements may have different or even limited cement properties compared to Ordinary Portland Cement but the greatest limitation is the availability of most of these materials.

Besides the approach to reduce the process CO_2 emissions by the reduction of the clinker content in cement or low-carbonate clinker, new binding materials as alternatives to cement, such as Celitement, Novacem or Calera are being investigated. However, these technologies are still at research or pilot scale. To what extent these materials could replace cement as binder in building materials is not currently foreseeable.

All of the techniques described above can contribute to a reduction of combustion and material related CO_2 emissions to a certain limited degree but the calculated potentials could not be simply added, as some of them counteract each other. Moreover some measures which enhance thermal energy efficiency require increased electrical energy demand and related indirect CO_2 emissions.

Nevertheless a simulated "blue map scenario" by IEA showed that 44 % of the target CO_2 reduction potential in the cement industry related to the base scenario in 2050 could be achieved by the conventional methods described above. This shows the prospects these methods still have but also the limits of the emission reduction potential.

Research and CCS Activities in the Cement Industry

The preferred technologies for CO_2 capture in the cement industry are oxyfuel and post combustion capture. Pre-combustion capture is at a disadvantage because it would not capture the CO_2 produced by mineral decomposition.

Post combustion capture

Post-combustion capture technology has been the subject of research and has already been proven in some industries. Although part of this experience could be transferred to application in the cement industry, some issues especially concerning the cement plant's flue gas composition and impurities still need to be proven at pilot scale.

Research activities that are currently on-going in the field of post-combustion capture include chemical absorption, adsorption, membrane, mineralization and calcium looping technologies. The most investigated technology is chemical absorption but this faces the challenge of a high energy demand. Developments in calcium looping or membrane processes may have the potential to increase the overall energy efficiency but further research and development is needed. There would be some synergies between calcium looping and a cement plant because the purge stream of de-activated calcium sorbent could be reused as raw material in the cement clinker production process.

Pilot and demonstration plant projects which are actively proceeding include:

Norcem, Brevik, Norway: Test centre offering the possibility to conduct several small scale or pilot trials of post combustion capture using cement plant flue gas (2013-2017). Companies involved in this project include Aker Solutions (amine scrubbing), RTI (dry adsorption with specialized polymers), KEMA, Yodfat and NTNU (membranes) and Alstom (calcium looing).

ITRI/Taiwan Cement Corp.: Pilot plant capturing 1 tonne CO_2/h from a cement plant and a power plant using a calcium looping process, commissioned June 2013.

Skyonic Corp.: Plant under construction, capable of capturing 83,000t CO_2/y from a cement plant in Texas, using the "SkyMine" process. In this process salt and water are electrolyzed to produce hydrogen and chlorine gases and sodium hydroxide solution, which is reacted with CO_2 in flue gas to produce sodium bicarbonate, which can be sold on the market. Other combinations of chemicals can also be produced.

Due to the already high level of knowledge, the technology of post-combustion capture has the potential for implementation in a relatively short timescale, but not before 2020 for full scale plants.

Oxyfuel

Unlike post combustion capture, oxyfuel technology requires adaptation of the cement clinker production process. Oxyfuel technology for cement production is still at the basic research and laboratory testing state of development. Detailed research is still needed before advancing to pilot-scale, which is the next logical step but currently no pilot plants are planned or initiated. As a pre-stage, ECRA is presently preparing a concept study for an oxyfuel pilot cement kiln. The time horizon for application of oxyfuel technology at several full size cements plants is expected to be not before 2025.

Hybrid technologies

Hybrid technologies in terms of a combination of oxygen enrichment and post-combustion technologies have not been actively investigated. The benefit of those combinations depends on several factors concerning the

energy demand, which interact with each other. Therefore it is not possible at present to make reliable statements on technical and economic barriers and potentials.

Stakeholders' Opinion on CCS

Cement industry stakeholders were surveyed by way of a questionnaire to determine their awareness, activities, interests and reservations about CCS.

Figure 2 shows the characterization of the participating stakeholders. The main feedback was given by companies from Europe, Middle East, Asia and North America. The greatest number of participants were cement producers but plant manufacturers, gas suppliers, technology providers and research centres also provided feedback. Approximately half of the companies are global players with international businesses. In summary the composition of the responding companies delivers a representative overview of the industry's view on CCS technologies.

Please see the opposite page for the responses to the stakeholder survey.

Evaluation of the questionnaire showed the following main results:

- Most repondents are aware of CCS technologies but the knowledge about CCS and the activities in this field is lower in the Middle East and Asia than in Europe.
- Approximately three quarter of the responding companies feel CCS is a relevant issue or an issue which will become relevant for them. Especially medium or smaller sized cement producers and plant manufacturer think that CCS is not relevant for them at this stage of development. Uncertainties about the technical feasibility and the avoidance of economic risk make them prefer tradional methods for CO_2 reduction.
- Nearly half the respondents, especially from Europe, are involved in CCS activities, mainly as part of a consortium with or without financial contribution. Most of the companies are at least aware of these research projects.
- Nearly 90 % of respondents think that these technologies have potential in the cement industry and would apply them, if they were available. The negating companies are those which are convinced of other technologies or too alienated by the uncertainties of the technical

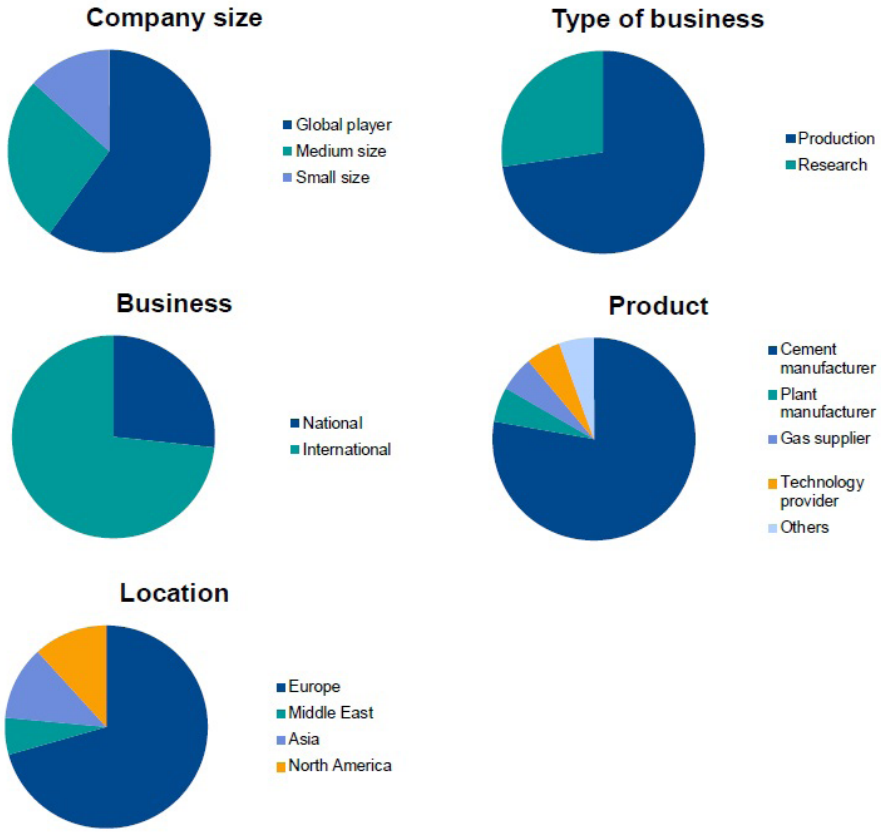


Figure 2 Companies responding to the stakeholder survey

feasiblity (including medium sized companies and plant manufacturers). Also some companies are not aware of capture technologies but they would apply them, if they became state of the art.

- More than half of the interviewees would contribute financially to research but only about a third would contribute to a pilot or demonstration plant due to high costs. The willingness to financially contribute to research or especially to pilot or demo plants is higher in globally acting companies.
- Alternatives to CCS for CO_2 reduction are seen in about 40 % of respondents and some 10 % are uncertain about the development of other technologies for emission control.

Technical and Economic Performance

The study evaluated the technical and economic performance and barriers to application of oxyfuel technology and post-combustion capture using chemical solvent absorption in cement plants.

Technical issues relating to the use of chemical solvent absorption for post combustion capture in cement plants are largely the same as for power plants. These include the possible need for secondary treatment to reduce the quantities of impurities such as SOx, NOx, particulates and other trace materials in the flue gas to avoid excessive degradation of the solvent and the need for disposal of degraded solvent waste. Space and HSE requirements may also constitute a constraint at some plants. The solvent reboiler consumes a large amount of energy and as there is only sufficient waste heat in a cement plant to provide about 15 % of this energy demand, an additional combined heat and power (CHP) plant is needed. The CO_2 emissions from the CHP plant can be captured along with those from the cement plant. Two CHP options were considered in this study: a coal fired boiler plant and a natural gas combined cycle (NGCC) plant. The optimum choice will depend on local conditions and fuel prices.

Oxyfuel technology can be integrated in the clinker production process using two different concepts – full or partial oxyfuel. In the partial oxyfuel concept, oxygen is used only in the pre-calciner and the rotary kiln remains air-fired. In the full oxyfuel concept oxygen is used in both the precalciner and the kiln. Both concepts seem likely to be suitable for retrofitting existing plants, although the plant specific space availability in the structure may limit the construction. As integrated systems, both concepts influence the process and the material conversion and greater effort will be required for operating and controlling the plant. Enhanced HSE measures will be required for handling high purity oxygen and carbon dioxide. While the thermal energy demand is only affected to a small extent, the electrical energy demand is doubled per tonne of cement product.

Figure 3 compares the Total Plant Costs (i.e. excluding owner's costs, interest during construction and start-up) of a reference plant without CO_2 capture and various plants with capture. The costs are for European plants producing

1Mt/y of clinker (1.36Mt/y of cement). The costs of the plants with post combustion capture are higher particularly because of the need to build a combined heat and power plant to supply steam for regeneration of the capture solvent. It should be noted that the capture rate in the partial oxyfuel case is about 60% compared to 90% in the other cases.

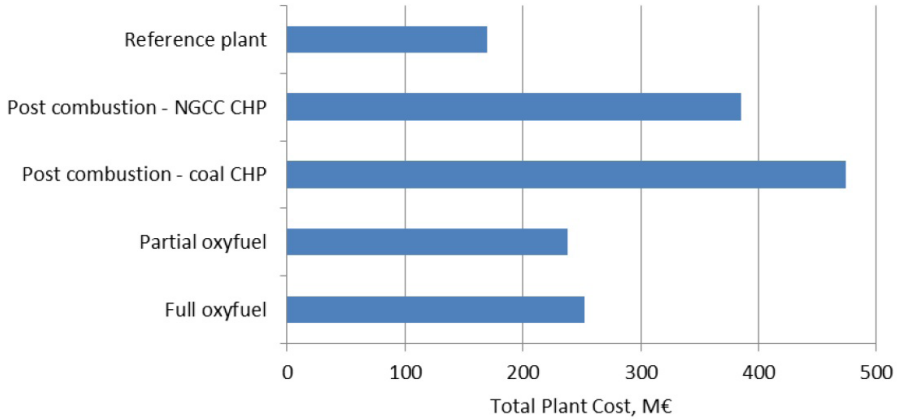


Figure 3 Comparison of Total Plant Costs

Figure 4 compares costs of cement production. The costs are based on coal and gas costs of 3 and 6 €/GJ respectively, an 8% discount rate, a 25 year plant life, an 80% annual capacity factor and an electricity value of €80/MWh, which is an approximate average of the costs of power generation with CCS in coal and gas fired power plants in recent IEAGHG studies. Details of other technical and economic assumptions used for these cost estimates are included in the study report.

The cement production cost is increased by 68-105% when applying post combustion capture and 36 to 42% when applying oxyfuel technology. In the case of the oxyfuel technologies this cost increase is mainly driven by the additional electricity demand, whereas the main costs for post-combustion capture are both additional electrical and fuel energy demand as well as the at least doubled investment cost. It should be noted that costs are subject to significant uncertainty and will depend on various factors including site specific conditions, fuel prices and future technology developments. These costs exclude CO_2 transport and storage costs. Cement plants are normally

located close to the source of limestone and have relatively small CO_2 outputs compared to power plants, which would tend to increase CO_2 transport and storage costs. However, if the plant was close to other sources of captured CO_2, a larger trunk pipeline could be used which would reduce costs. As an illustration of the impact of transport and storage costs, a cost of €10/t CO_2 stored would increase the cost of cement production by about €5/t for the full oxy-fuel case.

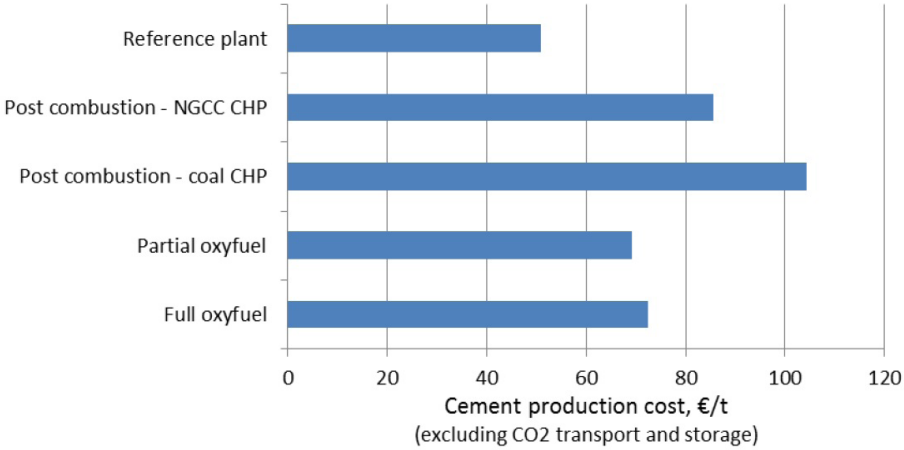


Figure 4 Comparison of cement production costs

The cost of avoiding CO_2 emissions depends on the definition of the quantity of emissions avoided. Different definitions could be used for cement plants with CCS:

- The direct emissions avoided at the cement plant site;
- The direct emissions plus the indirect emissions from power plants at other sites.

Oxy-fuel cements plants import electricity generated at other power plants, mainly for oxygen production and CO_2 compression. If this electricity is generated at power plants which emit CO_2, these 'indirect emissions' reduce the quantity of emissions avoided by CCS at a cement plant. In contrast, plants with post combustion capture would normally require an on-site CHP plant to provide the low pressure steam for CO_2 capture solvent regeneration. The CHP plant would generate some electricity from passing high pressure

steam through a back-pressure turbine and, in the case of an NGCC, from a gas turbine. This electricity is usually sufficient to provide all of the needs of the capture plant and there is a surplus, which displaces power that would otherwise be generated in external power plants. Including indirect emissions therefore increases the quantity of emissions avoided for cement plants with post combustion capture.

The cement industry's preferred definition of the quantity of CO_2 emissions avoided is the 'direct' emissions, because those are the emissions which a cement plant operator would be accountable for, and for which they would have to pay CO_2 taxes or purchase emission credits.

The quantity of indirect emissions depends on the specific CO_2 emissions of the electricity system. At the time when CCS is installed on a large scale at cement plants, electricity generation may already be mostly decarbonised, in which case the 'indirect' emissions would be small.

Direct costs of CO_2 emission avoidance compared to the reference plant, excluding costs of CO_2 transport and storage, are shown in Figure 5 (below). Including indirect emissions, assuming the same electricity value and specific emissions of 600 kg CO_2/MWh, would decrease the cost of emissions avoidance of post combustion capture by 9-14 €/t and increase the cost of oxyfuel by 4-6 €/t CO_2.

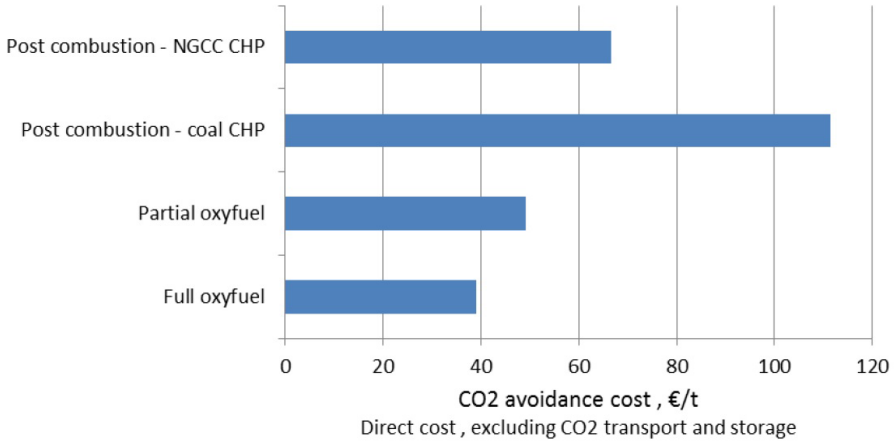


Figure 5 Comparison of CO_2 avoidance cost

The full oxyfuel technology shows the lowest cost of CO_2 avoidance. Regarding post-combustion capture, the combination with an NGCC CHP plant is less costly than a coal fired CHP plant, but this depends strongly on the relative prices of coal and gas.

Other studies have shown that a symbiosis of a cement plant with power plants and a joint CO_2 capture plant (carbonate looping) could reduce the specific costs of post combustion capture.

Sensitivities to various technical and economic criteria were assessed in the study. In particular, because global cement production is concentrated in less developed countries, the sensitivities of costs to two non-European locations, China and the Middle East, were assessed. CO_2 avoidance costs in these regions were estimated to be around 50% lower than in Europe.

The full oxyfuel technology shows the lowest cost of CO_2 avoidance. Regarding post-combustion capture, the combination with an NGCC CHP plant is less costly than a coal fired CHP plant, but this depends strongly on the relative prices of coal and gas.

Other studies have shown that a symbiosis of a cement plant with power plants and a joint CO_2 capture plant (carbonate looping) could reduce the specific costs of post combustion capture.

Sensitivities to various technical and economic criteria were assessed in the study. In particular, because global cement production is concentrated in less developed countries, the sensitivities of costs to two non-European locations, China and the Middle East, were assessed. CO_2 avoidance costs in these regions were estimated to be around 50% lower than in Europe.

Expert Review Comments

Comments on the draft report were received from seven reviewers in the cement industry and research and energy policy organisations.

A general view of the reviewers was that the report provided a good contribution to knowledge in the subject area. Key suggestions included a request for more information on the economic analysis and more detailed and up to date information on calcium looping, which were addressed in the main study report, along with various other detailed comments. The length

of time required for commercial demonstration was questioned by some reviewers and consequently discussion of this issue was expanded.

Conclusions

Established techniques can be used to reduce CO_2 emissions from cement production, including increased energy efficiency, use of alternative raw materials and fuels and reducing the clinker:cement ratio but these techniques are already being used to a significant extent. The scope to further reduce emissions using these techniques is therefore limited.

A survey of the cement industry, including cement producers, equipment suppliers and others has shown that most of the respondents think that CCS is relevant to them and they are aware of research projects, and half are involved in CCS activities, mainly as part of a consortium. More than half would contribute financially to research but only a third would be willing to contribute to pilot or demonstration plants due to high costs.

The preferred techniques for capturing CO_2 in cement plants are oxyfuel and post combustion capture. Post combustion capture is considered to have the potential for application in a shorter timescale because of relevant experience in the power sector but tests at cement plants will still be needed to determine the effects of the different flue gas compositions. Some pilot plant projects using various technologies are underway. Oxyfuel technology is still at the laboratory stage of development and there are currently no firm plans for pilot and demonstration plants.

This study indicates that oxyfuel technology will have a lower energy consumption and costs than post combustion capture using liquid solvent scrubbing. However, costs of CCS at cement plants still have relatively high uncertainties due to the absence of real plant data and site specific factors, in particular the various options for supply of steam for post combustion solvent scrubbing. Also, new technologies may in future reduce the costs and energy consumptions of CO_2 capture at cement plants.

The current globally unequal cost of emitting CO_2 would impair the competiveness of cement production with CCS. There is a significant risk of import of cement or clinker from countries with lower abatement costs, with corresponding carbon leakage. Underdeveloped legal frameworks for CO_2 storage in some countries are a further constraint on the development and

application of CCS technologies in the cement sector.

Recommendations

It is recommended that IEAGHG should continue to maintain a watching brief on CCS in the cement industry as part of its portfolio of activities on CCS in sectors other than power generation.

A further techno-economic assessment of oxyfuel technology, conventional post combustion capture and next generation capture technologies including calcium looping and membranes should be undertaken when or if sufficient information becomes available from operation of the cement industry pilot plant projects described in this report. This study could also include a more detailed assessment of options for providing the additional energy for post-combustion solvent regeneration, either by an additional power source on-site (coal or NGCC CHP) or in combination with a nearby power plant (cluster arrangement).

2013-08 INTERACTION OF CO2 STORAGE WITH SUBSURFACE RESOURCES

Key Messages

- Other subsurface resources may exist at similar depths and localities and therefore interact with CO_2 Storage. These include oil and gas, coal, natural gas storage, saline aquifer minerals, geothermal energy, potable groundwater and waste water disposal.
- Interaction of CO_2 storage with other resources can be positive or negative depending on the geology, existing resources, economic potential and the regulatory environment.
- CO_2 storage operations may be feasible, both adjacent to other resource uses or at different stratigraphic levels in the same locality, particularly if there is no detrimental pressure connection.
- Resource use interactions can occur at the same time or sequentially.
- Regulatory agencies should consider the following stages when evaluating resource development in relation to geological storage of carbon dioxide:
    - Identify all resources within region/ basin, map their distribution and assess their quality.
    - Establish priority of use between the various resources and CO_2 storage.
    - Assess proposed CO_2 storage project - site characterisation, MMV plans, contingency and mitigation planning.
    - Review injection plans and achievability; assess if they might lead to conflict
    - Review abandonment plan, longer term MMV, liability transfer arrangements.
- Delays in establishing CO_2 storage regulations could not only inhibit CO_2 storage project development, they could lead to future, detrimental resource interactions.

Background to the Study

Sedimentary basins that provide most of the world's CO_2 storage potential also host fossil fuel, groundwater and geothermal energy resources, as well as providing options for gas storage and permanent disposal of waste fluids. There is a need to define key factors that affect interaction of such resources with CO_2 storage, to provide policy makers and regulators with guidance on the allocation of pore space and resource interaction management, and to clarify the potential impact of interaction on storage capacity and availability. Storage could affect resource exploitation through fluid displacement and pressure effects beyond the extent of the CO_2 plume, as well as through direct interaction of the plume and its reaction products. Interactions could have beneficial effects, for instance by reservoir re-pressurisation, or negative effects by sterilising resources through contamination with CO_2 or its reaction by-products. This dual potential could be the case in regards to groundwater, where an increased pressure footprint caused by CO_2 injection could beneficially increase the recovery of groundwater resources, or conversely if CO_2 or the associated brine migrates out of the storage formation, there could be an adverse potential for it to reach adjacent potable groundwater resource and cause contamination, either directly or through any substances that may have been mobilised by CO_2.

The exploitation of resources, such as hydrocarbon production, may enhance CO_2 storage by de-pressurising reservoirs/aquifers and by providing re-usable boreholes and infrastructure as well as sub-surface data. This enhanced potential for storage may be durable in some cases, but temporary in others - such as circumstances where offshore oil and gas infrastructure has to be de-commissioned on completion of production, thereby limiting availability. Storage potential could also be negatively impacted, e.g. in locations where seal integrity has been compromised by poor well completions or by the fracturing of seals during shale gas production.

There may also be direct competition for the use of pore space by the proponents of other forms of sub-surface storage or disposal.

When considering locations of overlap, it is important to consider whether the overlap is geographical or whether the actual pore space is in competition. For example, in a recent IEAGHG study on potential impacts on groundwater

(2011/11), regional maps showing areas of geographical overlap of potential CO_2 storage locations and potable groundwater resources have been produced. However, in some areas where there is overlap, it is known that there are impermeable layers separating the two potential resources.

Similarly for locations of geothermal resources and potential CO_2 storage resources, there may be some areas of pore space conflict, but if looking at purely geographical overlap, there is the possibility for misinterpretation as geothermal energy for power production usually takes place at much greater depths than the optimum for CO_2 storage. For district heating generation projects, they are more likely to take place at similar depths, though this may not necessarily cause a conflict as the 2 technologies still have different requirements, such as CCS projects needing a caprock, which is not the case for geothermal projects.

In areas of geographical overlap, but no conflict of pore space, it may be potentially possible to have more than one activity, though this may need to be considered on a site specific basis and any planning and monitoring programme would need to take this into account.

It may also be possible, in some circumstances, for two activities to work in synergy with each other, such as CO_2 storage with hydrocarbon production, such as in enhanced oil and gas recovery or with geothermal energy.

CO2CRC, a consortium based in Australia and New Zealand, was commissioned by IEAGHG to undertake a study considering what subsurface resources may interact with CO_2 storage and how this can be managed.

Scope of Work

The objectives of the study were to:

1. Provide a comprehensive literature-based review of sub-surface exploitation activities that may affect storage operations, focussing in regions where large scale CCS development is currently focussed.
2. Provide a qualitative assessment of potential interactions and impacts using case-study sedimentary basins.
3. Provide policy makers, regulators and developers with a checklist of potential sub-surface resource interactions together with a preliminary explanation of possible impacts and management options

4. Where possible, provide case study examples of resource interaction issues have been successfully managed to enable multiple resource use.

CO2CRC were asked to refer to the following recent IEAGHG reports relevant to this study, to avoid obvious duplication of effort and to ensure that the reports issued by the programme provide a reasonably coherent output:

- Global Storage Resources Gap Analysis for Policy Makers (2011/10)
- Potential Impacts on Groundwater Resources of Geological Storage (2011/11)

In addition, the following active IEAGHG projects have strong links to this study and IEAGHG encouraged contact between contractors to avoid duplication of effort or unnecessary discrepancies in findings:

- Potential Implications of Gas Production from Shales and Coal for CO_2 Geological Storage (ARI, draft report)

Findings of the Study

This study summarised subsurface resources that could potentially interact with CO_2 geological storage, and presented relevant case studies that looked at how subsurface resource interaction has been managed previously. This is all brought together in a final chapter which considered how potential subsurface resource interaction with CO_2 storage can be dealt with and managed.

Subsurface Resources

Potential resources considered that may interact with CO_2 Storage are conventional oil and gas, shale gas and oil, coal (including natural gas extraction and underground coal gasification), gas hydrates, natural gas storage, minerals in the formation brine and sediments, geothermal energy, potable groundwater and the disposal of waste water. These could all potentially exist at the same depth that CO_2 storage is expected to take place at, Figure. 1.

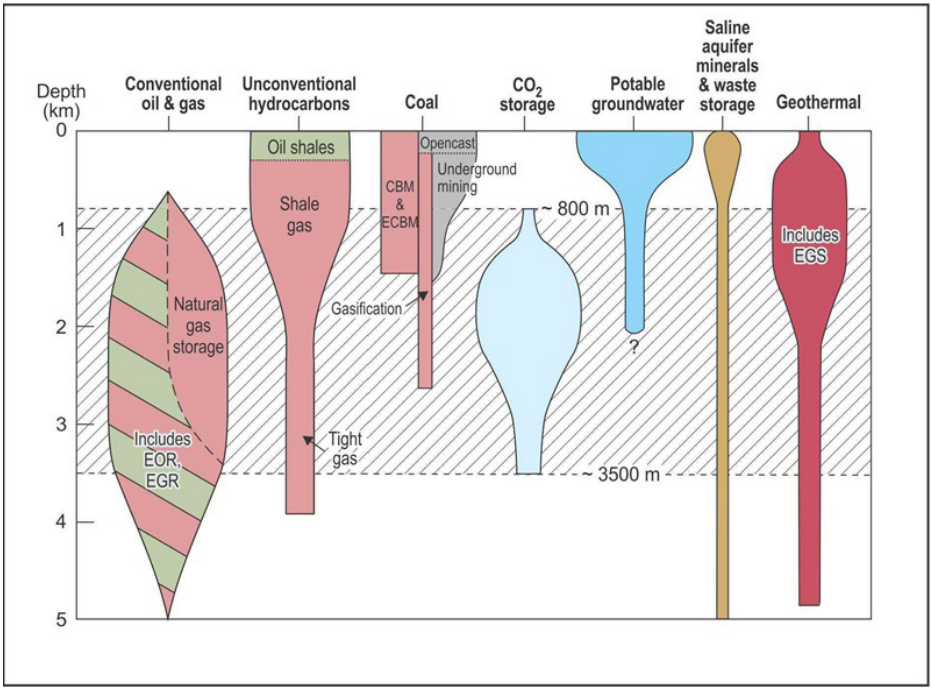


Figure 1. Schematic diagram of the typical depth ranges over which subsurface resources occur, including the use of pore space for CO_2 storage.

Most producing or prospective hydrocarbon fields occur within the 800-4000 m window desirable for CO_2 storage, and may therefore be affected by changes in pressure or fluid interactions caused by CO_2 injection. Interaction can be positive if it helps flush out residual hydrocarbons. Potential negative interactions could occur if pressure fronts or leaked CO_2 interfere with hydrocarbon production or CO_2 could exacerbate corrosion of pipes and degradation of cements used in exploration and development wells. Negative effects may be avoided by adequate seal and containment of injected CO_2 and anticipated pressure front effects. If a new oil or gas resource is discovered beneath an existing CO_2 storage site; corrosion-resistant well completion materials would need to be used, and pressure interference would need to be pre-assessed and mitigated. Pressure interference has occurred between nearby oilfields and a case study cited is the Zama oilfield, Canada. Water injection in one field caused a pressure increase at a site of acid gas injection, which limited the amount that could be injected. Therefore pressure effects

of injection projects near potential CO_2 storage sites, as well as potential effects of the storage site on other injection projects should be assessed and monitored carefully.

Natural gas storage sites have the potential to conflict with potential CO_2 storage sites, but it is not likely at a commercial scale as natural gas storage sites are generally much lower capacity than ideal CO_2 storage sites. This is to reduce the amount of cushion gas (that which is irretrievable once injected) and allows the gas pressure increases quickly during injection, which facilitates rapid gas withdrawal. The optimum volumes of natural gas to be stored are much smaller than the mass of CO_2 to be captured during the lifetime of a power/ industrial plant. However, as with oil and gas fields there may be pressure interference if the sites are close by.

Shale gas and oil have the potential to affect storage security if the formation from which the shale gas is produced is the same as the caprock immediately above the storage formation. However, the if shale gas formation is not integral to storage security, then even if the storage formation and shale gas horizon are in the same geographical area, then potentially both resources can be exploited, if the site is well managed and monitored. This would need to be assessed on a site by site basis.

CO_2 can be stored in 'unmineable' coal seams, whereby the CO_2 displaces methane on the coal surfaces due to preferential adsorption. The coal will then not be able to be used at a later date for another purpose, including underground coal gasification (UGC), without releasing the stored CO_2; therefore the various potential uses need to be considered prior to use of the resource. UGC by itself produces large quantities of CO_2 and will likely need to be done in conjunction with CCS.

Subsurface storage of waste fluids, or produced water from mining operations has the potential to influence CO_2 storage by competition for pore space, mixing by leakage and pressure perturbation. An example of waste water disposal is the Surat basin in Queensland, Australia, where production of natural gas from coal seams requires large scale extraction of water, for which the most practical disposal option is into the surrounding subsurface formations. The Surat basin contains a series of reservoir and seal layers with the potential for multiple uses including CO_2 storage and possibly

geothermal extraction. This will require extensive monitoring of injected and extracted volumes and pressure perturbations.

Potentially valuable minerals, as well as hydrocarbons may also exist within the formation waters of deep saline formations, such as lead, zinc, potash and rare earth elements as well as many other dissolved minerals. Which minerals exist will be site specific and will depend on a range of factors including source rock, tectonic history, basement rocks and hydrogeological and geothermal history. The potential for extraction of such minerals will also need to be assessed on a site by site basis. There is also the potential to combine mineral extraction and CO_2 storage with technologies such as bioextraction, or in the co-production of brine minerals.

When considering geothermal energy, many resources will not be in competition, such as high enthalpy systems and hot dry rock technologies. However, low enthalpy systems, which can be used for direct heating, have the potential to interact with CO_2 storage. This is likely to be limited to onshore areas as low enthalpy geothermal energy is not economical offshore. Options for synergies include using formation water extracted from CO_2 storage sites for pressure management for geothermal energy and CO_2-plume geothermal system (CPG), which uses CO_2 to extract heat. An example of where this could occur is in the Paris basin in France, which is currently used to supply heating to several districts in Paris. The geothermal resource could be adversely affected by CO_2 storage due to direct competition of pore space and remote pressure fronts. However, dense phase CO_2 can be used as a thermal transfer medium to enhance geothermal resource use or direct competition could be resolved by development of geothermal resource in areas of higher heat flow and CO_2 storage in areas of lower heat flow. Pressure effects will need to be taken into account in this case. It should also be noted that the requirements for CO_2 storage require the presence of a structural trap, whereas geothermal projects do not, which would mean the areas of interest for CO_2 storage could form a minor subset of the areas that are of interest to geothermal projects. Information sharing and co-operation between the 2 industries will be necessary for the exploration phase and beyond.

The majority of potable groundwater is found at depths much shallower than CO_2 storage would take place and will therefore have little direct interaction. However, if shallow groundwater is in the vicinity of a storage site it will need

to be considered in the monitoring programme. It can also be affected by pressure perturbations caused by injection of CO_2. This topic was covered in detail in a previous IEAGHG report on the potential effects of groundwater on CO_2 storage (2011/11). A case study considered was the Cassem project, UK, which used a hydrogeological model in conjunction with dynamic flow simulation modelling of CO_2 injection to determine the likely effects of CO_2 injection on potable groundwater. The findings showed a degree of impact to be highly sensitive to vertical permeability of the caprock. Recession of groundwater heads in the shallow unconfined aquifer occurs relatively slowly and lateral movements of the water interface are more strongly influenced by ongoing surface extraction than by CO_2 injection and migration.

A case study of management of the interaction between two subsurface resources is gas over bitumen in north-eastern Alberta, Canada. Bitumen can be extracted using steam assisted gravity drainage, whereby steam is injected to lower the viscosity of the bitumen by increasing the temperature. If the gas cap over a bitumen deposit is produced prior to the completion of bitumen production, the decrease in gas pressure may lead to a temperature drop negatively affecting the bitumen viscosity and making it impossible or uneconomical to produce. The outcome was the decision that bitumen must be produced before the gas can be produced. The significance of this example to CO_2 storage is that injection of CO_2 into reservoirs overlying a subsurface resource has the potential to increase the pressure in the underlying reservoir and potentially improve the production of the resource.

The Gippsland basin in Victoria, Australia is an example where several uses of the subsurface are expected, including oil and gas exploration, coal production, geothermal energy, potable groundwater extraction and CO_2 storage. Figure 2 shows licence boundaries for oil and gas production as well as the newer licences for CO_2 storage and geothermal energy production.

The broad geographical demarcation between the newer industries and existing oil and gas operations only partially considers distribution and potential for resources as currently understood and shows wariness to impinge on current profitable operations. The large blocks given to CO_2 storage and geothermal energy overlap geographically and it will be important to understand the likely 3D footprint of future operations to understand potential interaction and maximise socio-economic benefit of

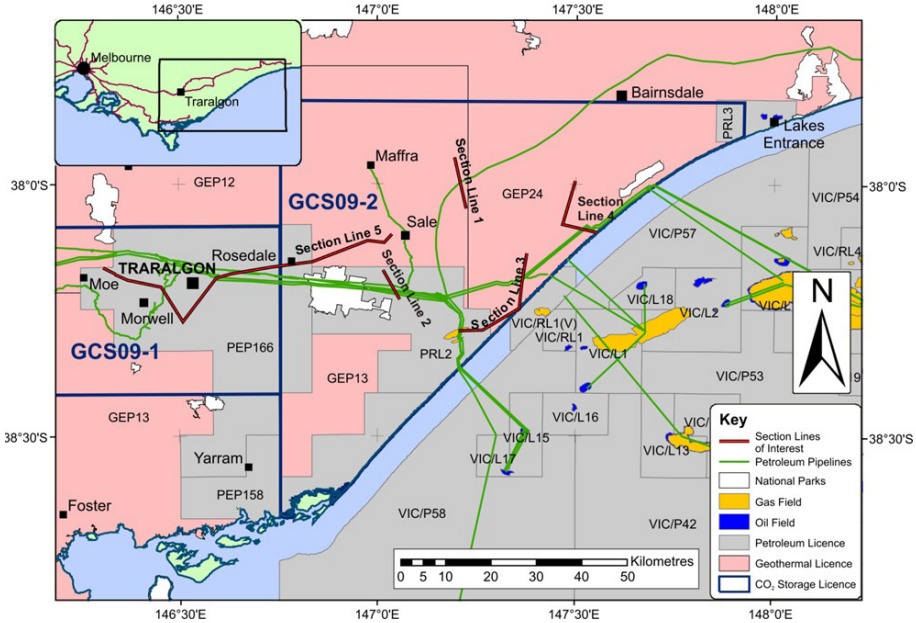


Figure 2 Map showing the coverage of state petroleum and geothermal licence areas across the onshore Gippsland Basin

the exploration mix as well as protect environmentally sensitive areas. In order to help balance exploration priorities and assess the effects of large scale CO_2 injection, a 3D model incorporating existing data (seismic, well data, known hydrocarbon fields and groundwater zones) has been produced allowing regional assessment of potential CO_2 storage areas with minimal risk of resource interaction.

Resource Interaction Issues and their Resolution

The case studies considered in this report illustrate that CO_2 storage can potentially have an influence on other subsurface resources, which in turn may influence the extent and timing of CO_2 storage projects. Influences can be positive or negative and some resources may overlap geographically, but have minimal effect on each other, especially if not in pressure communication. Potential influences are shown in Table 1.

*Note all references are provided at the end of the full report

Pore Space Resource	Positive	Negative
Oil	Might increase sweep efficiency hence more effective resource use; EOR can offset cost of storage, but not always usable; creates demand for CO_2 and hence improvement of capture technology; similar industries and service and supply needs; possible pressure enhancement	Pressure interference with existing operations; contamination of oil; infrastructure conflict; timing delays to CO_2 storage if EOR not feasible or wanted
Gas	EGR possible in some reservoirs (though rarely done); possible pressure enhancement	High cost of separating CO_2 from the produced gas if they mix; pressure interference with existing operations
Coal	CO_2 can flush out methane, creating valuable by-product	CO_2 would sterilize coal for mining or underground gasification
Groundwater	Could re-pressure low-productivity aquifers; pressure-relief wells used to increase CO_2 injection rates might produce useable water	Could acidify or contaminate potable water, or change hydraulic heads through pressure interference
Dissolved minerals	CO_2 could flush or displace saline water, enhancing water, and hence mineral extraction	CO_2 might react with some dissolved mineral salts, plugging pores
Geothermal	Better heat transfer medium than water; possible pressure enhancement	High temperatures might increase risk of corrosion; possible pressure interference with existing operations
Natural gas storage	Nil	Pore space unavailable for CO_2 storage for life of gas storage facility; pressure interference with existing operations
Waste disposal	Nil	Pressure effects or the presence of CO_2 may affect waste storage

Table 1 Positive and negative aspects of the interaction of CO_2 storage operations on other pore-space resources

If there is likely to be interaction between resources, decisions need to be made on how to go forward. Some regulations may distinguish priority of use, or assign different resources to different stratigraphic levels. The timings of potential resource interactions are relevant and can be classified as pre-implementation, during injection and post-injection. Pre-implementation considers options before the start of injection, such as which resource may have a higher priority, or at what point one resource should be exploited in regards to another resource, e.g. when should EOR be implemented in an injection project. During injection refers to any unexpected behaviour, such as unexpected plume migration or pressure development that may influence other resources. Post-injection refers to unexpected resource interaction after injection has ceased.

Risk assessment is necessary to deal with uncertainties by using past experience and analogues. They will allow regulatory agencies to assess the likelihood of affecting other subsurface resources and whether tying an area up under a permit is likely to lead to a successful outcome. A comprehensive risk model should support any CO_2 storage project and will be updated as more data becomes available.

Levels of certainty of storage capacity will be increased throughout the project as more is known. The initial capacity assessments will be based on the characteristics of the rock, inherited from its depositional environment and prediction of pressure and temperature conditions. As more information is known and if the capacity is less than expected, this may affect the plume size and potentially interaction with other resources.

Potential improved recovery of resources should be considered. Examples of this could be improvements to potable groundwater resources from increased pressure head; EOR, where CO_2 decreases the viscosity of oil, improving flow and production; or extraction of formation waters to mine dissolved minerals. Injection of CO_2 may also limit the use of other resources, such as storing CO_2 in coal which prevents its later use for UCG.

The rate of CO_2 injection needs to be economically viable without rupturing the seal and it is possible that the rate of injection may be less than initially predicted. If so, then solutions may include pressure relief wells and reinjection into shallower/ deeper levels, which may in turn affect other subsurface resources.

Seal integrity issues should be considered. Each storage site selected is expected to be secure, however mitigation plans will always be put in place for the unlikely case of failed seal integrity and other resources that may be affected by this need to be taken into account.

The pressure footprint of a CO_2 storage site will be much larger than the CO_2 plume itself and it will need to be determined if another resource is in pressure communication. Ground surface deformation should also be taken into account, as even though this is unlikely to be sufficient to affect other subsurface resources, it should be assessed on a case by case basis.

Any impurities in the CO_2 should be considered in terms of corrosion or potential contamination. The composition of the stream can affect storage capacity and CO_2 may react with minerals in the rock mobilising other substances, which should be taken into account.

Current infrastructure, such as old abandoned wells, can be a factor as the casing and cement could potentially be corroded by CO_2. It may also be possible to share pipeline infrastructure with oil or gas networks.

Monitoring and verification is an important aspect during all stages of a CO_2 project. There are many different monitoring methods and approaches and the best options may be site specific.

Regulatory conflict or overlap will need to be considered as resource use conflict can occur due to the wording of existing regulations or creation of new ones.

These potential influences to regulatory decisions are summarised in Table 2.

Factor	Stage	Scale	Resource Use Effects (main types)	Examples	References
Priority of use	Licensing round design	Basin	All	Gippsland	O'Brien 2011
Timing of interaction	Licensing, permitting, operation and post-closure	Basin and prospect	Hydrocarbons, EOR, gas or waste storage	Gippsland	Varma & Michael 2012

Factor	Stage	Scale	Resource Use Effects (main types)	Examples	References
Risk assessment	Permitting, financing, public acceptance; on-going	Prospect	All	In Salah	Bowden & Rigg 2004; Mander et al., 2011; Oldenburg et al., 2011
Storage capacity	Permitting and injection	Prospect	All	Gorgon	Flett et al., 2008
Improved recovery	Permitting and injection	Prospect	Oil, gas, gas hydrates, geothermal; extra resource extraction offsets cost	Weyburn-Midale	Buscheck et al., 2012; EGEC 2009; IEAGHG 2010/4; Nago & Nieto 2011; Regan 2007
Resource sterilisation	Permitting	Prospect	Coal, shale gas, groundwater, saline minerals, natural gas storage	Various, USA	Elliot & Celia 2012
Injectivity	Permitting and injection	Prospect	Variable; possible water production from relief wells	Gorgon	Flett et al., 2008
Seal integrity	Permitting and injection	Prospect	Groundwater, hydrocarbons	Gorgon	Flett et al., 2008

Factor	Stage	Scale	Resource Use Effects (main types)	Examples	References
Pressure fronts	Permitting and injection	Prospect and up to ~200 km distance	Groundwater, hydrocarbons, geothermal, waste disposal	Lussagnet/ Izaute, Zama field	IEA 2010/15; IEA 2011/11; Pooladi-Darvish et al., 2011
Surface deformation	Permitting and injection	Prospect (central)	Infrastructure, Geothermal	In Salah	Oldenburg et al., 2011
Composition of gas injected (e.g., CO2+H2S)	Permitting and injection	Source/ prospect/ migration path	Groundwater, geothermal	Laboratory/ Canada	Bachu & Bennion 2009; IEA 2011/4&11
Mobilisation of minerals and other substances	Operation and post-closure	Source/ prospect/ migration path	Groundwater, geothermal	Chimayo, Weyburn	Apps et al., 2010; Emberley et al., 2005; IEAGHG 2011/08; Keating et al., 2010
Infrastructure	Permitting through to post-closure	Prospect	Variable	Gorgon	Flett et al., 2008
Monitoring and verification	Permitting through to post-closure; important for public	Prospect and sur-rounds	All	Otway, Gorgon	Sharma et al., 2009

Factor	Stage	Scale	Resource Use Effects (main types)	Examples	References
Regulatory conflict or overlap	Licensing, permitting, operation	Potentially all scales	Variable	None known	None known

Table 2 Checklist of some of the major factors likely to be involved in regulatory decisions

Expert Review Comments

Comments were received from 9 reviewers representing industry and academia and were overall highly positive. Reviewers noted that some aspects of the case studies were not up to date and that there should be more information regarding waste water disposal. This was all addressed in the final report and the Surat Basin case study was added.

Conclusions

The interaction of CO_2 storage with other resources can be positive or negative depending on the geology, existing resources, economic potential and the regulatory environment. CO_2 storage operations may be feasible, both adjacent to other resource uses or at different stratigraphic levels in the same locality, particularly if there is no detrimental pressure connection between sites. On the other hand, if pressures associated with CO_2 storage are not confined then resource uses many kilometres distant from a storage site might be affected (beneficially or detrimentally). Resource use interactions can occur contemporaneously or sequentially. In particular, existing permits might preclude CO_2 storage and CO_2 storage might preclude future use of other resources.

Regulatory agencies should consider the following stages when evaluating resource development in relation to geological storage of carbon dioxide:

1. Identify all resources within the basin or region of interest, including "vacant" pore space, then map their distribution and assess their quality. It is important to do this, even using subjective criteria or estimates if there are few hard data. This will allow an assessment of the resources likely to be affected and the range of likely interactions. The Gippsland

Basin study by the Victoria State Government is a good example of this type of assessment.

2. Establish priority of use between the various resources and CO_2 storage.
3. Assess the proposed CO_2 storage project, its site characterisation, monitoring and verification plans, contingency and mitigation planning (e.g., how to cope with possible leakage, fault reactivation, loss of well integrity).
4. Review the injection plans and the likelihood that they will be achievable, and assess whether they might lead to cases of resource conflict (by seal rupture, pressure-front propagation or CO_2 plume migration into regions other than predicted or licensed to the storage operation).
5. Review the abandonment plans, longer term monitoring and verification planning and liability transfer arrangements.

Delays in establishing CO_2 storage regulations could not only inhibit CO_2 storage project development, they could lead to future, detrimental resource interactions. Nevertheless, time is needed to ensure regulations are clear and take into account potential resource prioritisation and interaction, as these issues are essential to the planning, costing, safety and surety of CO_2 storage projects. Assessments of potential resource uses in a region, and of possible usage interactions, should enable effective prioritising of opportunities in a region and efficient allocation and use of known or anticipated resources, and their potential effects on estimates of CO_2 storage capacity and injection scenarios.

Recommendations

There are several examples where interaction with other resources could potentially occur, but by looking at examples, including those from other industries, this may be able to be managed. In some cases this may not be the case and one resource may need to be prioritised over another depending on the priorities and regulations of the particular country.

This is a topic that will likely have more attention as there are more commercial sized CO_2 storage projects and it is recommended that IEAGHG continue to follow this topic and any updates, through future storage network meetings, namely the risk assessment network and by the study programme.

2013-09 INDUCED SEISMICITY AND ITS IMPLICATIONS FOR CO_2 STORAGE RISK

Key Messages

- The risks associated with induced seismicity at CCS sites can be reduced and mitigated using a systematic and structured risk management programme.
- Statistical models presently show the most promise for forecasting seismicity, but improved physical models are under development and may be key in the future. Both types will need to be tailored to the injection site.
- Site performance and management guidelines should be established prior to injection to facilitate: 1) definition of the acceptable levels and impacts of induced seismicity; 2) optimisation of the monitoring and mitigation programmes; and 3) the establishing of key control measures. Such guidelines have been developed for Enhanced Geothermal Systems and should provide the starting point for a management strategy of induced seismicity at CCS sites.

Background to the Study

Induced seismicity refers to seismicity caused by human/external activity above natural background levels in a given tectonic setting and is distinguished from triggered seismicity, where human activity affects earthquake recurrence intervals, magnitude or other attributes. The physics of triggered and induced seismicity is thought to be identical and both need to be considered during geological storage of CO_2. Induced seismicity may be observed during impounding of dams, mining and tunnelling operations, quarrying, underground solids/cuttings disposal, waste fluids disposal, oil and gas production, geothermal energy production and geological storage of gases and occasionally by rainfall. In some cases induced seismicity has led to projects being suspended, for example enhanced geothermal activities in Basel, Switzerland.

Injection and consequent geological storage of CO_2 may affect subsurface stress and alter in-situ fluid pressure and hence potentially induce seismicity. It is necessary to evaluate potential for and effects of induced seismicity

during risk assessment of storage projects. A best practice approach has already been proposed by the US WESTCARB Partnership based on protocols related to geothermal activities.

Induced seismicity may be caused by mechanical loads which can cause changes to the stress regime. Fluid pressures also play a key role in seismicity as pore pressures act against gravitational and tectonic forces and, if increased sufficiently, may cause rock failure. Pre-existing fractures may be stable in the stress regime before fluid injection, but fluid injection increases the pore pressure, which acts in opposition to the normal stress. If pore pressure is great enough to overcome the normal stress, then shear failure will occur.

Other factors that may affect seismicity are thermal and chemical stresses, which can have a weakening effect on the rock. This is likely in geothermal reservoirs, though usually occurs in conjunction with seismicity caused by changes in fluid pressure.

Induced seismicity can also be associated with hydraulic fracturing; this is when a rock is purposefully fractured by injecting water at high pressure with an aim to increase permeability. This has been observed during enhanced geothermal activities and in shale gas production.

Learnings from induced seismicity in other areas, e.g. geothermal activities and hydrocarbon exploration may be applied, but differences with CCS need to be taken into account; such as depth differences, type of sediment into which injection will take place, tectonic activity in the area, injection pressure, volume injected and the length of injection. These values will, for example be very different from those for enhanced geothermal activity which will likely be deeper, into basement rock, possibly in a tectonic area with higher injection pressures for short bursts.

Induced seismicity will also depend on several other factors, which may include the stress regime, fault orientation and locations, and rock friction. It is necessary that site characterisation takes into account any potential for induced seismicity; however, as more information becomes available during the lifetime of the project, through the monitoring programme, the risk in regards to induced seismicity can be reassessed. This may be in the form of real-time monitoring of any ongoing induced seismicity.

CO2CRC, a consortium based in Australia and New Zealand, was commissioned by IEAGHG to undertake this study.

Scope of Work

This study would provide a review of the mechanisms that cause induced seismicity and their application to geological storage of CO_2. The study would involve a detailed literature review of recent and ongoing research in this topic and an analysis drawn from the findings. Importantly, the study would focus on induced seismicity that may be caused by CO_2 injection and storage. Owing to the paucity of large scale CO_2 storage projects, it may be necessary to use findings from analogues (for example, steam assisted gravity drainage of heavy oil, cyclic steam stimulation in heavy oil recovery or produced water re-injection (also at hydraulic fracturing conditions) in oil and gas field operations). Particular issues to be considered and reviewed by the study include:

Weaknesses and threats to storage projects:

- Mechanisms that could potentially cause induced seismicity during injection and storage of CO_2 and the scale of the effect.
- Possible negative impacts on parameters associated with injection and storage, such as maximum injection pressure.

Strengths and Opportunities for storage projects:

- Increase in storage capacity owing to microseismic activity
- Monitoring of reservoir behaviour (caprock integrity) and displacement phenomena

General Overview of Risk Management Concepts (HSE Management):

- Hazards, threats, top events and consequences associated with induced seismicity
- Any preventative and recovery measures that may be taken

The study aims to highlight the current state of knowledge, to recommend further research priorities on these topics, and establish links and best practice sharing where applicable in other subsurface operations.

The contractor was referred to the following recent IEAGHG reports relevant to this study, to avoid obvious duplication of effort and to ensure that the

reports issued by the programme provide a reasonably coherent output:

- Pressurisation and Brine Displacement (Permedia, 2010/15)
- Caprock Systems for CO_2 Geological Storage (CO2CRC, 2011/01)
- Injection Strategies for CO_2 Storage Sites (CO2CRC, 2010/04)
- Extraction of Formation Brine from CO_2 Storage (EERC, 2012/12)
- Potential implications of gas production from shales and coal for CO_2 geological Storage (to be published, ARI)

Findings of the Study

This study considered the causes of induced seismicity and examples from CO_2 storage as well as relevant analogues. Empirical data are analysed and the observed relationships documented. Predictive modelling was then reviewed as well as risk management.

Induced earthquakes are indistinguishable from natural earthquakes in terms of their physical parameters such as frequency-magnitude distributions or waveforms produced. For example, earthquakes, including induced earthquakes, typically follow the Gutenberg- Richter relationship; for every magnitude 3 earthquake, there will be roughly 10 magnitude 2, and 100 magnitude 1 earthquakes, and so on.

The magnitude scale is a logarithmic scale so an M5 earthquake is 10 times greater than a M4 earthquake, which is 10 times greater than an M3 earthquake. In many case studies the magnitude is not consistently reported, e.g. whether local or moment magnitude is used, so the specific magnitude scale is ignored.

Events of less than M2 are considered microseismic events and can only be detected using seismological equipment, whereas events greater that M2 may be felt at the surface.

The dominant mechanisms that can result in induced earthquakes, within or close to subsurface reservoirs, include changes in stress field, reservoir pore pressure changes, volume changes of the rock (e.g., thermally induced) and applied forces or loads.

Case Studies

Induced seismicity at commercial and experimental CO_2 storage sites have many features in common. In general, induced seismicity reported for CCS sites have small numbers (<100/yr) and low magnitudes (M-2 to 1), so cannot be felt. The low numbers of induced earthquakes will partly reflect the fact that most CO_2 storage sites are monitored by a limited number of sub-surface geophones within existing wells. While cost effective, these geophone configurations are generally not optimal for accurately locating events or discriminating between ambient noise and small magnitude induced events. This sampling problem is exacerbated for permeable sand formations and saline aquifers where injection produces very low amplitude recorded events. In such cases peak amplitudes may be in the order of 10-7 m/s and are close to the noise floor of geophones used in wells. Not-withstanding these problems, no injection induced events >M1 have been produced by, and recorded at CO_2 storage sites.

Given the paucity of induced seismicity data for CO_2 storage sites, it is necessary to consider induced seismicity produced by water injection. Supercritical CO_2 is more compressible and less dense than water at pressures and temperatures typical of CCS reservoirs and these differences could cause variations in their patterns of seismicity. Higher compressibility of CO_2 compared to water makes it a 'softer' medium and could mean that its injection produces lower pressure increases and seismicity rates than water. Despite differences in the properties of water and supercritical CO_2, it is now accepted that they probably produce comparable induced seismicity magnitudes and productivity.

Other case studies considered are from the fields of petroleum production and stimulation, hydrothermal and petrothermal enhanced geothermal systems and waste fluid disposal. The mechanisms causing induced events differ across the different analogues making direct comparison difficult; these mechanisms are explained below.

Induced earthquakes associated with oil and gas extraction result from a reduction of pore pressure in the reservoir, which causes a contraction of the volume surrounding the extraction wells. The resulting stress changes are transferred to the surrounding rock volume and may trigger slip on existing

fractures or cause the creation of new fractures. In some cases this can cause subsidence at ground level. In the vast majority of hydrocarbon fields induced seismicity has either not been recorded, not studied in detail or not presented in the publically available literature. Due to this lack of information, there are limitations to what can be concluded about the causes, and associated risks of induced seismicity in hydrocarbon fields. It is clear however that induced earthquakes are generally small to moderate in magnitude (M≤4.5). In many cases, if present, induced seismicity must comprise events too small to be felt at the ground surface and recorded by regional seismograph networks (M≤3). It is possible that earthquakes in excess of M 7.0 were triggered by hydrocarbon operations, but for many proposed large magnitude induced events agreement has not been reached about their mechanical origins.

In a number of hydrocarbon fields the onset of seismicity has been linked to significant reductions or increases in reservoir pressures arising from production or water flooding.

Temporal relations between changes in reservoir conditions and induced seismicity are highly variable, with cases ranging from days to years.

The majority of induced seismicity in hydrocarbon fields appears to be from reactivation of pre-existing faults, while new faults are formed due to stresses caused by substantial subsidence. Differences in activity may be due to varying numbers of pre-existing faults or pre-extraction reservoir pressures. In an example in Texas (Cogdell field), induced seismicity was common at intersections or bends in basement faults; such fault complexities are often characterised by high densities of small-scale faults. Some of these apparent differences in the relative timing of changes in reservoir conditions and seismic productivity may be better resolved by improved datasets of the reservoir seismicity and dynamics. Additional data may also improve understanding of the relative importance of reactivation of pre-existing faults and generation of new faults for seismicity induced by hydrocarbon operations.

A range of geothermal sites were considered, both conventional, using low pressure fluid extraction and production and EGS (enhanced geothermal system) projects, where high pressure injection stimulation is required. Hundreds of geothermal fields are under production or development globally and the majority have not reported any felt induced seismicity. High

temperature geothermal reservoirs are generally in tectonically active zones, where a high level of natural seismicity is expected. Where seismicity occurs in other areas, it is thought to be due to increases in pore pressure as well as changes in 'roughness' of a fault. Other factors are displacement stresses associated with volumetric contraction caused by fluid extraction, thermal stresses and chemical stresses associated with injection of brine. In the case of EGS projects, seismicity can be associated with hydraulic fracturing.

In the relatively small number of operating EGS projects, there have been no known cases where any large induced seismic events have caused major damage or injury. Whether larger, low probability events can yet occur is still to be determined. Geothermal activities were terminated at Basel, Switzerland after a M3 induced event, which indicates the importance of understanding induced seismicity and suggests that its risks go beyond infrastructural damage and have implications for an entire industry.

Some investigations indicate that the smaller the strain energy placed in the formation, the smaller the probability of generating larger seismic events. Injection at lower pressures over longer periods, or more slowly building up injection pressures, then slowly reducing pressures as the stimulation period ends, may be advantageous. However, more research is needed on this.

Injection of waste into deep non-communicative aquifers is used to dispose of hazardous fluids, oilfield brine and as part of solution mining. Well documented occurrences of seismicity related to waste fluid are rare relative to the total number of active injection wells. There is evidence that if reservoir and injection conditions are not closely monitored and understood, induced seismicity is a potential outcome. Reported studies to date of waste water injection projects have shown that small to moderate earthquakes can be induced and, in the case of the Rocky Mountain Arsenal, three M≥5.0 earthquakes that caused minor damage in the city of Denver were the result. However, with careful planning and understanding of the reservoir, any risks can be minimised and should be low.

Observed Seismicity and Empirical Data Analysis

Empirical induced seismicity data from injection and extraction projects have potential value for informing risk management decisions at CCS sites. 35 sites from the literature were used for this analysis. Relationships were

analysed between induced seismicity parameters; i.e. maximum magnitudes, seismicity rates, b-values, timing and locations; and other reservoir or injection/extraction specific parameters; reservoir permeabilities together with injection/extraction volumes, rates and timing; from the literature.

Of great importance to note is the bias of the data available. Most injection and extraction sites do not have any significant induced seismicity and there is a bias of published data towards productive and large magnitude sequences as seismicity data is not often published for sites without significant seismicity. It is also important to note that CCS will be more closely regulated and monitored than has been the case in the past for other analogous activities. This regulation has the potential to further reduce induced seismicity at CCS sites compared to other injection/ extraction projects.

The maximum earthquake magnitudes of induced earthquakes are generally ≤M4.5 but on very rare occasions may exceed M6. Observations from the literature and this compilation indicate that the maximum magnitude of induced events may increase with total volume of fluid injected/extracted and the injection/ extraction rate. The volume-maximum magnitude relationship may arise because larger volumes of injection fluid have the potential to modify the stresses in larger volumes of crust and to encounter larger faults. It should be noted that the largest observed earthquakes are for fluid extraction projects, and so it is not possible to be certain if this is due to the fluid volumes or the different mechanisms associated with extraction projects.

Rates of induced seismicity are also positively correlated with injection rate and may be attributed to the rise in reservoir pressures expected for higher injection rates.

The rate of seismicity and the proportion of smaller to larger induced earthquakes in a sequence, i.e. the b-value for the Gutenberg-Richter relationship, also appear to increase with decreasing reservoir permeability. Reservoirs with low permeabilities (e.g., <0.01 mD) may have high rates of seismicity and b-values because they promote locally high stresses which generate many small new fractures. Induced earthquakes are typically spatially and temporally clustered.

The depth of earthquakes inferred to be induced by fluid injection or extraction are mainly <5 km from (or beneath) the surface and located within, or immediately adjacent to, the depth of the reservoir. Clusters of induced seismicity grow in dimensions with injection time and increasing injected volume. Where induced events reactivate pre-existing large-scale faults they form elongate epicentre distributions which increase rapidly in dimension in the fault

strike and dip directions. Most (~70%) induced events occur during injection/extraction with the number of events decreasing exponentially after injection/extraction ceases.

In all these analyses, it is important to note that other controlling factors, such as the state of stress and injection pressure and rates compared to formation pressure are not taken into account, due to the lack of information in the literature. These other controlling factors will need to be assessed for each site to get a fuller picture of the causes of induced seismicity.

Predictive Modelling of Induced Seismicity

Two main types of models, statistical and physical, have been used for modelling and predicting seismicity induced by fluid injection and both classes are in the relatively early stages of development.

A number of statistical models have been developed to predict temporal evolution, maximum magnitude and magnitude distribution of induced seismicity during and after injection. These statistical models, which were primarily developed for geothermal systems, typically rely on the Gutenberg-Richter relationship and/or the Omori-Utsu law and assume the occurrence of seismicity follows a Poisson distribution. Statistical models are now well established in the wider earthquake seismology community and could be developed to predict the seismic behaviour of a CCS injection system.

A particular challenge in developing robust statistical models to forecast induced earthquakes will be to test that they produce expected, unbiased and reproducible results. The development and refinement of induced seismicity forecast models will be facilitated by induced seismicity data for multiple projects being made widely available.

Many interacting factors contribute to the production of induced seismicity by fluid injection and numerical models need to fully couple fluid flow of different chemical species within a porous and fractured medium to elastic (and ideally, also inelastic) behaviour of the medium to account for the non-linearity effects.

Current numerical techniques are able to model multiphase flow and, in some cases, to couple fluid flow simulations with elastic models to account for the effect of pressure and temperature on strain/stress as well as the effect of strain/stress on permeability and porosity. Current models can highlight geometric and dynamic cases with significant risk of induced seismicity. Such models can be used to identify cases where the risk of induced seismicity can be minimized or avoided by adapting injection strategies.

The utility of these models is strongly dependent on the quality of the input data, including knowledge of the orientation and magnitude of the local stress field; the local fault network including any faults which may be effected by the pressure front; the hydraulic properties of the medium, such as permeability, diffusivity; and the elastic properties of the medium, such as elastic moduli and thermal expansion coefficient.

Obtaining these data and testing the model outputs using induced seismicity data will be critical for improving the utility of numerical models.

Only a few studies have considered the geochemical effects of CO_2 on fault friction and determining the long-term effects of CO_2 on fault rock behaviour is challenging, due to scaling issues.

Risk Assessment and Management

For the majority of existing fluid injection or extraction projects, induced seismicity has not significantly disrupted operations. The risks presented by induced seismicity are variable and include lack of public acceptance and support, damage to infrastructure and rupture of the seal or reservoir. Thresholds for triggering unacceptable risk may vary for different risk factors and CCS sites. Events near to (e.g., < 10 km) injection facilities and as small as M3 could cause damage to infrastructure and injury, while events as small as M2 may raise stakeholder concern.

A systematic and structured risk management programme in which risks associated with induced seismicity are identified and risk reduction, mitigation and control measures outlined will be critical for CCS projects. An eight step protocol for the assessment and management of induced seismicity has been proposed for EGS sites and should form the starting point for CCS sites. These steps are 1) Review laws and Regulations; 2) Assess Natural Seismic Hazard Potential; 3) Assess Induced Seismicity Potential; 4) Establish a Dialogue With Regional Authority; 5) Educate Stakeholders; 6) Establish Microseismic Monitoring Network; 7) Interact with Stakeholders; 8) Implement Procedure for Evaluating impact of induced seismicity.

Risk reduction and mitigation measures (Table 1) should be carried out during pre-site selection, site selections and characterisation; and site operational phases:

Phase	Risk Activity	Reduction and Mitigation Activity
Pre-site Selection (CCS Framework)	Stakeholder Uncertainty	Establish scientific and legal criteria for discriminating natural and induced earthquakes.
		Identify key stakeholders that will be impacted by induced seismicity and devise policies for engaging with stakeholders (e.g., government, regulators, public, NGOs).
		Introduce clear and usable CCS legislation for management of induced seismicity.
		Devise management protocols and acceptable earthquake magnitude thresholds for individual sites.
		Interact with stakeholders (e.g., regulators and operators) to ensure that risk assessment methods and process provides required outputs for induced seismicity.
		Governments regulate CCS and accept long-term liability for induced events.
	Seismicity	Preliminary regional assessment of potential for induced and natural seismicity.
	Public Acceptance	Survey public attitudes and perceptions toward and, knowledge of, seismicity induced by injection of fluid (and its risks) in local area of potential storage sites.

Phase	Risk Activity	Reduction and Mitigation Activity
Site Selection and Characterisation	Seismicity	Site specific assessment of potential for induced and natural seismicity.
		Measure reservoir stresses and predict change in reservoir stresses due to injection.
		Determine possible impact of rock properties and pre-existing faults on seismicity using fracture gradients and fault frictional properties.
		Integrate geomechanical, dynamic fluid flow and risk modelling for preferred storage site to forecast seismicity and estimate its impact on fluid flow.
	Monitoring	Develop mitigation and remediation plans (i.e. Induced Seismicity Management Plan) for potential seismic events using predefined magnitude and reservoir pressure thresholds.
	Public Acceptance	Educate and consult public about induced seismicity and risks.
	Economics	Develop economic modelling of CCS system for storage site incorporating induced seismicity. Highlight uncertainties in the economics arising from induced seismicity.
Site Operation	Monitoring	Record and analyse induced earthquakes in real time.
		Monitor reservoir pressures and plume migration to confirm pre-injection models.
		Modify monitoring and remediation plans as required.
	Mitigation	Adjust injection rates, injection intervals and number of wells to maintain induced earthquakes within pre-defined magnitude range and locations.
		Introduce financial compensation for damages and interference associated with induced seismicity.
	Public Acceptance	Reassess public response and perceptions to seismicity. Increase public communication and community support as required.
		Report induced seismicity to general public in near real time.
		Continue open dialogue with public regarding seismicity and general operations.
	Economics	Rerun economic models if critical seismicity thresholds are exceeded.

Table 1: Summary of tasks recommended for risk reduction and mitigation of induced seismicity for CCS projects.

An understanding of the expected size, number, location and timing of induced earthquakes is required for risk assessment and management of seismicity generated by injection of CO_2. Tools for forecasting induced

seismicity are of two main types: Tools that estimate generalities of induced seismicity prior to injection; and tools that provide more accurate estimates of the behaviour of the expected seismicity after injection has commenced. Category 1 tools are qualitative and include the use of empirical datasets together with preliminary physical and statistical models. Category 2 tools will be quantitative and include site-specific physical and statistical models. Statistical models presently show the most promise for forecasting induced seismicity; however, physical models could become key predictive tools in the future.

Monitoring and mitigation of induced seismicity should be an important component of commercial scale CO_2 storage projects. The design of monitoring networks for induced seismicity could vary between sites depending on a range of factors including; desired event magnitude range, site location and reservoir depth, levels of background seismicity and ambient noise and cultural site constraints (e.g., existing infrastructure and financial priorities). To optimise the utility of monitoring and mitigation programmes site performance and management, guidelines for induced seismicity should be established prior to injection.

Guidelines include setting the acceptable level (i.e. magnitude range and productivity) and impacts of seismicity and outlining the control measurements to be implemented if original expectations are exceeded.

There are also some potential benefits of induced seismicity to CCS. Firstly improved monitoring as mapping the locus of induced seismicity in real time provides a potential means of charting the movement of the pressure front associated with CO_2 injection, however further work is required to understand better relationships between locations of induced seismicity (for a given magnitude), pressure changes in the reservoir and the CO_2 plume. The pressure change would also need to be great enough to induce microseismicity, which will be dependent on a number of factors particular to the storage site. Secondly there will be increased permeability and therefore injectivity, due to hydraulic fracturing, though there is also the possibility that this could reduce sweep efficiency and therefore capacity; therefore effects must be determined on a site-by-site basis.

Expert Review Comments

Expert comments were received from 10 reviewers, representing industry (corporate sponsors of IEAGHG) and academia. The reviews were overall positive and key technical suggestions included more discussion on other controlling factors that could affect the current data and more discussion of the processes and mechanisms causing induced seismicity. These comments were addressed in the final report.

Conclusions

Induced seismicity has been widely reported over the last 40 years. To date few induced earthquakes have been recorded at CO_2 storage sites, however, the volumes of injected CO_2 are small and the onsite seismograph networks are often limited. Injecting commercial-scale volumes of CO_2 has the potential to produce induced seismicity at shallow depths of <5 km, but this will need to be considered on a site by site basis as there will be several controlling factors governing the likelihood of induced seismicity.

Observations from case studies and compilation of empirical data in this study indicates several potential relationships such as maximum magnitude of induced events may increase with total volume of fluid injected/extracted and the injection rate. The volume-maximum magnitude relationship may arise because larger volumes of injection fluid have the potential to modify the stresses in larger volumes of crust and to encounter larger faults. However, when considering empirical relationships, it is important to note the bias in the data and that the majority of sites do not produce induced seismicity to any significant degree. There are also a number of other controlling factors which will be specific to the site in question, but were not documented in enough detail to apply them to this study.

A particular challenge in developing robust statistical and physical models to forecast induced earthquakes will be to test that they produce expected, unbiased and reproducible, and, ultimately, informative results, which can be used as part of the risk assessment. The risks associated with induced seismicity at CCS sites can be reduced and mitigated using a systematic and structured risk management programme.

Risks to CCS projects associated with induced seismicity may include:

1. loss of public support due to concern about potential seismicity or from actual observed events;
2. ground shaking causing damage to property or injury;
3. loss of integrity of the reservoir though fracturing of the reservoir or of the seal.

The risks associated with induced seismicity at CCS sites can be reduced and mitigated using a systematic and structured risk management programme. While precise forecasts of the expected induced seismicity may never be possible, a thorough risk management procedure will include some level of knowledge of the possible behaviour of induced seismicity. Risk management will require estimates of the expected magnitude, number, location and timing of potential induced earthquakes. Such forecasts should utilise site specific observations together with physical and statistical models that are optimised for the site. Statistical models presently show the most promise for forecasting induced seismicity after injection has commenced, however, with further development physical models could become key predictive tools that are informative prior to injection. Combining forecasts with real-time monitoring of induced seismicity will be necessary to maintain an accurate picture of the seismicity and to allow for mitigation of the associated risks as they evolve. Site performance and management guidelines should be established prior to injection to facilitate: 1) definition of the acceptable levels and impacts of induced seismicity; 2) optimisation of the monitoring and mitigation programmes; and 3) the establishing of key control measures. Such guidelines have been developed for Enhanced Geothermal Systems and should provide the starting point for a management strategy of induced seismicity at CCS sites.

A number of information and knowledge gaps have been identified for induced seismicity. Understanding of induced seismicity and the associated risks would be improved by;

1. Increasing the induced seismicity catalogues publically available for development and testing of physical and statistical models,
2. Undertaking more systematic studies of sites populated by well constrained subsurface information and seismicity catalogues that are

completely recorded down to small magnitudes,

3. Improving the physical reality of physical models by modelling such factors as, poroelastic effects, multiple species of fluid and non-critically stressed systems,
4. Studying the scaling effects on seismicity associated with a move from pilot projects to full commercial implementation of CO_2 storage,
5. Developing standard risk management procedures and guidelines for induced seismicity for CCS projects and,
6. Filling induced seismicity knowledge gaps in the CCS community by collaborating with seismologists working in other industries.

Recommendations

Induced seismicity has not occurred to a significant degree on a CO_2 storage site and while analogues can be used for comparison and to help formulate a risk assessment plan, there are differences in the industries that cannot always be applied to CCS. Work is continuing in this area, with more CO_2 storage sites using microseismic monitoring and induced seismicity being accounted for in risk assessments.

It is recommended that IEAGHG continue to follow this topic, through the research networks (namely the risk assessment, modelling and monitoring networks).

2013-10 POTENTIAL IMPLICATIONS OF GAS PRODUCTION FROM SHALES AND COAL FOR CO_2 GEOLOGICAL STORAGE

Key Messages

- Exploitation of gas from both shale and coal will leave the formations with increased permeability and injectivity and therefore with increased potential to store CO_2.
- Large scale demonstration has yet to take place to confirm CO_2 storage capability and capacity for both shale and coal. Though demonstration projects are more advanced for coal with several small scale projects injecting CO_2 into wet coal seams (where there have been some injectivity problems related to coal swelling) and one project into an already dewatered coal seam.
- Overlap between potential shale gas exploration and potential storage reservoirs in deep saline formations may be considerable geographically, but much less so in 3D. Therefore use of both resources should be possible if well managed, though this will need considered on a case by case basis.
- There are still some uncertainties regarding CO_2 storage in shale and coal, and knowledge gaps where further research is needed have been identified as part of this study.

Background to the Study

Production of natural gas from both shale formations and coal deposits is rapidly developing as a major energy supply option in regions including North America, Europe and Australasia. Significant exploitation of these resources could affect CO_2 geological storage potential.

Coal deposits have long been regarded as a potential CO_2 storage option, in association with coal bed methane (CBM) production. Coal deposits used for enhanced coalbed methane (ECBM) are typically those that are too deep or too thin to be currently economically mined.

All coal deposits have varying amounts of methane adsorbed onto the pore surfaces. The methane may initially be recovered through dewatering and depressurisation i.e. as coal bed methane (CBM). Additional recovery and/or

storage can then take place by injection of CO_2 into the formation. The CO_2 can be preferentially adsorbed onto the surface of the coal, thereby trapping the CO_2 in the coal deposit or trapped in the coals cleat system. As it is now likely that additional recovery/storage operations using CO_2 will take place after the initial dewatering and depressurisation, the integrity of the coal seam will need to be considered and whether it is still a receptor for CO_2. This approach to coal seam CO_2 storage may also overcome the injectivity problems encountered with the pilot CO_2-ECBM projects. The cost of storage of CO_2 may be offset by the production of methane. However this approach to coal seam storage is new and it is not known whether the CBM production process leaves behind a reservoir that is suitable for CO_2 storage.

Shale formations constitute the most common, low-permeability caprocks that could prevent migration of buoyant CO_2 from underlying storage units, particularly deep saline aquifers.

Organic-rich shales may also form potential storage units for CO_2 based on trapping through adsorption on organic material (similar to coals), although this has not been demonstrated on a field scale. Lately, oil and gas companies combined horizontal drilling and rock fracturing technologies to produce oil and gas from shales, particularly in North America. Whilst these technologies open up the possibility of using shale formations as actual storage media for CO_2 by increasing permeability and injectivity, the same technology may compromise the integrity of shale caprocks in some basins.

Advanced Resources International (ARI), a company based in the USA was commissioned by IEAGHG to undertake this study.

Scope of Work

The main aims of the study are to assess the global potential for geological storage of CO_2 in shale and coal formations and the impact of gas production from shales on CO_2 storage capacity in underlying deep saline aquifers by compromising caprock integrity. The study would comprise a comprehensive literature review to provide guidance on the following issues:

- Global status of hydrocarbon production from shales and CBM and potential effects on CO_2 storage both in the producing shales/ coals themselves and underlying hydrocarbon reservoirs and/or deep saline

formations. The focus should be on gas production, but with reference to oil production from shales;

- Current status of research into geological storage of CO_2 in shales and coals;
- Potential nature and rate of trapping processes; mechanisms of storing CO_2.
- CO_2 injectivity into shales and coals, with reference to fracturing practices employed by industry;
- Containment issues arising from shale fracturing, both for shales as a storage medium per se, and in terms of caprock integrity for underlying storage units, particularly deep saline aquifers;
- Methods for assessing storage capacities for CO_2 storage in shales and coals;
- High level mapping and assessment of theoretical/effective capacities;
- Potential economic implications of CO_2 storage in shales and coals.

The contractor was asked to refer to the following recent and ongoing IEAGHG reports relevant to this study, to avoid obvious duplication of effort and to ensure that the reports issued by the programme provide a reasonably coherent output:

- Brine Displacement and Pressurisation (Permedia, Report 2010/15)
- Caprocks for Geological Storage (CO2CRC, 2011/01)
- Injection Strategies for CO_2 Storage Sites (CO2CRC, Report 2010/04)
- Impacts on Groundwater Resources (CO2GeoNet, 2011/11)
- Resource Interactions for CO_2 Storage (CO2CRC, 2013/08)

Findings of the Study

CO_2 Storage in Shale and Coal

Coal seams often contain gases such as methane, held in pores on the surface of the coal and in fractures in the seams. Conventional coal bed methane (CBM) extraction is achieved by dewatering and reducing the pressure in the coal seam, such that adsorbed methane is released from the porous coal surface. However, conventional CBM extraction may leave up to 50% of the

methane in the seam after development and production operations have been completed. As much as another 20% could potentially be recovered through the application of CO_2-ECBM. The fact that some CBM is high in CO_2 content shows that, at least in some instances, CO_2 can safely remain stored in coal for geologically significant time periods.

Gas shales can also adsorb CO_2, possibly also making shale formations significant targets for CO_2 storage. The process of enhancing the recovery of methane and the storage of CO_2 in shales could occur by the same basic mechanism as that for coal, and the organic matter in gas shales has large surface areas similar to that found in coal. These shales may also form potential storage units for CO_2 based on trapping through adsorption on organic material, as well as with the natural fractures within the shales.

Both shale and coal therefore can theoretically geologically trap CO_2 securely, though the extent of its effectiveness is still being assessed. Finally, deep coal seams and gas shales are widespread and, especially in the case of coal seams, exist in many of the same areas as large, coal-fired, electric power generation facilities.

The same advances that are allowing the potential of shale gas resources to be economically developed -- horizontal drilling and hydraulic fracturing -- open up the possibility of using shale and coal formations as actual storage media for CO_2 by increasing permeability and injectivity.

Methane Production from Coal and Shale

In coal seams, methane desorbs from the micropores of the coal matrix when the hydrostatic pressure is reduced, such as from the drilling of a well, and flows through the cleats to a wellbore. Coal seams are often shallow, and sometimes coexist with surface aquifers, while shale and tight gas are more often found at greater depths.

Coal bed methane reservoirs generally have a higher concentration of gas than shale reservoirs, generally because the organic content of coals is typically higher than that of shales. Shale reservoirs nearly always need to be hydraulically fractured, while perhaps only half of coal seam gas reservoirs require such fracture stimulation.

There are three main methods which can induce methane release from coal formations:

- Reduce the overall pressure, usually by dewatering the formation, generally through pumping
- Reduce the partial pressure of the methane by injecting another inert gas into the formation
- Replace the methane on the surface of the organic material with another gas, such as CO_2.

Dewatering and reservoir pressure depletion is a simple but relatively inefficient process, recovering less than 50% of the gas in place. Lowering the hydrostatic pressure in the coal seam accelerates the desorption process. Once dewatering has taken place and the pressure has been reduced, the released methane can be produced. CBM wells initially primarily produce water; then gas production eventually increases, while water production declines. Some wells do not produce any water and begin producing gas immediately, depending on the nature of the fracture system. Once the gas is released, it is usually free of impurities; and can be easily prepared for pipeline delivery. Some coals may never produce methane if the hydrostatic pressure cannot be efficiently lowered.

Hydraulic fracturing or other permeability enhancement methods are used to assist recovery but, even so, because permeability is normally low, many wells at relatively close spacing must be drilled to achieve an economic gas flow.

Coal bed methane production potential is determined by a number of factors that vary from basin to basin, and include: fracture permeability, development history, gas migration, coal maturation, coal distribution, geological structure, well completion options, hydrostatic pressure, and produced water management. In most areas, naturally developed fracture networks are the most sought after areas for CBM development. Areas where geological structures and localised faulting have occurred tend to induce natural fracturing, which increases production pathways within the coal seam.

Dewatering and reservoir pressure depletion is a simple but relatively inefficient process, recovering less than 50% of the gas in place. Lowering the hydrostatic pressure in the coal seam accelerates the desorption process. Once dewatering has taken place and the pressure has been reduced, the released methane can be produced. CBM wells initially primarily produce water; then gas production eventually increases, while water production declines. Some wells do not produce any water and begin producing gas immediately, depending on the nature of the fracture system. Once the gas is released, it is usually free of impurities; and can be easily prepared for pipeline delivery. Some coals may never produce methane if the hydrostatic pressure cannot be efficiently lowered.

Hydraulic fracturing or other permeability enhancement methods are used to assist recovery but, even so, because permeability is normally low, many wells at relatively close spacing must be drilled to achieve an economic gas flow.

Coal bed methane production potential is determined by a number of factors that vary from basin to basin, and include: fracture permeability, development history, gas migration, coal maturation, coal distribution, geological structure, well completion options, hydrostatic pressure, and produced water management. In most areas, naturally developed fracture networks are the most sought after areas for CBM development. Areas where geological structures and localised faulting have occurred tend to induce natural fracturing, which increases production pathways within the coal seam.

Dewatering and reservoir pressure depletion is a simple but relatively inefficient process, recovering less than 50% of the gas in place. Lowering the hydrostatic pressure in the coal seam accelerates the desorption process. Once dewatering has taken place and the pressure has been reduced, the released methane can be produced. CBM wells initially primarily produce water; then gas production eventually increases, while water production declines. Some wells do not produce any water and begin producing gas immediately, depending on the nature of the fracture system. Once the gas is released, it is usually free of impurities; and can be easily prepared for pipeline delivery. Some coals may never produce methane if the hydrostatic pressure cannot be efficiently lowered.

Hydraulic fracturing or other permeability enhancement methods are used to assist recovery but, even so, because permeability is normally low, many wells at relatively close spacing must be drilled to achieve an economic gas flow.

Coal bed methane production potential is determined by a number of factors that vary from basin to basin, and include: fracture permeability, development history, gas migration, coal maturation, coal distribution, geological structure, well completion options, hydrostatic pressure, and produced water management. In most areas, naturally developed fracture networks are the most sought after areas for CBM development. Areas where geological structures and localised faulting have occurred tend to induce natural fracturing, which increases production pathways within the coal seam.

Production from shale gas proceeds in a similar fashion; though, with few exceptions, shales do not have to be dewatered to allow gas desorption to occur. Also, in general, shale formations are often too deep and of such low permeability to facilitate economic production using just vertical, simple fractured wells.

Three factors have come together in recent years to make shale gas production economically viable: 1) advances in horizontal drilling, 2) advances in hydraulic fracturing, and, perhaps most importantly, 3) increases in natural gas prices. Although known for decades, what "changed the game" was the recognition that one could "create a permeable reservoir" by using intensively stimulated horizontal wells.

Experience to date has shown that each gas shale basin is different and each has a unique set of development criteria and operational challenges. Because of these differences, the most effective development approaches and well drilling and completion strategies for a particular basin tend to evolve over time.

Injectivity Issues

During primary methane production, reservoir compaction due to pressure depletion will occur, which causes an increase in the effective horizontal stress as the reservoir is confined laterally. Gas desorption from the coal

matrix will also occur resulting in coal matrix shrinkage, and thus a reduction in the horizontal stress and an increase in cleat permeability.

During ECBM/CO_2 storage in coal, adsorption of CO_2, which has a greater sorption capacity than methane, causes matrix swelling and in contrast to gas desorption, could potentially have a detrimental impact on cleat permeability of coal. Swelling of coal in the presence of CO_2 can reduce the permeability of coal seams, thus affecting the viability of ECBM or CO_2 storage operations. Early research suggested that matrix shrinkage/swelling was proportional to the volume of gas desorbed/adsorbed, rather than change in sorption pressure. Laboratory studies and field tests on the impact of matrix swelling on coal permeability have confirmed these results. However, such results were not consistently the case. Other factors that could affect the CO_2 injectivity in coal bed reservoirs are thermal effect of CO_2 injection, wellbore effects and precipitate formation.

To alleviate the impact of matrix swelling on injectivity, horizontal well configurations can be used. Numerical simulations have shown increased capacity for Northern Appalachian coals. Horizontal wells can also be designed to take advantage of the orientation of natural fractures in the rock. Well injectivity could also be increased using a CO_2-alternating-N2 injection strategy. The optimum gas mixtures depend on whether CO_2 storage or methane recovery is the primary objective, operational constraints and economics associated with gas treatment.

Similar issues are expected regarding CO_2 injection in shale's; however research to date is not sufficiently advanced to confirm this.

CO_2 Storage Integrity

The practice of testing seal integrity is not routinely performed as part of CBM production projects, but will be critical in determining the viability of a coal seam as a CO_2 storage site. A recent study considering processes leading to risks of developing leakage pathways include insufficient CO_2-Coal contact volume due to coal bed heterogeneity; injectivity loss due to coal swelling; leakage through pre-existing faults/ discontinuities and outcrops; CO_2/methane desorption due to potential future water extraction. General conclusions with regard to storage in coal seams are:

- There is a higher risk of leakage for open cavity well completions than cased well completions.
- Coal properties and available technology should minimise the risk that hydraulic fractures, used as part of well completion, will grow beyond the coal layer; though techniques to monitor fracture height need further development and demonstration.
- The processes of depressurisation during dewatering and methane production, followed by repressurisation during CO_2 injection, lead to risks of leakage path formation by failure of the coal and slip and discontinuities in the coal and overburden.
- The most likely mechanism for leakage path formation is slip on pre-existing discontinuities which cut across the coal seam. Sensitivity studies need to be performed to better evaluate this risk.
- Relationships between the amount of slip and the increase in flow (if any) along a discontinuity need to be developed.

Generally higher permeability shales are more suitable for gas production and this has been the current focus in the industry; these would also be potentially suitable for CO_2 storage. Whereas lower permeability shales are not commercial for gas production, but would be good candidates as potential caprocks for CO_2 storage.

It is possible that the production of hydrocarbons from shales may affect seal integrity and hence the potential use for CO_2 storage of formations directly underlying the shale formation may be compromised, however it will not affect other deeper saline formations or hydrocarbon reservoirs at other levels in the sedimentary succession. If a shale formation was thought to be producible for gas after already being used as a caprock for CO_2 storage, it is possible that part of the formation may be produced without affecting the stored CO_2; particularly in laterally extensive formations, though this would have to be evaluated on a site specific basis.

Shale formations are geographically and geologically extensive and most basins in the world containing shale gas resources cover large areas. If overlap does occur between formations targeted for shale gas development and production and formations targeted for CO_2 storage, there will likely still

be substantial storage capacity available where overlap does not occur to provide decades of storage capacity at current rates of emissions.

Once a shale formation has been fractured for hydrocarbon production, there remains the possibility of utilising the formation for CO_2 storage. There is also the possibility of using CO_2 to facilitate fracturing, though this may only be possible in certain geological settings. An example is a low pressure reservoir where fracturing liquids can become trapped because the pressure differential is not sufficient to push the liquids back to the wellbore. In some cases, the use of CO_2 for hydraulic fracturing is advantageous because it can be pumped as a liquid and then vaporises to a gas and flows from the reservoir leaving no liquid or chemical damage. The process is best applied in tighter (less permeable), low pressure, dry gas reservoirs where stimulation liquids are foreign to the formation and would reduce its permeability to gas, and also in higher permeability reservoirs where near wellbore formation damage can be removed with this non-damaging process.

RD&D Status of CO_2 Storage in Shale and Coal

As indicated previously the process for CBM extraction is likely to proceed first by conventional means and then secondly by CO_2 injection or CO_2-ECBM to produce additional methane. Research on direct injection of CO_2 into wet coal seams has been undertaken but pilot projects have suffered injectivity problems due to coal swelling around the injection well.

To date there has been only one pilot test of CO_2 injection into an already dewatered coal seam, the CONSOL Marshall County project in the USA. This project is supported under the USDOE's Carbon Storage Programme it commenced in April 2001 and will end in December 2014. A recent status report from the USDOE (May 2013) is included as Annex 1 to the main report of May 2013, approximately 3,265 metric tons of CO_2 have been injected at pressures of up to 6.4 MPa into two thin coal seams (considered to be unmineable because of their depth and thickness) which lie at depths of 375 to 500m. The current injection rate is 5 tons per day and there are plans to increase the injection rate to try and attain an injection rate of 17 tons per day. No breakthrough of CO_2 has been observed in any of the production wells, indicating that CO_2 remains stored in the coal seam. Indications are that the production wells may be showing signs of increased methane production as

a result of increased sustained CO_2 injection rates. Clearly this is an important project with regard to the feasibility of CBM production followed by CO_2 Storage. It is also worth noting that unlike other geological storage tests, the target reservoirs are shallow (only 375 to 500m). CO_2 will therefore not be injected as a supercritical fluid. Previous estimates by IEAGHG on the storage potential in coal seams set a limit of 800m as the upper level where CO_2 injection should be considered.

Based on a review of past and ongoing R&D related to CO_2 storage in coals and updated for this study, five key knowledge gaps and technical barriers were identified:

1. A lack of globally disaggregate information on the available storage capacity in deep, unmineable coals
2. A lack of guidelines for establishing location-specific criteria for defining "unmineable coals"
3. A lack of sufficient, widely available geological and reservoir data for defining the favourable settings for injecting and storing CO_2 in coals, particularly the lack of data on deep coal depositional settings and reservoir properties
4. Insufficient understanding of near-term and longer-term interactions between CO_2 and coals and between N_2 and coals, particularly being able to develop site/location specific models of coal swelling (reduction of permeability) in the presence of CO_2 and N_2, coal shrinkage with release of methane (increase in permeability), and the physics of CO_2/methane exchange under actual reservoir conditions of pressure and confinement.
5. Need for formulating and testing alternative reliable, high volume CO_2 and/or N_2 injection strategies and well designs, in multiple reservoir settings. This would help reduce the number of wells required for storing significant volumes of CO_2 from power plants and other industrial sources of CO_2 (and N_2)

Research on the potential for recovering methane and storing CO_2 in gas shales is significantly less advanced than that for coal seams. Reservoir characterisation and reservoir simulation work demonstrate that shales can store CO_2 based on trapping through adsorption on organic material as well as in natural fractures within the shales. Sufficient testing of this concept with

site-specific geological and reservoir data and detailed reservoir simulation, verified by field tests, in a variety of gas shale settings is needed.

The key knowledge gaps and technical barriers identified for shales are:

1. Lack of information on available storage capacity in shales in all but a few, targeted settings.
2. Lack of geological and reservoir data for defining favourable settings for injecting and storing CO_2 in shales, particularly lack of data on shale depositional settings and reservoir properties. This is true for assessing both the production of methane and CO_2 storage potential in shales.
3. Understanding near-term and longer-term interactions between CO_2 and shales, particularly the mechanisms of swelling in the presence of CO_2, shrinkage with release of methane, and the physics of CO_2/methane exchange under reservoir conditions.
4. Formulating/testing alternative reliable, high volume CO_2 injection strategies and well design.
5. Integrating CO_2 storage and enhanced recovery of methane in shales.

Global Gas Reserves and CO_2 Storage Potential

Global potential for hydrocarbon production and CO_2 storage in coals and shales were assessed with estimated recoverable resources estimated at 23.5 Tcm (trillion cubic metres) of recoverable coalbed methane resource and 188 Tcm of recoverable shale gas. World CO_2 storage potential in coalbeds was estimated to be 488Gt. A breakdown by country can be seen in the main report as well as a discussion on why these estimates are higher than those previously assessed in earlier IEAGHG studies on CO_2-ECBM potential.

There have been regional estimates, but no previous work on global CO_2 storage potential in shales. In this study to estimate the resource, the US Energy Information Administration (EIA) was used as a base. The methodology includes; conducting preliminary geological and reservoir characterisation of shale basins and formation(s); establishing the areal extent of the major shale gas formations; defining the prospective area for each shale gas formation; estimating the risked shale gas in-place and calculating the technically recoverable shale gas resource. Risked CO_2 storage potential was calculated as 740Gt. The breakdown by region is shown in the main report. It should be

noted that data was not obtainable for all basins, so a number of potentially significant shale gas resources were not included in the assessment.

Expert Review Comments

Comments were received from 8 reviewers representing industry and academia and were overall positive. Changes made from the reviewers' comments include restructuring the report, further discussion of implications of gas extraction on the reservoir, explanation of methods for calculation of storage capacity and additional references.

Conclusions

Exploitation of gas from both shale and coal leaves the formations with increased permeability and injectivity and therefore with increased potential to store CO_2. Both shale and coal appear to preferentially adsorb CO_2, allowing CO_2 to be both adsorbed and stored in the newly opened fractures. In the case of gas production from coal, the coal seam is usually dewatered by pumping, though methane can also be produced by pumping through an inert gas or by replacement with another gas, such as CO_2. To produce gas from shale, which is usually a tighter formation than coal, a combination of horizontal drilling and hydraulic fracturing is needed, whereas with coal vertical drilling may be sufficient depending on the geology.

With both shales and coal there has been a lack of large scale testing to prove storage capability and potential capacity. However, demonstration projects of storage in coal seams are still significantly more advanced than shale.

Reservoir characterisation and reservoir simulation work demonstrate that shales can store CO_2 based on trapping through adsorption on organic material as well as in natural fractures within the shales. Sufficient testing of this concept with site-specific geological and reservoir data and detailed reservoir simulation, verified by field tests, in a variety of gas shale settings is needed.

Research on direct injection of CO_2 into wet coal seams has been undertaken but pilot projects have suffered injectivity problems due to coal swelling around the injection well. The CONSOL project in the USA is the only one to test injection into an already dewatered coal seam, where approximately 3,265 metric tons of CO_2 have been injected at pressures of up to 930 psi into two thin coal seams at depths of 375 to 500m. The current injection rate is 5

tons per day and there are plans to increase the injection to try and attain an injection rate of 17 tons per day. No breakthrough of CO_2 has been observed in any of the production wells, indicating that CO_2 remains stored in the coal seam.

Based on a comprehensive review of the status of research into geological storage of CO_2 in shales and coals, the key knowledge gaps and technical barriers identified that could impact the achievement of this potential include a lack of critical formation-specific information on the available storage capacity in coal seams and gas shales; lack of geological and reservoir data for defining the favourable settings for injecting and storing CO_2 in coals and shales; understanding the nearer- and longer-term interactions between CO_2 and coals and shales; formulating and testing alternative reliable, high volume CO_2 injection strategies and well designs; and developing integrated, cost-effective strategies for enhanced recovery of methane and CO_2 storage in both coals and shales. Therefore, additional work in further addressing these key knowledge gaps and technical barriers is recommended.

The other issue to consider with shale gas exploitation is the potential overlap of formations suitable for shale gas exploitation and those suitable for use as a caprock above deep saline formations that have the potential to store CO_2. Studies show considerable geographical overlap of deep saline formations in the United States with potential shale gas production regions; however the potential storage reservoir and overlying caprock may be separated vertically by several layers from the potential shale gas horizon and may have minimal interaction. Storage project developers and regulators overseeing these projects will need to pay close attention to the interplay of shale gas and CO_2 storage development activities. Subsurface activities such as CO_2 storage and shale gas operations require geological review, ongoing monitoring, and regulatory oversight to avoid conflicts. With sensible safeguards, CO_2 storage reservoirs can, in most areas, coexist in the same space with conventional and unconventional oil and gas operations, including shale gas production and hydraulic fracturing.

Recommendations

CO_2 storage in coals and shales remain a possibility, though further research and demonstration is still needed, particularly regarding larger scale testing of CO_2 storage in both shales and coals following gas exploitation. It is therefore recommended that IEAGHG continue to follow the progress of these demonstration projects, particularly the US CONSOL project, which is the most advanced demonstration project looking into CO_2. IEAGHG could also include progress of work in this area within the research networks.

2013-13 THE PROCESS OF DEVELOPING A CO_2 TEST INJECTION: EXPERIENCE TO DATE AND BEST PRACTICE

Key Messages

- Data from 45 small scale projects and 43 large scale projects have been compiled in order to extract learnings and best practice guidelines were reviewed.
- No project is the same, and there is not a perfect template, however lessons learnt from previous projects can be applied to new projects.
- There needs to be an agreed and well defined workflow with clear decision points.
- At a very early stage, there needs to be very clear protocols for data collection, use of samples, input into databases, publication and dissemination of scientific outcomes.
- Key performance indicators need to be agreed with the regulators so that objectives of monitoring are clear.

Background to the Study

There are a significant number CO_2 injection sites around the world of varying size, all of which could provide useful learning experiences for anyone attempting their first test injection. Many projects will have gone through project planning, risk assessment, permitting processing etc; the learnings of which may be useful for future projects.

The purpose of this study is to document experience of the development of CO_2 injection projects in order for countries looking to embark on their first CO_2 test injection to refer to. This first test injection is considered to be in the order of 10,000 t CO_2 per year. They will then be able to refer to the experience and lessons learned through the development and operation of CO_2 test injection projects elsewhere in the world.

The initial stages of any injection project will be a desk based assessment and initial site selection, followed by exploration and detailed site characterisation, obtaining permitting for injections and setting out a monitoring plan.

Every storage site will have gone through various stages and processes before injection can start. These will differ depending on the size, location, local

regulations and the geology of the site. However, the processes, if not the details may be common amongst all sites, including site characterisation and license permitting (though regulations will vary throughout regions). Many CO_2 demonstration sites have been the first of their kind and regulations and permitting have developed alongside the project. For a country hoping to start their first injection it would be useful to be able to access one document that outlined the whole process with a timeline and pointed to relevant sources of information.

There are several best practice documents and guidelines available; these vary in scope and technical detail. A number of non-site specific best practice guides have been produced, such as NETL's risk assessment and site selection manuals and WRI's CCS guidelines that outline the entire process. There are also best practice guidelines considering learnings taken from particular projects, such as the SACS, best practice for the storage of CO_2 in saline aquifers, which uses, amongst others, learnings from the Sleipner storage site in the North Sea. Other examples of best practice guides are the QUALSTORE best practice guide and the EU Guidance documents. There are several documents outlining issues regarding public communication including guidelines from NETL and WRI. The Global CCS Institute recently commissioned CO2CRC to produce a summary of best practice guides, including a summary of the varying areas of coverage and technical detail. The document is publically available on their website: **www.globalccsinstitute.com/publications/review-existing-best-practice-manuals-carbon-dioxide-storage-and-regulation**.

CO2CRC, a consortium based in Australia was commissioned by IEAGHG to undertake a study compiling learnings from test injections.

Scope of Work

This study does not intend to redo work already carried out, but to produce an over-arching document, which follows the process of setting up a test injection. This document would identify gaps in best practice guides as well as point readers towards available information. The document produced would order the steps and processes that the user would need to go through during the management of the test injection; from scoping of the project (including success criteria), site selection, planning, injection and closure. Many of the steps will happen simultaneously, but an order can still be established along

with an expected timeline. This would be broad enough to allow for different permitting and legal processes in different countries as well as different site specific technical issues.

The study was suggested to be carried out in 4 parts;

The first part will be the identification of test injection projects. To date there has been a significant number of CO_2 test injection projects conducted around the world including: Frio, Otway, Ketzin, Nagaoka, as well as a significant number of US Regional Partnerships Phase II projects. Each of these projects would have to have gone through significant planning and development before entering into operation. The projects identified should have relevance to pre-commercial CO_2 test injections and pilot projects in the order of 10,000 t CO_2 per year.

The second part will be the identification of key development issues. For each project identified it would be valuable to document development information around project scoping, development of success criteria, project planning, planning a monitoring program, site selection, risk assessment, public engagement, legal and regulatory requirements, permitting, scheduling, costs, funding, staffing, skills required, management processes, reporting, reviewing and any unexpected hurdles and their solutions.

The third part will be looking at trend analysis. Once information is gathered, trends across projects could be analysed identifying what processes are common across projects and when and why processes may differ.

The fourth part will be the development of a test injection manual or best practice guide. Once information from existing projects has been gathered and trends analysed, a CO_2 test injection development manual could be produced. This will be an overarching document with all the steps needed in the process of setting up a test injection.

A follow-up of this work is the possibility of producing a webtool, whereby users will be able to enter information they have and be able to access the appropriate parts of the guide as well as relevant reference documents. This work will not be part of the current study, but the contractor was asked to keep this in mind when producing the guide.

CO2CRC were asked to refer to the following recent IEAGHG reports relevant

to this study, to avoid obvious duplication of effort and to ensure that the reports issued by the programme provide a reasonably coherent output:

- Injection Strategies for CO_2 Storage Sites (CO2CRC, 2010/04)
- CCS Site Selection and Characterisation Criteria (Alberta Research Council, 2009/10)
- Global Storage Gap Analysis for Policy Makers (Geogreen, 2011/10)
- What we have learnt from large scale demos, phase 1 and 1b (IEAGHG 2009/2011)

Findings of the Study

Information from 45 small scale injection projects and 43 large scale injections projects have been compiled in order to look at trends and put together learnings. Small scale projects were considered to be those injecting less than 100,000 tonnes, though the majority of projects inject considerably less (<15,000 tonnes).

Key Development Issues

A decision pathway for any project, including small scale projects, is needed, such figure 2, where there will be defined decision points which may be dependent on availability of funds, regulatory approval, risk assessment and geological suitability. How closely such a pathway is followed appears dependent on the project and those with an industrial partner may be more likely to follow closely, however there generally appears to be more flexibility with small scale projects than with larger ones.

Figure 2 The generalised project decision pathway

The first phase 'identify and assess' can take from between a few months to several years, depending on the starting point of a project. A project can start from a desktop study and compilation of possible options, though often it can depend on where CO_2 is available or if an oil company makes a site available for injection.

The 'select concept phase' aims to narrow down the site options to one (possibly with backup options) by developing a higher level of confidence of several factors including geology, logistics, cost and regulations. This is the phase where contact with the regulator is necessary and if there are not already regulations in place a set of key performance indicators (KPIs) may need to be agreed. There should also be communication with stakeholders, including the local community. This phase is usually 1-2 years.

The 'define' phase will further reduce uncertainty and define and finalise the project scope enough to take the project to the final investment decision (FID). The time scale will vary greatly with the complexity of the project; if an existing operator has control, possibly a matter of months, otherwise a minimum of a year should be expected.

The 'execute' phase happens after the FID and construction and equipment installation can take place. Necessary systems for approvals and cost controls need to be in place and in the case of a greenfield site; this phase will take around 12 months. This concluding act of this phase will usually be injection of CO_2.

Provided the previous phases have been undertaken carefully and all permits are in place, the 'operate' phase should run smoothly. It is necessary in this phase to draw up plans for abandonment. The timing of this phase will depend on the objectives of the project.

The 'abandon' phase includes the stages of suspension, closure and abandonment. Suspension is temporary and may be of short duration, but the decision to close the site has implications for decommissioning and KPIs may need to be agreed with the regulator. Abandonment will involve plugging and abandoning any wells, unless they will be used for some other purpose. Required monitoring after closure, will depend on the regulator as will liability transfer.

Trends in Project Development

Projects can only be compared in a general way, as they are all different and there are also only a limited number. When looking at the geographical distribution it can be seen that the majority exist in North America, partly due to the success of the Regional Carbon sequestration Partnership Program and partly due to the availability of CO_2 for the purposes of EOR. There are also

often fairly pragmatic reasons for the general location of a project, though obviously the geology is always a factor.

The main purpose of projects is demonstrating storage, but there is not always a clear statement of project objectives, and though 1/3 of projects are labelled as research, the specific purpose is not often given. The objectives of a project may also change over time.

Projects have a range of ownership and governance models, with 23% energy company owned, 17% by government, 16% by a single research organisation and 44% by a research alliance. Even if a project is owned by a single organisation, most projects involve collaborative arrangements between organisations, which can be a mix of industry, government, research bodies and academia. There does not appear to be a preferred structure within small scale projects, though it is important to have a clear governance structure and decision making process, so that risks can be managed.

Projects can only be compared in a general way, as they are all different and there are also only a limited number. When looking at the geographical distribution it can be seen that the majority exist in North America, partly due to the success of the Regional Carbon sequestration Partnership Program and partly due to the availability of CO_2 for the purposes of EOR. There are also often fairly pragmatic reasons for the general location of a project, though obviously the geology is always a factor.

The main purpose of projects is demonstrating storage, but there is not always a clear statement of project objectives, and though 1/3 of projects are labelled as research, the specific purpose is not often given. The objectives of a project may also change over time.

Projects have a range of ownership and governance models, with 23% energy company owned, 17% by government, 16% by a single research organisation and 44% by a research alliance. Even if a project is owned by a single organisation, most projects involve collaborative arrangements between organisations, which can be a mix of industry, government, research bodies and academia. There does not appear to be a preferred structure within small scale projects, though it is important to have a clear governance structure and decision making process, so that risks can be managed.

Learnings from Case Studies

Projects where particular technologies or approaches have been successfully applied, have been used as case studies to extract more in depth information regarding site characterisation, modelling, monitoring and risk assessment.

Site Characterisation

Most small scale projects do not follow the theoretical pattern of project development that has been suggested in the literature as being optimal for large commercial scale operations. Generally, small scale projects are opportunistic, typically initiated by research organisations; they rely on an alliance with industrial partners for operational expertise and access to suitable locations, site selection and therefore depends very much on whic sites can be made available.

Most small scale projects do not follow the theoretical pattern of project development that has been suggested in the literature as being optimal for large commercial scale operations. Generally, small scale projects are opportunistic, typically initiated by research organisations; they rely on an alliance with industrial partners for operational expertise and access to suitable locations, site selection and therefore depends very much on which sites can be made available

Storage sites within depleted fields or with an EOR component may only need minimal site characterisation, but deep saline reservoirs will usually be data deficient and require project specific data collection even when these reservoirs are located within the footprint of an existing production project.

The degree of pre injection site characterisation that pilot scale projects have engaged in varies considerably. The variability reflects the range of sites chosen for the experiment, including the availability of prior data, and the type of storage being investigated. Progress to larger scale demonstrations or full industrial scale projects will require a more extensive prior characterisation of the proposed site, and more exhaustive modelling than is seen in most small scale projects. Larger projects are also likely to benefit from early pilot scale projects.

Modelling

Reservoir simulations are performed routinely to assess CO_2 injection tests and

provide valuable information for system design, permitting, and monitoring. The simulations are also useful for some less obvious functions including provision of a systematic framework for integrating site characterisation data; as a communication tool to help people better understand CO_2 storage; and building confidence in the CO_2 storage process if the models demonstrate that the project is thoroughly researched, well designed, and properly operated.

In most published cases, models provided an adequate simulation of the CO_2 storage process, particularly in the prediction of the pressure response during injection. However, very rarely could the models fully describe the entire CO_2 storage process.

In most cases, projects follow a generalised workflow for reservoir simulations which consists of:

- Analytical injection model and volumetric storage capacity estimations during site screening.
- Simplified, possibly 2D-radial, scenario modelling using homogeneous parameter distributions including uncertainty analysis during the pre-feasibility phase of a project. Model parameterisation is based on pre-existing and literature data.
- Predictive modelling of the injection process in specific reservoir intervals during the detailed site characterisation phase. Additional data from core analysis, logging and initial well tests are used to better constrain reservoir parameters. Well test (i.e. brine injectivity test) will provide data for initial model calibration.
- Model calibration and validation during the injection and post-injection phases. Measured data from the M&V program are compared to model predictions and the model is continuously updated resulting in improved confidence in the model's predictive capability.

As in any other modelling field, the type, resolution and dimension of the reservoir model should be appropriate to the specific requirements and objectives of a project. Reservoir models associated with pilot projects that have research objectives related to the detailed behaviour of CO_2 in the

subsurface (dissolution rates, residual saturation, CO_2-water-rock interactions) may require high resolution models and extensive computational effort. However, depending on the complexity of the subsurface, a simple 2D radial model may be sufficient to predict the maximum plume extent and, in conjunction with M&V, satisfy regulatory requirements for a relatively simple test to demonstrate safe injection and storage of CO_2. The more detailed and calibrated modelling results from pilot injection projects can be matched with (semi-) analytical or simple 2D models that are less data intensive and require less numerical effort, the higher the confidence in providing an adequate modelling process that is time- and cost-effective.

Monitoring

Monitoring is used primarily as the basis of assuring that undesired or unexpected events that are identified in the risk assessment of the project, and that the likelihood of them occurring is not increasing. Though other objectives include pre injection monitoring for developing site baselines and adding to the data collation in site characterisation; and varied assessment of the storage activity relative to performance targets and reporting requirements, providing modelling calibration and storage effectiveness guidance.

However, for test injection activities, where R&D on monitoring technology may be a focus, knowledge of processes in the sub surface becomes vital, and can be extended to include understanding the performance and limitations of monitoring technologies in assessing these processes. Therefore monitoring in test injection projects may be used for a variety of purposes. This may include monitoring (and benchmarking monitoring techniques) for spatial distribution of injected fluid or changes in fluid saturations; geomechanical and structural events/changes to the subsurface; physical/chemical changes to injection interval and overburden; and/ or physical/chemical changes in the near-surface/surface/atmosphere.

Baseline monitoring to establish natural variability should be undertaken as soon as the evaluation of the site commences and certainly well before injection of CO_2 is initiated. Project monitoring should take place as soon as changes are made in the subsurface, typically associated with the start of injection of CO_2. In the case of EOR or ECBM, project monitoring may start

with the production of hydrocarbons rather than the start of fluid injection. However, there are many considerations required in developing effective monitoring operations and the planning for monitoring ideally should start no later than early within the evaluation stages of a CO_2 storage project.

For many of the test injection projects, the planning for monitoring commences at the very onset of the opportunity definition, as a key purpose of a test project typically includes R&D into monitoring technologies. Field trials of the effectiveness of particular monitoring techniques falls within the evaluation stage, so that findings (including realised technology restrictions), can be considered in the more mature monitoring plan. When projects require monitoring of the biosphere; seasonal variability and related factors typically require long term biosphere characterisation, which needs to start at the start of the "Define" stage. The commencement of the project build phase typically coincides with the deployment of the majority of the monitoring infrastructure (such as dedicated observation wells) and the commencement of baseline monitoring (such as initial 4D seismic). Monitoring of the performance of the CO_2 injection will typically extend beyond the conclusion of CO_2 injection, with the time depending on the requirements of the regulator and match between modelling and monitoring results. Assurance monitoring is likely to continue through to near the end of the closure of the project, again depending on regulatory requirements. In some circumstances assurance monitoring may be continued by the regulator or some designated body, post closure.

Risk Assessment

Information and documentation for risk assessments for test injection projects was very limited. In some cases this may be due to this being carried out by the industrial partner and the research organisations not having access, in some cases it may not be published. Otway was used as a case study as all information was available.

Risk assessment is updated throughout the project. The risk response plan resulting from risk assessments evolves along with the stages of the test project's characterisation through to operation and monitoring observations. Early in the project's characterisation and data acquisition stages, a risk targeted-uncertainty reduction process should take place. In ideal cases the

development of a field for a test injection project provides an opportunity to collect much of the necessary data for some uncertainty reduction, such as a sampling and logging program to accompany the drilling of the injection or monitoring well. In some cases, if risk levels warrants and budget allows a targeted uncertainty reduction characterisation program may be required. It is at points such as these that risk- and cost-based decisions on project continuation may result in major project changes or project cancellation.

As a project progresses towards execution and operation, working thresholds are able to be established to assure risks associated with containment and performance are maintained at an acceptable level. Understanding these thresholds assists in forming the basis of the monitoring plan in terms of capabilities of technologies to determine whether these thresholds are being approached. An example of this is fracture pressures, where a reasonable uncertainty range should be developed according to the existing data, a pressure threshold determined, iterative modelling of pressure to injection design so that maximum pressure is comfortably below the threshold, a pressure monitoring system designed installed, and an operational response plan developed if pressure approaches the threshold.

During the operational stages all risks should either be sufficiently below an acceptable risk level or have contingency measures in place to respond to an undesirable event taking place.

The level of cost and effort applied to a risk response and monitoring plan should be based on the assessment of that risk with all its likelihoods and consequences considered. In all cases the project activities should follow appropriate industry standards and best practices in the management of risk.

Figure 1 shows a compilation of features from the small scale projects, though it is important to note that this does not aim to be statistically meaningful, or to show what a project should entail, but should give some idea of general features and may be useful at the earliest stages of developing project concept.

PROJECT PARAMETER		PROJECT TYPE				
		DSA	EOR	DOGF	ECBM	Basalt
	Max Number of Projects	18	9	4	11	2
	Time (start of injection) (years)	3	2-3	3	3	5-6
	CO2 Source	Multiple	Geological	Natural Gas	Multiple	Food/ Magmatic
	Transport	Mainly truck	Pipe + Truck	Onsite	Truck	?
	CO2 injected (tonnes)	15,000	20,000	64,000	2,000	2,000
	Injection Rate (tonnes/day)	127	74	84	31	36
	Injection Pressure (psi)	1,662	1,240	1,980	1,995	362
	Injection Depth (m)	1,600	1,600	2,900	700	700
	Cost US$	12	12	60	6	17
Percentage of Projects Using the Specific Technology	Donwhole Seismic	100	40	100	40	50
	Groundwater Monitoring	70	80	50	80	100
	Soil Monitoring	40	100	70	30	100
	Atmospheric Monitoring	60	60	50	30	100
	Biological Monitoring	20	0	20	40	100
	Tracer Analysis	40	40	20	60	100
	Electromagnetic	20	10	0	0	0
	Gravity	0	20	0	0	0
	Pressure Logging	100	70	100	100	100
	Thermal Logging	90	60	100	100	50
	Wireline Logging	90	70	80	40	100
	Observation Well	60	40	80	80	50
	Geochemical	80	60	100	100	100
	INSAR	0	0	0	10	0
	Reservoir Modelling	90	90	100	100	100
	Coring	100	60	100	100	0
	Reflection Seismic	100	60	100	60	0
	Geological Model	90	80	100	90	50

Figure 1 Project parameters according to types of projects

	Pre-feasibility	Site Selection	Capacity Estimation	Simulation & Modelling	Construction
SACS	Basic	Technical	Technical	Technical	-
NETL (SS)	Basic	Detailed	Technical	Basic	-
NETL (RA)	-	-	-	Technical	-
NETL (MV)	-	-	-	-	-
NETL (GS)	Technical	Technical	-	-	-
NETL (PO)	-	-	-	-	-
WRI (CCS)	Basic	Detailed	Basic	Basic	Basic
WRI (CE)	Basic	Basic	-	-	Basic
DNV	Detailed	Detailed	Detailed	Basic	-
DNV (Wells)	Detailed	Detailed	-	-	-
CO2Cap	-	Basic	Basic	-	Detailed
GEOSEQ	-	Basic	Basic	Basic	-
CO2NET	-	Basic	Basic	Basic	-
IEA	-	-	-	-	-
CO2Cap (R)	-	-	-	-	-
MRCSP	Basic	Basic	-	Basic	Technical
CO2Care	-	-	-	-	-
GCCSI/ICF	Detailed	Basic	Basic	Basic	Basic
CO2CRC	Detailed	Detailed	Basic	Detailed	Detailed

-	Not Covered
Basic	Briefly covered in a generic way
Detailed	Comprehensive discussion, generally generic
Technical	Provides technical detail of projects, generally comprehensive
NETL (SS)	Best Practuces for: Site screening, site selection, and initial characterization for storage of CO_2 in deep g
NETL (RA)	Risk analysis and simulations for geologic storage of CO_2
NETL (MV)	Best Practices for: Monitoring, verification, and accounting of CO2 stored in deep geologic formations
NETL (GS)	Best Practices for: Geological storage formation classification: Understanding its importance and impac
NETL (PO)	Best Practices for: Public outreach and education for carbon storage projects
WRI (CCS)	Guidelines for CCS
WRI (CE)	Guidelines for community engagement in CCS

Figure 3 Scope and content of some best practice manuals

Operation	Closure	Monitoring & Verification	Risk Assessment	Community Consultation	Regulation
Basic	Detailed	Technical	Detailed	Basic	Basic
-	-	-	Basic	Basic	Detailed
-	-	-	Technical	-	-
Technical	Technical	Technical	Basic	-	Basic
-	-	-	-	-	-
-	-	-	-	Technical	-
Basic	Detailed	Detailed	Detailed	Basic	Detailed
Basic	Basic	Basic	-	Detailed	Basic
Detailed	Detailed	Basic	Detailed	-	Detailed
-	-	-	Technical	-	-
Detailed	Basic	Technical	Basic	-	-
-	-	Detailed	-	-	-
Basic	-	Basic	-	-	-
-	-	-	-	-	Technical
-	-	-	-	-	Technical
Technical	-	Technical	-	-	-
-	Technical	-	-	-	-
-	Technical	-	-	-	-
Detailed	Basic	Detailed	Detailed	Detailed	Detailed

eological formations

cts on CCS opportunities in the United States

Best Practice

Best practice guidelines were reviewed, while few cover the entire chain, the more specific guidelines tend to cover particular aspects in more detail. So it may be best to use guidelines together, or focus on the ones which cover the aspect being researched. Figure 3 (on the previous page), shows the level of detail that can be found for specific aspects, further details can be found in the report.

Observations from test injections considered in this study, show that collaborative agreements may be necessary at this stage of development and realistically a significant level of financial involvement from government is required. Another common thread in virtually all projects is to link research institutions with industrial partners, in order to advance the science with practical field based trials (with the industrial partner proving the operational experience).

Expert Review Comments

Comments were received from 9 reviewers representing industry and academia and were overall highly positive, with all reviewers agreeing on the usefulness of the work. Comments included updates on projects, clarifications on the terms used in the decision pathway, improvements to some diagrams and inclusion of a summary expressing the use of small scale pilot projects. This was all addressed in the final report.

Conclusions

This study provides an indication of how a project might be organised and undertaken, the conditions that might prevail (depth, amount of CO2 likely to be injected, injection rate, timing, cost) and the range of technologies that should or might be deployed, though these parameters will vary depending on the objectives of the project and the particular features of the site.

As well as the learnings derived from the project compilation, any new injection project should use the information available from previously written best practice manuals and

guidelines. The guidelines reviewed in the study are project based, often focused on different aspects of a project and vary greatly in the amount of detail given. There is no single all-encompassing "best practice" for small scale projects that can be followed to the letter. Rather there are many lessons to

be learned from the 45 small scale projects that have been reviewed in this report which will be applicable to other projects to varying degrees.

The objectives of the project must be agreed and clearly defined in a manner that addresses the expectations of all key stakeholders, whilst recognising that as a research/pilot project, not all objectives will necessarily be achieved. For this reason, it is also important to also prioritise objectives as well as retain the necessary degree of flexibility so that if there are unexpected outcomes, objectives can be modified or re prioritised in a sensible manner. If the project is being undertaken by a consortium, ensure that there is full alignment between all participants on issues such as budgets, funding, responsibilities, liabilities, governance, confidentiality, communications, operations and management and board responsibilities. To the extent possible it should be ensured that there is alignment of funding, budgets, and the expenditure profile over the life of the project.

There needs to be an agreed and well defined work flow with clear decision points to enable the project to be logically taken from identification of the opportunity through to the operate stage and finally the abandon stage. There should be agreement on how and on what basis the project will be abandoned at the conclusion of the project including ensuring that there is adequate funding available meet abandonment (including remediation) requirements.

Engagement with the local community should be at the earliest possible opportunity; ensuring that they learn about the project from members of the project and not from the media. A local liaison officer or community officer, who lives in the vicinity of the site and who can act as the first point of contact, but at the same time ensure that the opportunity is there to talk directly to the scientists and engineers and establish an open and transparent approach to all aspects of the project. Also a broader communications strategy should be in place, at the regional national and international levels, for the project, particularly once it starts moving towards the operational phase, in order to provide positive stories on the project to the media and also to address any incidents at the site, should they occur.

Key performance indicators will need to be agreed with the regulators, so that objective of monitoring are clear and to ensure that the project can confidently move forward in the knowledge that the "ground rules" will not change in the middle of the project. Where regulations already exist ensure that will meet the needs of the project, and that you can meet the requirements of the regulations.

Comprehensive characterisation of the site needs to be undertaken and a system in place so that all models are updated as new information becomes available. Characterisation should include a broad understanding of the geological setting of the site including depositional environments of reservoirs and seals, structural setting, geomechanical properties, seismicity, ground waters (dynamics and composition), geological and reservoir models. There should be a monitoring regime that will deliver data to address key performance indicators, address regulatory needs, meet community expectations and provide assurance to the community. Though before injection takes place, baseline data should be collected and there needs to be adequate knowledge of natural variability, both temporal and spatial, for all key parameters.

Risk assessment and management should be embedded within all aspects of the project including research, monitoring and operations.

The closure and abandonment stages of small scale projects are in general not well documented; it is important the information relating to these concluding activities is captured and made available, including information on any post closure monitoring.

Recommendations

A great deal of effort has gone into compiling data for all of the projects considered in the study and they have been placed in a useable format. The information is very relevant and useful for any new project and also existing projects to see what learnings there are from different projects. It is therefore recommended that IEAGHG make full use of this data by compiling a searchable database and hosts this information on the website. If this cannot be carried out internally, it is suggested that this be contracted out. This information should also be updated on a regular basis, which could be by utilising the contact details on the data sheets.

2013-07 KEY MESSAGES FOR COMMUNICATION NEEDS FOR KEY STAKEHOLDERS

Background to the Study

CO_2 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_2

In general perceptions of CO_2, 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_2 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_2, 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_2?'** With so many perceptions about CO_2 being misconceptions, it was decided to start with a very short briefing note, describing the physical properties of CO_2, clarifying the difference between CO_2 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_2 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_2 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_2 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_2?'** 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_2, 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_2'** An important topic, this note explains that there are a multitude of technologies and tools available to monitor the CO_2 both during injection and after to ensure that the injected CO_2 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_2, 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.

2013-11 POTENTIAL FOR BIOMETHANE PRODUCTION AND CARBON DIOXIDE CAPTURE AND STORAGE

Key Messages

- Biomethane production in combination with carbon dioxide capture and storage (CCS) has the technical potential to remove up to 3.5 Gt of greenhouse gas emissions from the atmosphere in 2050. This is in the context of the required emissions reductions from the energy sector of over 30 Gt by 2050 (IEA CCS Roadmap 2013). Annual greenhouse gas emission savings could be almost 8 Gt in 2050 if natural gas is replaced by biomethane production with CCS.
- The maximum technical potential is provided by large scale gasification based production of biomethane with CCS which could have potential in regions where large scale infrastructure is already in place for the transport of biomass, natural gas and CO_2. Small scale biomethane production with CCS based on digestion, suitable for biomass with high water content, is most likely restricted to niche market applications. The technical potentials are limited by the availability of sustainable biomass
- The economic potential depends strongly on the CO_2 price and natural gas price, and is much lower than the technical potential for all scenarios, the highest potential being 0.4Gt by 2050.
- Overall, the potential is most likely restricted to those regions that have favourable (high) natural gas and CO_2 prices and favourable infrastructure.

Background to the Study

In 2011, the IEAGHG R&D Programme published a report on the global potential of six technology routes that combine biomass with CCS titled: Potential for Biomass and Carbon Dioxide Capture and Storage (IEAGHG 2011/06). The study considered four electricity production routes and two routes for biodiesel and bio-ethanol production. This study addresses two additional technology routes combining the production of biomethane with the capture and storage of the co-produced CO_2.

Scope of Work

The aim of this study is to provide an understanding and assessment of the global potential - up to 2050 - for BE-CCS technologies producing

biomethane. It makes a distinction between: *Technical potential* (the potential that is technically feasible and not restricted by economical limitations) and the *Economic potential* (the potential at competitive cost compared to the reference natural gas, including a CO_2 price).

The study assesses two concepts to convert biomass into biomethane: gasification (followed by methanation) and anaerobic digestion (followed by gas upgrading). The types of feedstock taken into account are energy crops, agricultural residues and forestry residues. For digestion it also considers biogenic municipal solid waste, and animal manure and sewage sludge as feedstock.

Findings of the Study

Table 1, Figure 1 and Figure 2 summarise the most eminent results of this assessment. The results show the maximum technical potential in 2050 is found for the gasification route with CCS. In this route 79 EJ of biomethane is produced, leading to the removal of 3.5 Gt of CO_2 from the atmosphere. This is a significant potential when compared to the current (2009) global natural gas production of almost 106 EJ. On top of that, the substitution of 79 EJ of natural gas with biomethane would result in an additional greenhouse gas emission reduction of 4.4 Gt of CO_2 equivalents. In total, almost 8 Gt CO_2 eq. can be reduced through this route[1] and with it provides a significant reduction potential compared to the global energy-related CO_2 emissions, which grew to 30.6 Gt in 2010 (IEA 2011).

The total technical potential for the digestion based route with CCS (digestion-CCS) is lower, 57 EJ, as a smaller fraction of the biomass potential for energy crops and residues (forestry and agriculture) can be used in this technology route as the technology is less suitable for the conversion of lignocellulosic biomass. The potential of the more suitable feedstock for digestion, being municipal solid waste (MSW), animal manure and sewage sludge, is relatively small. The potential of these sources sums up to almost 12 EJ (0.7 Gt CO_2eq) of biomethane in the year 2050.

[1] Note that 1 Gt of negative emissions is not the same as 1 Gt of emission reductions. Generally speaking, the emission reduction potential of BE-CCS options is equal to the amount of negative emissions plus the emissions of the technology or fuel it replaces, in this case natural gas. Throughout the remainder of the report it indicates negative emissions, not avoided or reduced emissions, unless otherwise indicated.

Technology Route	Year	Technical Potential				Economic Potential	
		Primary energy	Final energy	CO_2 stored	GHG balance (CO_2 eq)	Final energy	GHG balance (CO_2 eq)
			EJ/yr	Gt/yr	Gt/yr	EJ/yr	Gt/yr
Gasification	2030	73.1	44.8	2.4	-1.8	2.7	-0.1
Gasification	2050	125.6	79.1	4.3	-3.5	4.8	-0.2
Anaerobic digestion – EC and AR*	*2030*	*43.3*	*26.0*	*1.2*	*-1.1*	*1.4*	*-0.1*
Anaerobic digestion – EC and AR*	*2050*	*74.7*	*44.8*	*2.1*	*-2.1*	*2.4*	*-0.1*
Anaerobic digestion – MSW	*2030*	*5.1*	*3.1*	*0.1*	*-0.1*	*3.1*	*-0.1*
Anaerobic digestion – MSW	*2050*	*10.6*	*6.4*	*0.3*	*-0.3*	*6.4*	*-0.3*
Anaerobic digestion - Sewage/ Manure	*2030*	*7.4*	*3.0*	*0.2*	*-0.2*	*3.0*	*-0.2*
Anaerobic digestion - Sewage/ Manure	*2050*	*13.8*	*5.5*	*0.4*	*-0.4*	*5.5*	*-0.4*
Anaerobic digestion – Total	2030	55.9	32	1.5	-1.4	7.4	-0.4
Anaerobic digestion – Total	2050	99.1	26.7	2.8	-2.7	14.3	-0.8

*Energy Crops and Agricultural Residues

Table 1 Overview of global technical and economic potential per BE-CCS route for the view years 2030 and 2050

One of the interesting features of biomethane production for grid injection is that the separation of CO_2 is already an intrinsic step in the production process. This means that the incremental costs of adding CCS is potentially low.

The economic potential for biomethane-CCS is dominated by the CO_2 price and the natural gas price, which may vary per location. For almost all combinations of feedstock (energy crops, agricultural residues and forestry residues) and conversion technology there is only an economic potential at high natural gas prices (>11 €/GJ) combined with CO_2 prices of at least 20 €/tonne. An exception is the use of municipal solid waste (MSW) and sewage sludge in combination with anaerobic digestion which show already an economic potential at a CO_2 price of 20 €/tonne CO_2 and natural gas price of 6.7 €/GJ. The economic potential is the highest for digestion-CCS of animal manure/sewage sludge and MSW. When assuming a CO_2 price of 50 €/tonne, the economic potentials in 2050 reach 5.5 EJ (-0.4 Gt CO_2 eq) for animal manure/sewage sludge and 6.4 EJ (-0.3 Gt CO_2 eq) for MSW. Drivers for the deployment of biomethane are (EU) targets for biofuels, increasing security of supply (e.g. by reducing the import dependency of natural gas), and the presence of existing natural gas transport and distribution infrastructure.

Barriers typical for the deployment of digestion-CCS are high biomass transport costs which limit the plant size and it is likely that the small size of digesters also results in a high cost for connecting to the CO_2 and natural gas infrastructure. Nevertheless, anaerobic digestion-CCS of MSW, sewage sludge and animal manure might become a promising niche application that offers the opportunity to process waste, reduce carbon emissions and produce valuable biomethane. Further it is important for the digestion-CCS route to look for possible valuable end-use of captured CO_2 to enhance business case for smaller systems with CO_2 capture (e.g. CO_2 use in industry and in horticulture).

The gasification-CCS route fits best with a large scale infrastructure for the transport of biomass, natural gas and CO_2; that is, a more centralised production of biomethane combined with CCS. The implementation of decentralised production of biomethane and end-use, in combination with CCS is deemed unlikely, due to infrastructural requirements for both CO_2 and natural gas.

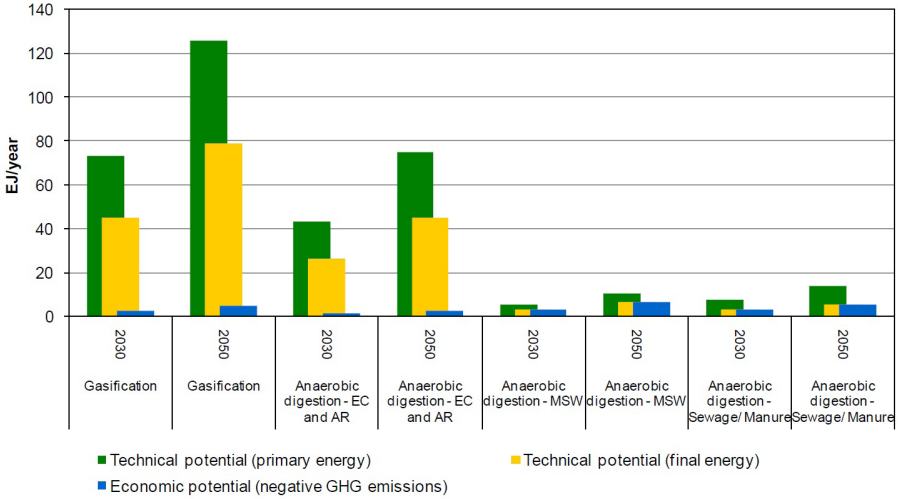


Figure 1 Global technical and economic energy potential (in EJ/yr) per BE-CCS route for the view years 2030 and 2050. Note that potentials are assessed on a route by route basis and cannot simply be added, as they may compete and substitute each other.

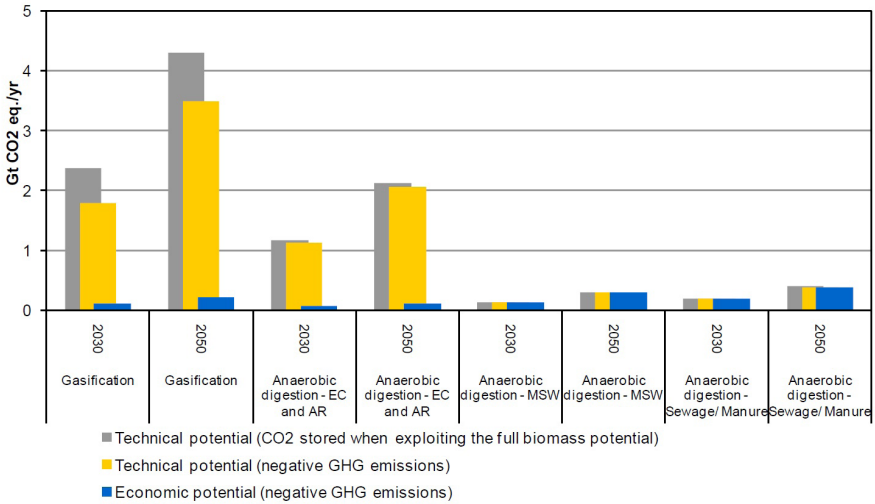


Figure 2 GHG emission balance (in Gt CO_2 eq/yr) for the global technical and economic potential per BE-CCS route for the view years 2030 and 2050. Note that potentials are assessed on a route by route basis and cannot simply be added, as the biomass resources may compete with each other.

Expert reviewer's comments

Comments were received from five reviewers. Overall, the reviewers thought that with the revisions, the report would be a good contribution to the subject.

The majority of the negative comments stemmed from the need to have read the original report IEAGHG 2011/06 for the methodology and assumptions, and these peer reviewers were different to those used on that report (only one being the same). This follow up report on biomethane refers to the original report for assumptions and detailed explanation of methods. It was therefore recommended that the report's conciseness was improved to enable this report to be seen as an addendum of the original report. Though more concise, further explanation in some areas of the report was necessary, such as sustainability criteria used and when stressing the major findings by putting them in context to the approach used, uncertainty and why this is important.

The terminology in the draft report appeared a little inconsistent, and needed to be revised, and a little more discussion/explanation was needed when discussing terms to assist readability. There were various technical aspects which needed addressing also. There are some assumptions and discussion points which would be useful to address, such as avoided methane emissions versus GHG savings, the sustainability criteria, CO_2 price allocation producer versus end user and branched or centralised grids; and discussion points which could be easily removed as they add little to the report.

The reviewer's comments were then addressed by the contractors in a revised final report.

Conclusions

- Biomethane production in combination with carbon capture and storage has the technical potential to remove up to 3.5 Gt of greenhouse gas emissions from the atmosphere in 2050
- Annual greenhouse gas emission savings could be almost 8 Gt in 2050 if natural gas is replaced by biomethane production with CCS.
- The economic potential depends strongly on the CO_2 price and natural gas price.

- Large scale gasification based production of biomethane with CCS could have potential in regions where large scale infrastructure is already in place for the transport of biomass, natural gas and CO_2.
- Small scale biomethane production with CCS based on digestion is most likely restricted to niche market applications.

Overall, it is concluded that the economic potential for biomethane combined with CCS is most likely restricted to those regions that have favourable (high) natural gas and CO_2 prices, and have favourable infrastructural conditions. A logical next step in understanding the potential of technology routes that combine biomethane production with CCS would be to assess more location specific (region, country, local area) conditions. The combination of elements like presence of suitable industry, infrastructure and biomass import facilities, and technical knowledge may provide synergies for economical production of biomethane combined with CO_2 removal and re-use or storage. A focus could be on regions with demand for CO_2 (industry, horticulture) or starting CCS infrastructure, (dense) natural gas infrastructure, high (local) availability of biomass and/or high natural gas import.

2013-12 FRONT END ENGINEERING DESIGN STUDIES FOR DEMONSTRATION SCALE CCS SYSTEMS SERVING LONGANNET AND KINGSNORTH POWER STATIONS IN THE UNITED KINGDOM (UK FEED STUDIES 2011 - A SUMMARY)

Background

The UK DECC funded FEED studies for two potential CCS projects in the UK as part of a first competition for funding of a full scale demonstration. A key aim of the FEED was thus to assist in selection of a winning project but the participants were also required to narrow the range of projected costs and clearly identify the cost risks and establish upper and lower limits. DECC also had the intention of making results public to enhance learning and information exchange.

Initially 9 consortia entered projects into the competition but only two proceeded into the FEED phase. One of these withdrew before the full FEED was developed so some elements of this FEED are less well developed.

The FEED's were funded with public money and hence the documentation has been made publically available where it does not include confidential material. It is if considerable worldwide interest to those engaged in the emerging CCS industry.

The front end engineering design of a project aims to define all elements required to execute the project so that detailed engineering, procurement and construction can proceed without significant changes, delays or cost overruns. The scope of the FEED documentation usually includes basic specification of the required processes, layout, routing and site locations. It would also usually identify standards to be applied, permits and permissions required along with safety and environmental risks and measures to control these to acceptable levels. It would also set out a preferred contracting and procurement strategy, a project schedule and develop costs estimates of sufficient accuracy based on these to allow firm investment commitments to be made. If long lead equipment lies on the critical path of the schedule, requisitions for this may also prepared so that procurement can start as soon as the investment decision is made. While some choices may be left to be made during detailed design these should not be of a type which would

significantly affect the project within established levels of time, resource and cost contingency. Thus the exact scope and contents of a FEED will vary with the type of project and its context.

Approach

IEAGHG executive committee agreed that it would be useful if the salient information from the published FEED documents was reviewed and summarised in a publication. A total of 329 documents have been made publically available containing a wealth of detailed information which is time consuming to extract. The task of reviewing and summarising this information was shared amongst four members of IEAGHG technical staff each concentrating on different areas according to their expertise. They reviewed all the FEED documentation in detail and have extracted and prepared summaries of the salient information in 10 separate chapters. A condensed tabular format was chosen to aid comparison between the two projects. Important references to the many separate documents which make up the full FEED studies are also included. A selection of the key figures and diagrams as well as heat/mass balance tables is also presented.

This overview summarises the IEAGHG synthesis report described above.

Introduction

The two developments for which FEED's were prepared are for CCS projects at Kingsnorth with CO_2 stored in the depleted Hewitt field in the Southern North Sea and at Longannet in Scotland with CO_2 to be stored in the depleted Goldeneye field in the Northern North Sea.

A key difference between these projects is that Kingsnorth would be a new build power station, albeit on the site of the existing station which would be retired from service. Longannet would be an addition to an existing coal fired power station. Furthermore the CO_2 from Kingsnorth would be injected via a new platform and wells whilst that from Longannet would utilise the existing Goldeneye platform and wells. The designers thus faced some significantly different issues in preparing their FEED studies.

Main Findings and Results

General Descriptions of the Proposed CCS systems

A brief description of each project is given below. This is followed by more detailed descriptions of the main elements of each CCS system. Figures 1 and 2 near the end give a general impression of the key features of each project.

Kingsnorth/Hewett
The existing Kingsnorth facility is situated on the north bank of the Medway estuary in Kent. It consists of four 500MW coal fired subcritical steam power plants and is expected to be retired by 2015. A new coal fired supercritical steam power plant consisting of 2 units (nos.5 and 6) each of 840MWe gross output is proposed to be built on the same site. Just under 50% of the flue gases from one of these new units (no. 5) would be fitted with a demonstration post combustion carbon dioxide capture unit. Parts of some of the existing infrastructure and utility systems (such as the CW system) would be reused.

The design includes a later expansion of the capture plant which would recover CO_2 from all of the power station flue gases. The initial amount would be just over 2.1 million t/y rising to just over 8.6 million t/y in phase 2. However the FEED considers only the first phase of the project in detail.

The CO_2 would be dried and compressed to sufficient pressure for direct delivery by pipeline to the storage site. It is proposed to pipe the CO_2 overland via a 36" line to a landfall point 10km away on the south bank of the Thames estuary just west of All Hallows-on-sea. The offshore section is 260km to a location, as yet to be defined, above the Hewett gas field.

The CO_2 would be injected into the Upper and Lower Bunter sandstones of the depleted Hewett gas field from a new wellhead platform. The final location was not fully determined in the FEED study. Initially there will be 4 injection wells with 3 in use and one spare.

In phase 2 a further 5 wells will be drilled. In addition the project includes abandonment of 28 existing wells. The estimate CO_2 storage capacity of the Hewett field is 200Mt.

Cost estimates were prepared for the project which indicated a central cost of approximately £1.2 billion.

Longannet/Goldeneye

The existing Longannet power station has four 600MW coal fired units (nos.1-4). They came into operation between 1969 and 1973. They operate with subcritical steam conditions and are fitted with electrostatic precipitators (ESP). They do not currently have Flue Gas Desulphurisation (FGD) or NOx reduction but it is planned to add Sea Water FGD (SWFGD) and Selective Catalytic Reduction (SCR) units progressively to all the units by 2015. In addition a new supercritical 800MW coal fired plant with single reheat and equipped with full emission controls is planned for start-up in 2019.

Two 50% capacity CO_2 capture trains are proposed and will together process a portion of the flue gas from one of the existing power plants. Connections will be made to two units (no.2 and no.3) downstream of the newly installed FGD and SCR units. Flue gas will only be drawn from one unit; the alternative connection is to allow the CCP to continue to operate if one of the connected units has to be shut down. The design allows for the CCP to be able to process flue gas from the 5th (new) unit when this comes on line. The CCP plant design capacity is primarily based on treating 49% of the flue gas coming from the new unit.

A small gas fired turbine power plant with heat recovery will be installed to provide steam and electrical power for the CCP thus avoiding much of the need to tie in to the existing power plant for these utilities. Some surplus power will be generated which will be exported.

The CO_2 stream from the CCP's will be compressed and then de-oxygenated and dried for transmission by pipeline. The first section of the pipeline is 260 km overland from Longannet to a new compressor station at Blackhill near the St. Fergus oil and gas terminal. It re-uses an existing 36" line forming part of the national gas grid, but includes a new section of 18 km from the power plant to the tie-in point. The onshore section will operate at low pressure so that the CO_2 is always in the gaseous phase. The Blackhill compressor station near St. Fergus compresses the CO_2 to 120bar for onward transport in the dense phase though the existing 101.6km 20" line to Goldeneye. A short 1.5km section of new line runs from the compressor station to the Goldeneye line tie in. The existing Goldeneye platform will be used for injection but with major alterations to the topside facilities. The 5 existing wells will be used for injection and observation. The existing tubing will be removed and smaller

diametertubing of higher grade low temperature steel will be installed.

The CO_2 capacity of the Goldeneye structure was conservatively estimated to be 37Mt. Cost estimates were prepared for the project which indicated a central cost of approximately £1.34 billion (-12%+15%). This compares with an initial pre-FEED estimate of about £1.18 billion (-30%+50%).

Power Stations

New Kingsnorth Power station
EON's proposed new 2 trains 1680 MWe gross coal fired supercritical steam power plant with single reheat will be constructed someway north of the old units (1-4). Steam conditions would be HP 600°C, 286.5 bar(a), IP 619°C, 56 bar(a), LP 231°C, 233 bar(a). Thermal efficiency (based on LHV) without CCS would be 45%. The units would be designed for full integration with CCS utilising LP steam extracted from the IP/LP crossover as the main heat source for solvent regeneration. The efficiency when 50% of the flue gas is treated in the capture unit is estimated to be 40%. The units will be equipped with ESP, SCR and FGD and the flue gas to be treated in the capture plant is ducted from a point downstream of the FGD. Treated flue gas is returned to the main flue gas stream downstream of the extraction point after which the full stream is reheated in a gas/gas exchanger before entering the main stack at around 90°C.

The CO_2 transport system is designed for future capture from the flue-gases of both units. The FEED recognises that the IP/LP crossover pressure and steam turbines can be designed for optimal extraction of steam for the CCS process. It specifies provision of attemperated steam by-passes around the LP turbine to the steam condensers for control when extraction conditions deviate from normal. The design also includes steam throttling valves downstream of the extraction point to ensure that the extraction pressure does not drop too low as steam flow changes. At this stage however the choice of optimum design point for the steam system i.e. with no steam extraction, with demonstration rate extraction or full capture rate extraction was not chosen.

The CCS plant requires a range of other auxiliaries which are integrated to various degrees in the design. The FEED study has made choices on how these will be provided which are to some extent driven by the specifics of the existing brown-field site. Some elements of the existing infrastructure and

utility systems such as a significant part of the existing Cooling Water system would be reused. The only caveat is that were the CCS plant to be expanded to process 100% of the flue gases it might be difficult to meet the maximum discharge temperature requirements back into the Medway.

The CCS plant auxiliaries will be served by a single separate 11kV transformer and distribution system. Large drives both in the power plant and CCS plant such as the CO_2 compressors and flue gas fan are to be Variable Speed Drives (VSD's) as Direct On Line (DOL) starting would complicate compliance with the Grid connection requirements. Because of the lower reliability of VSD's 2x or 3x 50% units are to be installed depending on criticality of each machine's service. New connections to the electrical grid were originally foreseen but if the existing plant is decommissioned before the new units come on stream some of the old connections can be used. A new reserve electrical connection from the grid for auxiliary power serving both the power plant and the CCS plant is specified. The inclusion of reserve connections for the CCS plant is included because the study considers that it will not be operationally desirable for the CCS plant to shut down due to a fault in its primary auxiliary power system.

The FEED indicates that the basic supercritical steam power plant design cannot comply with UK Grid Code frequency control requirements. This is because there is less energy stored in the once through steam system than in a subcritical plant. It is suggested that the CCS plant should be part of an electrical load shedding system aimed at assisting in Grid frequency control compliance for the plant. However this on its own would be insufficient and additional measures would be required. Solutions would need to be developed during detailed design and could include renegotiation of the requirements. Condensate stop whereby steam extraction for condensate preheating is temporarily stopped is one feature included in the design. The status of CCS plants in load shedding may thus be a significant issue for new build projects. The dynamics of CCS LP steam extraction stop may be worth investigation.

Longannet power station

The FEED study only covers the tie in to the existing power plant and brief mention of the tie in to a proposed new 800MW. This is notionally specified

with steam conditions of 600°C 275 bar(g) with single reheat to 610°C giving an efficiency of 45% (LHV). The flue gas composition from the new unit will be slightly different (higher CO2 content) and this is taken into account in the capacity rating of the CCP.

The new CCS plant will be built as a standalone facility with minimal use of existing systems although some basic utilities can be provided by extension of those at the existing power station. In particular the cooling water system of the existing power plant has capacity and would be extended to service the capture plant including the new dedicated gas fired combined cycle plants which provide the electrical power and heat. Demineralised water will also come from the main plant but a new holding tank is required to allow peak demands to be met. The gas supply to the new auxiliary heat and power plant is taken from the existing supply to Longannet power station.

Flue-gas tie-ins are provided in the ducts of Units 2 and 3 downstream of the newly installed FGD units. There would be isolation dampers so that either one or the other of these units but not both would feed the Carbon Capture Plant (CCP) through a common transfer duct. The design calls for a minimum of 10% of the abstracted flue gas to go to the chosen unit's stack directly in order to prevent backflow. This equates to a minimum load of 363MW when the CCP is at full capacity. In the event that units are shut down the operational precedence would ensure that the one supplying the CCP was the last off. Processed flue gas from the two CCP trains is exhausted through a common dedicated stack with multiple flues and thus does not rejoin the flue gas system of the existing power plant.

Key features of the design of the new auxiliary power plant will be described in this section. The plant will have two trains comprising gas turbines of 47MW each generating power at 11kV and 50 Hz. Hot turbine exhausts are fed to Heat Recovery Steam Generators (HRSGs) at 544°C to raise HP steam at a single pressure of 26 bar(g) and 325°C. The system is provided with supplementary duct burners. Connections via dampers to a single shared stack are provided between the turbines and the HRSGs. The HP steam passes through a single back pressure turbine and at full load exhausts at 4.2 bar(g) and 165°C but this temperature will be higher at part load. This pressure allows for throttling control valves to supply to the CCP regenerator reboilers

at 3.8 bar(g) saturated (at 160ºC). A desuperheater is provided. A small slip stream of HP steam is let down to provide MP steam at 9.5 bar(g) for the boiler feed water (BFW) deaerator. The steam turbine has a full power output of 30.6MW. A feature of the design is provision of HP steam desuperheating bypasses around the steam turbine one for each HRSG with a 100% capacity spare. These can be used for supplying LP steam whilst the steam turbine is being started up or maintained.

The new power plant produces an excess of power over that required for the CCP. This power would be exported via a new 275kV connection to the Grid. Full connection to the existing 11kV grid was rejected because of the engineering complications and concerns about electrical instability which might be introduced.

CCP Plant Kingsnorth

The capture plant would make use of Mitsubishi Heavy Industries' (MHI's) proprietary hindered amine process. This was chosen amongst other reasons because of its low energy consumption. The single train plant would process approximately half (47.3%) of the flue gas from the proposed new Unit 5 of the new power plant and the auxiliary power and heat used by the CCP would reduce the power output by approximately 100MWe. The plant specification calls for a flexible design capable of operating from 25%-100% capacity with frequent load changes and high ramp up capability of 4%-6% of the maximum continuous rating per minute in the mid-range.

The chosen solvent (KS-1™) offers a high rich loading 1.5 times higher than MEA, and claims degradation rates of 10% those for MEA. Furthermore the process employs a proprietary absorber heat optimization which enhances energy consumption by an estimated additional 10%. Before entering the main absorber column the flue gas is further cleaned and cooled in a quench column. This has three sections. The first contacts the flue gas with a pH controlled solution of caustic soda for deep removal of SO_2 required for prevention of degradation of the solvent. It then passes upwards through a wet Electrostatic Precipitator (ESP) and finally is cooled by direct contact with cold water. The low temperature is required to optimise the absorption of CO_2 by the absorption solvent. The design of the quench system is proprietary to MHI. The column is a large rectangular tower 10M x 14M and 49M high. A

blower is situated downstream of the quench column and draws the flue-gas into the absorber. This will be constructed as a rectangular column 10M x 17m and 72M high. After counter current contact with the circulating solvent the flue gas is water washed in two stages. Above this the column contains a "Deep amine recovery" section but no further details of this proprietary process are given in the FEED. The rich amine is partly heated by exchange with hot lean amine and is then regenerated in 2 x 50% capacity packed stripper columns 7M in diameter and 39M tall. A side draw and return is installed on each column and this exchanges with the hot lean amine as part of MHI's proprietary energy saving arrangements. However details of the conditions are not disclosed. The stripper operates at a slight overpressure and delivers CO_2 to the suction of the export compressors at 0.59Bar(g). A conventional amine reclaimer system is installed on a slip stream of the lean solvent and is designed for intermittent operation.

CO_2 compression and purification Kingsnorth

For the demonstration phase of the project CO_2 will be transported in the gaseous phase. The transport pipeline will however be designed to accommodate capture of CO_2 from both of the proposed new generation units or roughly 4 times the demonstration capacity. The required injection pressure is initially low and rises as the storage fills. It is planned to convert to higher pressure dense phase operation later should phase 2 be implemented.

For the first phase, two trains of 50% capacity 4 stage integral gear compressors are recommended. Initial outlet pressure is 32 bar(g) rising to 40 bar(g) as the reservoir fills. The option to recover heat from the inter stage coolers was reviewed and rejected in favour of seawater cooling. This results in slightly lower compressor power but a slight loss in overall power generation efficiency. However this loss is outweighed by the increased size and cost of the compression plant. The compressed CO_2 is dried in a mole sieve unit to a water dryness of 24 ppm. TEG drying was considered as an alternative but rejected for several reasons including potential inability to maintain water content within specification, potential emission of TEG and potential contamination of the CO_2 which could affect injectivity. Mole sieves on the other hand had the advantage of stable operation, rapid achievement of water specification and better reliability.

No oxygen removal is specified on the basis that the maximum of 200 ppm expected will not cause corrosion problems in the system. However no details of the material selection for the injection wells are presented and this conclusion differs from that made during the Longannet FEED study where deep oxygen removal is required to protect the selected 13% Cr well tubing. The FEED investigated and compared several methods for deep oxygen and the analysis seemed to favour a catalytic reactor in the hot discharge of the final compression stage. A number of alternatives for supplying or generating the hydrogen for the oxygen destruction in this reactor were also investigated but no choices or recommendations were made.

CCP Plant Longannet

There are two identical 50% capacity carbon dioxide capture trains in the design. After the flue gas flow splits it is first treated in a direct contact quench cooler, one per train. These serve both to cool the stream but also to remove SO_2, SO_3, NO_2, HF, HCl and particles such as fly ash and corrosion products. The contact fluid is water to which caustic soda is added to control the pH to close to 7. The contacting/quenching fluid is circulated using stainless steel pumps through an external Titanium plate exchanger cooled with seawater. The quench towers are of rectangular cross section 10m by 8m and are 19.4m high. They are constructed of concrete with an epoxy lining and have a stainless steel packing. The treated fluegas cooled to about 39°C then passes through an axial flow blower with variable pitch vanes which raise the pressure to about 73mb to overcome the pressure drop in the absorber towers. CO_2 is absorbed in the absorber columns by counter current contact with a proprietary MEA solution. The designers, Aker Clean Carbon, do not reveal the specification/supplier of the proprietary amine solvent. The absorber is a rectangular concrete structure with internal lining (not specified) 60m in height but with cross sectional dimensions not revealed. The absorbers contain an absorption section above which is a conditioning section followed by a demister. Exact details of the water balance and conditions in the wash section are not revealed. The solvent is regenerated in a conventional arrangement but full details of the system are not revealed. P&ID diagrams for the absorber/regenerator system stream compositions are not shown in the Heat and Mass balance table although other process conditions are shown. The regenerator operates slightly above atmospheric

pressure with a top pressure of 0.84bar(g) and a bottom temperature of 122.1°C. A reclaimer system is provided for batch-wise regeneration of amine from Heat Stable Salts (HSS).

CO_2 Compression and Purification at Longannet

The CO_2 from both capture trains is combined for compression. It will be compressed from 0.5 bar(g) to 37 bar(g) and 30°C and exported via the National Grid pipeline in the vapour phase. 2 x 50% capacity electrically driven integral gear compressors were specified with the exact number of stages to be determined during detailed design. All inter stage and final coolers are to be constructed with 22% duplex stainless steel shells and titanium or titanium clad tubes.

An oxygen removal unit consisting of a 22% duplex stainless steel pre-conditioning vessel containing a catalyst bed is placed in the hot outlet of the last stage of compression. The catalyst is palladium supported on alumina. A small excess of hydrogen is added to convert any oxygen in the CO_2 to water. After oxygen removal the CO_2 is cooled before entering a mole sieve drying package designed to reduce water content to <50 ppm. This specification was chosen to avoid hydrate formation and free water in the pipeline. Mole sieve regeneration is achieved by flowing a slip stream of CO_2 through the off line bed using a small compressor and electrical heater. The hot regeneration gas exhausting from the regenerating bed is cooled to knock out water and returned to the inlet of the drying system. The CO_2 is metered before passing into the transport pipeline. There is further compression at the pipeline landfall site which will be described in the sections on the pipeline transport.

Pipeline Transport Kingsnorth

The planned 260 km 36" pipeline is designed to cater for the initial demonstration phase and a later full capture phase at which point the flow would be quadrupled to 26,400 t/day with the injection pressure rising as the reservoir filled. Most of the line is offshore and there will be no booster compression. A key design requirement is to avoid two phase flow conditions. The maximum pressure which can be allowed in the initial transport gas phase is 39bar(g) and this is based on the minimum winter air temperature of -6°C adopted for flow assurance purposes. Minimum ground and seabed temperatures are all several degrees higher than this.

For operation of the system in the dense phase a minimum pressure of 79 bar(g) is specified. Design pressure is set at 150 bar(g) and a minimum design temperature of -85°C onshore and -20°C offshore. These temperatures apply under conditions of depressurisation. An electrical heater is specified at the offshore platform to heat the arriving CO_2 so that low temperatures do not occur when it is throttled for injection. Electrical power for this and other services is provided from onshore.

Other key features are fiscal flow metering onshore at the power station, flow metering for leak detection only at the platform and ultrasonic metering in the CO_2 venting system to allow any venting losses to be quantified. The line will be equipped with pig launcher receivers for the onshore section and the offshore section. To avoid mill scale entering the injection wells despite best endeavours to clean the line at start up, a set of filters will be installed offshore.

Considerable attention was paid to the requirements for venting under all routine and emergency conditions in the FEED study. It was concluded that a key requirement for safety is an automatic block valve at the landfall to prevent the considerable inventory in the offshore line flowing back to exacerbate a leak or rupture in the onshore section. The effect of automatic blowdown in the event of an onshore full bore rupture was modelled and it was shown that this would have little effect on quantities released at the rupture and it is thus recommended that such a system is not installed.

The preliminary wall thickness for the onshore section is 27mm with a 5mm bitumen coating. This includes a 1.5mm corrosion allowance. The onshore section will be buried at a depth of 1.1m along its entire length. Additional sectionalisation valves are envisaged if detailed engineering studies indicate that pipeline CO_2 inventories are such that these are needed to limit the amounts released for safety reasons in the event of a leak. At this stage the possible numbers and locations were not determined but the preference is for these to be installed below ground. A tie-in point will be provided near the land fall so that CO_2 from third party sources could be tied in without interrupting operations. The offshore section is specified with preliminary wall thickness of 23.8mm also with a 1.5mm corrosion allowance. Coating is specified as 5mm bitumen and 50mm concrete. Subject to requirements for protection against anchoring and fishing activities along the route the

pipeline would not be trenched and buried.

Well Head Platform Hewett

The pipeline terminates at a new platform. The FEED proposes that this should be a liftable jacket located on piled foundations on which a lift installed integrated deck would be placed. This was chosen as it is cost efficient, allows for easy decommissioning in line with regulations and can be supported by locally available construction yards. A key design consideration was the CO_2 venting system. This will be designed only to vent the topsides equipment. It is assumed that pipeline depressurisation and full process flow venting will not be required. The facility will be designed for the full pipeline pressure. The maximum quantities for topside only venting were found to be low enough to allow a low level downwards pointing vent to be used. This would not be the case if the other venting services were required. To avoid venting of the pipeline CO_2 contents in the event of a planned line depressurisation the CO_2 would first be displaced into the reservoir with another fluid such as air. A variety of issues associated with design of the vent system are addressed including measures to cope with low temperatures and possible hydrate blockages. However detailed design details and specifications have still to be developed. The platform would be protected against full flow release events by installation of 2 remote operated riser isolation valves in series.

Pipeline Transport Longannet

Transport of the captured CO_2 will be for the most part through existing natural gas pipelines adapted appropriately for CO_2 service. The first overland section will make use of parts of National Grid's gas pipeline system. Sections of 36" line running from just north of the town of Denny to the St Fergus terminal will be made available. The design pressures of these lines, 70 bar from St Fergus to Aberdeen and 84 bar south of Aberdeen, dictated that transport be in the gas phase and a key design requirement was that there should be no risk of two phase flow under all conditions. Considering the minimum ground temperature this set the maximum incidental pressure at 37.5 bar(g) and the design operating pressure 10% lower at 34 bar(g).

Due to space limitations a full metering and pigging station could not be located near the plant. A new above ground installation (AGI) would thus be built to the north of the Longannet site near Valleyfield. The short section of

24" line would have only pig launching facilities at Longannet but this would allow frequent pigging of this short section enabling condition monitoring data to be accumulated without having to pig the main line. From Valleyfield a new section of 36" line would run to Dunipace north of Denny where a tie in to the no10 feeder system would be made. The FEED established that single block valve isolation would be adequate rather than double block and bleed. There are about 16 above ground installations along the route and also cross connections between the multiple gas lines. The cross connections would have to be removed and also the valves at these stations changed to be suitable for CO_2 service. In addition a decision was made to provide 24" bypasses and 8" bypass bridles across pipeline section isolating valves at these stations so that these valves could be exercised without interrupting flow.

At St Fergus the CO_2 has to be compressed further for transport in the dense phase to the offshore platform. A new site was chosen for this compressor station at Blackhill which is located just to the Northwest of the terminal. Here 3 x 50% compressors would be installed with a discharge pressure of 120 bar(g). Two would be electrical with variable speed drive and one would be driven by a gas turbine. Design studies on the existing offshore pipeline indicated that to avoid running ductile fractures the gas temperature should be limited to maximum 29°C. To achieve this limit the non-condensable gases in the CO2 have to be limited to 1% and the hydrogen component within this to max 0.3%. In extreme summer conditions this maximum temperature could not be guaranteed by using cooling water in the Blackhill compressor after coolers. Thus a propane chilled aftercooler would also be installed at the Blackhill compressor station which would lower the temperature to 15°C.

A fiscal metering system would be installed at the outlet of the Blackhill compression station. A short section of new buried 12" line skirts the St Fergus site to tie in to the existing 20" line to Goldeneye through an existing 12" tie in point. The design pressure of this line and the discharge system of the compressor station would be 132 bar(g) to match that of the existing offshore line. Full flow vent reliefs for example due to back flow or from compressor over pressure would be avoided by installation of HIPPs systems.

Wellhead Platform Goldeneye

An existing seabed non return valve with flow towards shore will be removed. A new remote operated subsea ball valve will be installed. The line and riser section downstream will be replaced to have a higher design pressure able to withstand thermal expansion of any locked in dense phase CO2 under normal conditions. The CO2 will be filtered in the dense phase through 2x100% filters before passing through a meter and then a letdown valve. From downstream of this valve low temperatures are expected due to the expansion and all equipment downstream will be executed in stainless steel selected for this service. A new manifold and flow lines to 5 injection wells will be installed. New stainless steel Christmas trees equipped with hydrate inhibitor injection points will be provided.

Construction of the Longannet Supplementary Power Plant and CCP

A number of options for construction of these facilities were studied as a result of which preferred methods were selected. The costs estimates for the project are based on these methods. For Longannet it was found to be feasible to build most of the new facility in the form of pre-assembled modules or pre-assembled racks. The large stripper columns would be dressed and fitted with some reinforcing steel for transport and up-ended on site onto their foundations. Special attention was paid to dressing the upper part of the strippers which might interfere with the up-ending operation with a key aim being to avoid having to scaffold up to this area. Three options for unloading barges at Longannet were investigated, two involved shore based crane lifts from supply barges and the third use of a roll on/roll off barge. The latter roll on/roll off option was selected. Cost were estimated to be lower mainly because labour costs for building as modules would be less than in the case of stick build.

Wells at Hewett

Injection wells

The new wells will be fitted with 7" tubing and will be deviated with an angle up to 50 degrees. In order to control temperatures in the tubing due to throttling the delivery pressure will initially be lower than the maximum of 35 bar(g). The starting pressure in the Lower Bunter is low, 2.69 bar(a). During the demonstration phase it will not be necessary to reheat the CO_2. In the

second higher capacity phase transport will switch to dense phase with an arrival pressure at the platform of 79bar(g). At this stage throttling will be required and to avoid low temperature and two phase flow the well head heater will have to be brought in to service. The reservoir will be filled to no more than hydrostatic pressure which at 1198.8 meters depth will be 117 bar(a). As dense phase injection proceeds the pressure difference across the well tubing due to the combined effects of friction and hydrostatic head effects will change so that initially 8 wells will be required progressively dropping to 6 wells as the reservoir fills up.

Other wells

To ensure the integrity of the storage reservoir, existing well penetrations will need to be plugged to an acceptable standard for CO_2 service. There are 28 existing wells and none are abandoned to the required standard. All will have to be abandoned with CO_2 resistant materials.

Wells at Goldeneye

The existing wells at Goldeneye will be reused for injection. They are fitted with 7" tubing but flow studies indicate that using this size would cause too low temperatures in the well due to the need for throttling at the wellhead. Consequently the tubing will be replaced in a smaller diameter so that friction is increased and the drop in temperature reduced to acceptable levels. The upper part of the new tubing diameters will be 4.5" reducing with depth to smaller sizes in the range 4.5",4",3.5" and 2.875". A number of combinations will be installed so that injection rates can be matched to a selection of wells. The upper sections of tubing will be executed in super Cr13 which has better low temperature properties. To further manage the temperatures in the wells an insulating non-water based fluid will be introduced into the annuli.

Other wells

There are 13 abandoned exploration and appraisal wells in the vicinity of the Goldeneye platform. The quality of the abandonment is good but any intervention would be costly as the wells are cemented and have had the well heads removed. Four of the wells are outside of the structure. Only one well is considered a potential risk because of abandonment quality but lies 10km West of Goldeneye and the CO_2 plume is not expected to reach it.

Reservoirs

Hewett

The Hewett gas reservoir consists of two main sands, the Upper and Lower Bunter. The Lower Bunter is well suited to CO_2 storage having excellent quality sands and an extensive seal from a series of shales and this reservoir would be the target for injection. The reservoirs are sealed to the South West and North East by faults. A static model was built with 5 horizons and 97 faults were identified of which 17 were modelled. Extensive work was carried out to review the time depth conversion making use of information from existing wells. To the North East of the Hewett field there are a number of other fields designated as the "D" fields from their names.

A detailed model of the target reservoirs was made in which porosity and permeability were incorporated based on data from well logs and cores. Estimates of capacity were made. A concern is the possible juxtaposition of the reservoir sands across the fault between the Hewett and Little Dotty fields which could thus potentially provide a migration pathway. There is also some evidence of a juxtaposition of the Lower and Upper Bunter sands which would also have implications for the development of the CO_2 plume. The logs from the existing wells are of poor quality partly due to washouts in some sections of shale. It was also not possible to make good predictions of water saturation from the available data. Reservoir static modelling was carried out in Petrel and the model was exported to GEM for dynamic modelling.

An outline of the intended monitoring programme was produced to cover operational, plume development and integrity management. Essential requirements were defined and also a set of recommendations considered essential were:-

- Full continuous monitoring of well inlet temperature, pressure, flowrate (per well and total).
- Annulus pressures (A and B), and either annulus bleed/top-up density and volume or alternatively a downhole annulus gauge.
- Downhole pressure and temperature. CO_2 sampling on seabed, riser, and platform, both during operations and after abandonment.
- 4D baseline survey, and further 4D on a time schedule (e.g. 5 years),

- Campaign-based wireline logging including as a minimum Pulsed-Neutron and Cement Bond Log from Surface to total well depth, and other logs as required, covering all wells on a rotational basis.

A number of other techniques are recommended for investigation and possible deployment in the main aimed at reducing residual uncertainties about the reservoir integrity and performance.

Goldeneye

Goldeneye was discovered in 1996 and brought into production in 2004. It is a gas condensate field with a thin oil rim. The reservoir has a strong aquifer drive and as a result pressure has dropped from an original 262bar(a) to 152bar(a). It is estimated that injection of 20 million tons of CO_2 would raise the pressure to between 241 and 259 bar(a) but will then drop back due to dissipation into the aquifer. The reservoir is sealed to the East South and West by structural traps and to the North by a pinch-out. It is sandstone reservoir with average porosity of 25%and permeability of 790mD. Extensive work was carried out to model the reservoir, determine the storage capacity and evaluate the integrity of the seal. A static model was constructed on the basis of the asset model used for development and production. The original input data used in this model was used. However the boundaries of the model were extended to cover movement of the CO_2 plume and some rebuilding of the model was required. Changes were made to enable a focus on the evaluation of capacity and containment. The changes included modifications to layering to better model thin buoyant CO_2 plumes and more focus on porosity and permeability in the under-burden. Several variants of the model were constructed because the first model, based on that used for field management, did not give a good history match with the production to date. Further work is needed to test the models and develop a robust dynamic model of the CO_2 injection.

The study also developed a Monitoring, Measurement and Verification (MMV) plan. This has several objectives including comparing actual and modelled behaviour of CO_2 and formation fluids in the storage site, detecting significant irregularities, detecting migration, leakage of CO_2 or significant adverse effects on the environment and assessing the effectiveness of corrective measures.

A key foundation of the monitoring plan is acquisition of a pre-injection baseline for both the environment and subsurface. During the project a range of techniques are planned including:-

- Multi-beam echo sounding, seabed sampling and continuous tracer injection,
- Well integrity monitoring using a range of down hole sensors and logging tools,
- Seabed CO_2 detection below the platform,
- CO_2 injection conformance based on pressure, saturation and flow monitoring
- Time lapse seismic.

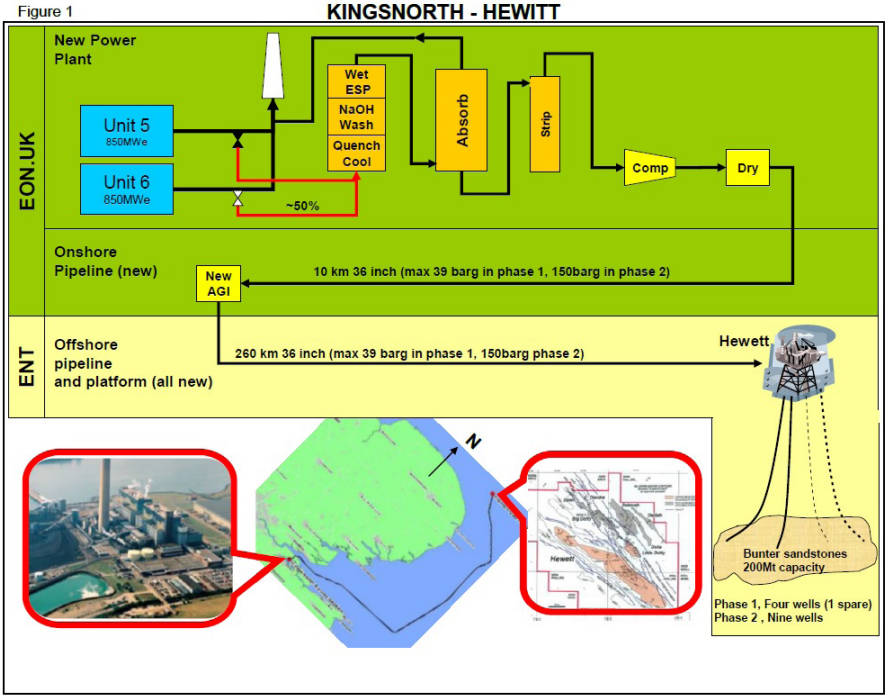


Figure 1 An overview diagram of the Kingsnorth Project

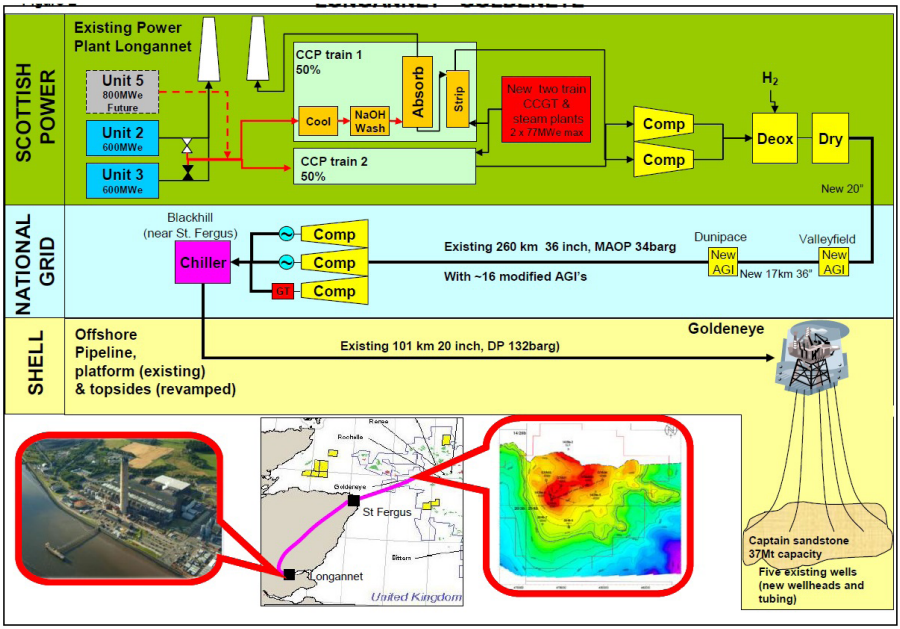


Figure 2 An overview diagram of the Longannet project

Project costs

Kingsnorth/Hewett

The FEED lays down the basic structure of the cost estimates for both CAPEX and OPEX which have been prepared on a top down basis. All the key elements to be considered in arriving at the full costs are defined. They are in general all inclusive of such items as transport to site, storage, taxes, spares etc. Individual items were to be costed with a central (50%) low (5%) and high (95%) values and any specific risks to the validity of the estimates described. Costs were to be based on fixed date 1st April 2011 and exchange rates to be used where foreign currency was involved were defined.

The work also involved extensive analysis of the cost and schedule risks using simulation software. This enabled a more detailed profile of the likely costs for the entire project to be generated. For the CAPEX the results of the analysis based on 1000 runs using a modified form of Monte Carlo simulation (Latin Hypercube in which random points are picked from a number of predetermined bands) gave the following results:

- Mean £1.365 Billion
- 90% chance of lying between £1.177 and £1.355 Billion.
- Absolute minimum £1.005 Billion, Absolute maximum £1.747 Billion

The analysis also identified the reasons for the main risks and quantified the range of their cost effects. The major ones are not unique to CCS projects and top of the list were:

- Uncertainties in materials process
- Changes in plant related commodity prices.

Amongst those related to CCS were:

- Previously unknown environmental impacts of PCC,
- Delay in pipeline consents due to public concerns and other factors,
- CCP/power plant co-commissioning difficulties,
- Delay in Unit 5 operation preventing flue gas supply to the CCP,
- Uncertainties in capture plant and compression plant design and,
- Failure of current license holder to abandon wells in way suitable for CO_2 storage.

The mid cost estimates show that the split between the main components was as follows:-

Development costs 6.0%	
Capture Plant	17.8%
Compression/conditioning	8.0%
Transport system	49.5%
Injection facilities	12.5%
Geological storage	6.3%

The mid estimate shows the expenditure phased over 6 years as:-

Year 1	2.5%
Year 2	13.8%
Year 3	30.0%
Year 4	36.3%
Year 5	11.3%
Year 6	6.3%

Longannet/Goldeneye

The three consortium members each have their own rigorous cost estimating processes. The costs presented in the FEED study are thus the results of three underlying cost estimates. Despite the differing estimating processes a common division of the costs was used so that costs were allocated to one of 15 categories. The mid estimate for the entire system is based on 2010 costs and amounted to £1,145.5 Billion. To this was added a contingency of about 17% bringing the total to £1,340.3 Billion. The split between the main elements was approximately:

CCP and associated compression at Longannet	57.3%
Transport pipeline and booster compression	26.3%
Offshore injection facilities	13.4%
Misc development costs (FEED/surveys)	3.0%

The overall estimate post FEED was considered to have an accuracy of -12% to +15%. This makes the estimate range including contingency from £1,200 to £1,519 Billion.

Abandonment costs were also estimated for all elements of the CCS system. A breakdown of these is given in this report. The total is £281.3 Million which amounts to 24.6% of the mid CAPEX (excluding contingency).

Annual operating costs were also estimated as £51 million/y fixed and £81.4 million/y making a total of £132.4 million/y. A more detailed breakdown is given in Chapter 6 of this report.

Consents and Environment

Kingsnorth

The main work on consents focussed on the power station for which a section 36, Electricity Act, consent was obtained without objections in 2006 for the new units 5 and 6 but without the capture plant. An application was also made in 2007 for the environmental permit to operate (PPT). Both would have to be resubmitted to include the capture plant. The FEED study expected the storage of ammonia and diesel at the site to invoke COMAH regulations but noted that CO_2 was not currently regarded as a COMAH substance.

The onshore pipeline is short and will be a local pipeline under the Pipelines Act. It was noted that the Health and Safety Executive (HSE) was consulting on

whether to extend the Pipeline Safety Regulations to include CO_2 as a named substance. It would then be regarded as a major hazard and compliance with these regulations would be required. Planning consent for the onshore pipeline and associated above ground facilities would be required. Temporary construction sites would also be required but it was noted that these are usually "permitted developments" under the Town and Country Planning Act. The offshore pipeline would require a "works authorisation" under the Petroleum Act which gives permission to construct and operate. An additional Food and Environmental Protection Agency (FEPA) licence will however be required for the intertidal area. A Petroleum Operations Notice (PON) would be needed for the offshore discharge of any chemicals used particularly during the construction and commissioning activities.

The exact location of the proposed new platform was not determined at the time of the FEED study, thus it was not possible to progress the Environmental Statement which would be needed. It was noted that some offshore survey work would have to be undertaken to complete this statement. Once the location of the new facilities is known a "Consent to Locate" would be required under the Coastal Protection Act and the Continental Shelf Act extension of this. Furthermore if the location of the facilities presented any obstruction or danger to navigation the consent of the Secretary of State is also required. An Environmental Impact Assessment (EIA) would also be a requirement under the Offshore Petroleum Production and Pipelines (Assessment of Environmental Effects) Regulations which themselves are to be amended to cover CO_2 storage. In addition a number of different environmental and other permits will be required for the various offshore operations involved in the new platform, from seismic acquisition through well drilling, well workovers, CO_2 injection decommissioning and abandonment.

The FEED outlines how the protection of the environment would be addressed during the various phases of the project from design through construction to operation and abandonment. Energy efficiency, climate change, water use efficiency; selection of materials, environmental enhancement, pollution control would all be addressed in an integrated and focussed way as the post FEED design was developed.

Longannet

Environmental impact assessments and certain environmental statements and summaries are required.

The FEED study produced a detailed register of consents and licenses and also performed an analysis of the risks which the processes of obtaining consents posed to the project. An overall plan for the permitting and consent processes was also produced. Although the various sections of the project were the responsibility of specific consortium members the three partners worked jointly together with the regulators on permitting and consents. An early start to this element of CCS projects is strongly recommended and it was observed that permitting for such a system is complex and needs careful management.

A few of the risks are related to the immaturity of regulation for example the status of CO_2 under Control of Major Hazards regulations (COMAH), the issue of a carbon storage license by the Department of Energy and Climate Change (DECC) which is contingent on their completion of a Strategic Environmental Assessment (SEA).

Health and Safety

In both demonstration projects there will be no transport of dense phase CO_2 on land apart from a short section near St Fergus. As a result the risks to the public from supercritical CO_2 leaks did not have to be addressed in detail. For the future commercial scale phase of the Kingsnorth project, which would use the same short overland section of pipeline, they were touched on but a full analysis was not done. Management and acceptance of this risk is possibly going to be the most controversial aspect of complete CCS systems together with that posed by onshore storage. Thus the Health and Safety work undertaken during FEED for these projects does not appear to have raised any particularly difficult issues. The nature of the work undertaken and a few significant points are outlined below.

Longannet

Health and Safety was addressed by each consortium member using a structured approach and well recognised techniques such as HAZID, HAZOP and dispersion modelling. In addition a contractor (Mott McDonald) was commissioned to conduct a full chain end to end safety review which draws

together the results and recommendations from the individual studies and highlights the important ones. The consortium published 7 reports covering HSE issues which were generated during the FEED. Chapter 10 of this report summarises the main findings from each of these 7 documents and their onward reference.

Major release scenarios for CO_2 and amine were examined at the Longannet site and it was concluded that effects would be contained within the site thus offering no risk to the public. The only risk which could spread outside was a toxic risk from a major spillage of amine which could potentially enter the wild life food chain. An insidious risk was identified relating to work at the base of the cooling tower where certain failures in the plant might cause a build-up of CO_2 and hence a asphyxiation hazard which would not be present in a normal power plant. Within the process plants and around venting systems the risk of cold burns to personnel was identified and also risks of material failure if the correct low temperature materials are not specified. It was however noted that correct material selection, procedures and appropriate insulation could prevent these risks.

It was also highlighted that the specification of the CO_2 was all important for corrosion (H_2O and O_2 content) and low temperature behaviour (non-condensable gas content) and that good operational analysis and monitoring systems would need to be provided to assure this. Back flow from the high pressure to lower pressure parts of the system was also identified as a risk which would require protection by high-integrity pressure protection system (HIPPS). Another point emerging from a review of safety critical equipment was that CO_2 detection both on and offshore would be a new addition.

Kingsnorth

The FEED produced 7 documents relating to HSE and in this project these were all coordinated by E-ON. These included, a Health and Safety Philosophy, a HAZID report, a design risk register, ALARP design review, a Dispersion Modelling Strategy and an assessment of CO_2 pipeline release consequences. The Health and Safety Philosophy provides the overarching plans for addressing Health and Safety issues. It sets out the way in which key elements affecting Health and safety will be managed during the life of the project including:-

- Construction safety management
- Hazard identification
- Operability reviews
- Interface management
- Training

A 6 step schedule for formal Hazard identification is proposed, the first of which was undertaken and reported during this stage of the FEED. Most of the hazards identified were typical and mainly affected aspects of the site layout. Of particular note was repeated identification of hazards relating to venting of CO_2 under both planned and unplanned conditions.

Conclusions

The work carried out during the FEED studies undertaken as part of the first UK competition for CCS funding has advanced the understanding of the detailed engineering requirements for such projects and firmed up the costs considerably. This has increased confidence in both design requirements and cost estimates. Most design issues were resolved in sufficient detail during the FEED but more investigation appears to be necessary in two areas. One is on the effects of releases of supercritical CO_2 from overland pipelines. The second is on the efficiency of processes for reheating supercritical CO_2 after it arrives at an injection site to condition it before it is injected into a storage reservoir.

The competition was launched in 2007 by the then Department for Business, Enterprise and Regulatory Reform but was cancelled four years later by the Department of energy and Climate Change (DECC) on the grounds of protecting value for money and because the project could not be funded within the £1 billion budget agreed at the 2010 Spending Review. However the results of engineering and design studies completed by bidders, upon which the Government spent £40 million (63 per cent of the £64 million it spent in total on the competition), may help to reduce the costs of future carbon capture and storage projects. A new competition was launched in April 2012, and closed in July 2012. Four full chain (capture, transport and storage) projects were shortlisted in October 2012.

On 14th January 2013, all the shortlisted bids submitted revised proposals. On 20th March 2013 the government announced two preferred bidders:

- Peterhead Project in Aberdeenshire, Scotland – a project which involves capturing around 90% of the carbon dioxide from part of the existing gas fired power station at Peterhead before transporting it and storing it in a depleted gas field beneath the North Sea. The project involves Shell and SSE.
- White Rose Project in Yorkshire, England – a project which involves capturing 90% of the carbon dioxide from a new super-efficient coal-fired power station at the Drax site in North Yorkshire, before transporting and storing it in a saline aquifer beneath the southern North Sea. The project involves Alstom, Drax Power, BOC and National Grid.

Initially there were 8 bids and following a detailed analysis of these 4 projects were shortlisted. The two other projects, Captain Clean Energy and Teeside Low Carbon projects were appointed as Reserve projects.

The Government will now undertake discussions with the two preferred bidders to agree terms by the summer of 2013 for FEED studies, which will last approximately 18 months. A final investment decision will be taken by the Government in early 2015 on the construction of up to two projects. The Peterhead project will again make use of the depleted Goldeneye field and its existing offshore pipeline, platform and wells. This project will also again make use of post combustion capture fitted to an existing power plant although this is gas fired, not coal fired. It is thus likely that a lot of the work undertaken in the Longannet FEED study will be relevant to this new project.

Since the first competition FEED studies were published the existing Kingsnorth power station which started operation in 1970 has been decommissioned (March 2013). This was as a result of implementation of the EU's Large Combustion Plant Directive legislation. There is currently no application for consent to build the proposed new supercritical plants which featured in the FEED study.

The White Rose project will make use of oxy- combustion technology and includes the possibility to co-fire biomass along with the coal fuel. This project plans to make use of a saline aquifer rather than a depleted oil or gas

field. It thus represents a significant technological step out from the projects which featured in the previous competition.

Recommendations

It is proposed that IEAGHG monitors the availability of new FEED material developed during the second UK competition and informs IEAGHG members if it is considered worthwhile to do a further in depth review of such new documentation.

Notes:
If any readers should want to perform calculations or further work based on the information provided in this FEED Studies Review, it is recommended that the original FEED documents are consulted (available on the Department of Energy and Climate Change website). Care should be taken when using and referencing figures, tables and references, as numbering of these in each sub-chapter is consistent within the sub-chapter but independent from the other sub-chapters.

2013-16 INFORMATION SHEETS FOR CCS

Terms and Concepts

Carbon

Carbon is one of the basic building blocks of life on Earth; humans and other animals are all carbon based, and as an example, humans are about 18% (or just under one fifth) carbon.

Because of its role in creating and forming life, carbon is continually on the move, being absorbed and released by living things during life, growth, and finally death. This movement of carbon into different places and things is referred to as the Carbon Cycle, and describes how the carbon can move from one location to another; from a living animal or plant, through decomposition into gas form into the atmosphere, before being reabsorbed by plants breathing, or by the sea or other water bodies.

Carbon Dioxide - CO_2

This is what CCS is all about: carbon dioxide (CO_2). CO_2 is a gas made up of carbon and oxygen. It is a large component of what humans and other animals breathe out, and what plants breathe in. In return, plants breathe out oxygen, and humans and animals breathe this in, completing part of a cycle.

CO_2 is also released by burning fossil fuels (see below) in generating electricity, and this is the main focus of CCS; capturing this and preventing it from being released into the atmosphere.

The Greenhouse Effect

Closely linked with both global warming and climate change, the greenhouse effect is what causes these to occur. The 'greenhouse effect' is so called because the effect is exactly like being in a greenhouse where the glass prevents heat escaping back out, whereas in the atmosphere it is gases such as CO_2. There are a few other gases that have the same effect, but the impact of CO_2 is greater, and more directly linked to human activity. These gases are collectively known as greenhouse gases because of the role they play in this process.

The greenhouse effect is important; without it, life on this planet would not have been possible, but the impact humans are having on the amount of CO_2 in the atmosphere is increasing this effect beyond the Earth's capability

to correct it. Since the industrial revolution in the 1800's, the amount of CO_2 in the atmosphere has increased greatly, as a direct result of burning fossil fuels like coal, oil and gas. We need to reduce the amount of CO_2 released by the burning of these fossil fuels, but of course we cannot instantly reduce the amount of electricity used by humans, so we need to find a way to remove the CO_2 from the exhaust gases from power stations; hence the need for CCS.

Carbon Dioxide Capture and Storage (CCS)

CCS is the name given to the process where CO_2 is captured from power stations or other sources, transported via pipelines or ships and injected into storage formations deep underground preventing the greenhouse gases from reaching the atmosphere and contributing to the greenhouse effect.

Fossil Fuels

Coal, oil and gas are fossil fuels. These fuels were created when organisms died 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 they are exposed to over a very long period of time. All of these carbon-rich materials can be burned as a fuel to produce energy. Currently, over 80% of the world's energy comes from burning fossil fuels.

Coal

Coal was 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. Coal is the world's second largest source of energy, providing 30% of the total supply. Due to the scale of its use and the large amount of carbon it contains, burning coal is the largest source of CO_2 emissions to the atmosphere from human activity, at 40% of the total.

Oil

Oil was formed from large quantities of tiny sea based organisms (such as algae) that have been buried under layers of other rocks over hundreds of millions of years, and subjected to high heat and pressure deep underground. Around 4 billion tonnes of oil is produced and used each year, making it the third largest source of human CO_2 emissions, at 18% of the total.

Gas

Usually referred to as natural gas to distinguish it from other types of gas, natural gas is, like oil, made from the remains of ancient living organisms that have been buried deep in underground rocks. Although it occurs on its own in reservoirs, gas is also often found in the same reservoirs as oil. Natural gas makes a major contribution to human CO_2 emissions at around 10% of the total.

Rocks and Geological Terms

Rocks can broadly be classed into three types depending on how they were made. Igneous rocks are formed from cooling molten rock (from volcanoes etc.), sedimentary rocks are formed from the accumulation of lots of individual rock grains and other materials (such as sand) 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_2 storage can take place.

Sedimentary Rock

One of the more common sedimentary rocks is sandstone, made from ancient beaches or deserts that have been buried and compressed. 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. These pores are not empty – they contain other substances including air, water, natural gas, oil and CO_2.

Reservoir Rock

Sedimentary rocks in which oil or gas are found are often called reservoir rocks. These tend to have a high 'porosity' (meaning lots of the rock volume is made up of pores), and 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_2 as lots of CO_2 can be relatively easily injected into them.

Cap Rock

If oil or gas can move through the rock, what stops the oil or gas moving through the rock to the surface? In most cases, reservoir rocks are overlain by layers of other rocks (usually also sedimentary). Often these rocks have a

lower porosity so that substances can't move through them very easily, if at all. These rocks can 'seal' a reservoir by preventing the escape of the oil, gas, water or CO_2 in the reservoir rock and are called cap rocks.

Deep Saline Aquifer (Deep Saline Formation)

Another type of reservoir rock where CO_2 can be stored is a deep saline aquifer. A deep 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 any other purpose.

If a deep saline aquifer has a suitable cap rock above it, CO_2 can potentially be injected into it for storage purposes. CO_2 is currently being injected for storage at a commercial scale (i.e. millions of tonnes per year) into deep saline aquifers in Norway and other locations around the world.

Depleted Oil and Gas Fields

Old oil and gas reservoirs, where as much of the oil or gas as is possible has been produced, are good options for storage. Because these reservoirs have contained oil and gas in the past, we know a lot about them, and we can also be reassured that the cap rock has sealed the reservoir without it leaking for millions of years.

Enhanced Oil Recovery

CO_2 can also be injected into oil reservoirs where production has slowed; this can make the costs of producing the remaining oil much cheaper, and is used widely around the world. This process is commonly referred to as CO_2 Enhanced Oil Recovery, or CO_2-EOR.

CO_2-EOR works by injecting CO_2 so that it effectively pushes or flushes the remaining oil towards the production wells, making it easier and cheaper to extract.

CO_2-EOR, as well as allowing more oil to be produced, has taught us a huge amount about how to inject CO_2 and how it behaves in deep underground rocks.

Summary

This sheet is not intended to cover all the terms that will be used in relation to CCS, but it should cover most of those needed to form an understanding of

the process, the elements and technical ideas involved, and how each stage works.

CCS is a process consisting of several stages and each stage has its own technical terms, but here we aim to provide an introduction to the main terms.

Information Sheet 1: Setting the Scene: Climate Change

What is Meant by 'Climate Change'?

As we all know, weather can change every day, when we talk about the 'climate' and specifically 'climate change' we are talking about long term averages and patterns, usually of at least three decades, if not more. Climate change refers to long-term changes in these averages, and includes factors such as rainfall and temperature. Climate change can lead to an increase in the severity and frequency of extreme weather events, such as the floods of 2007 which affected many areas of the UK.

While there are some natural forces that affect the climate, the levels of greenhouse gases in the atmosphere have a direct impact, and humans are largely responsible for recent increases in greenhouse gas concentrations, since the industrial revolution and the burning of fossil fuels for the generation of electricity.

We Live in a Greenhouse

The 'greenhouse effect' is so called because the effect is exactly like being in a greenhouse; in a greenhouse it is the glass that prevents heat escaping back out, whereas in the atmosphere it is gases such as Carbon Dioxide (CO_2). There are a few other gases that have the same effect, but the impact of CO_2 is greater, and more directly linked to human activity. These gases are collectively known as greenhouse gases because of the role they play in this process.

The Impact of Humans

There is a lot of debate as to whether climate change is a direct impact of human activities, but the Intergovernmental Panel on Climate Change (IPCC) recently concluded that the rises in global average temperature was 'very likely' a result of man-made greenhouse gas emissions. In this instance, 'very likely' means a greater than 90% chance.

Global temperature increases correspond very closely to the industrialisation of our civilisation, and as a result of this industrialisation, we 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_2 and other greenhouse gases into the atmosphere.

What is Carbon Dioxide?

Carbon dioxide (CO_2) is the most important of greenhouse gases. Made up of one carbon and two oxygen atoms, which are two of the most commonly occurring elements on the planet, it is the most influential greenhouse gas. It is also the one that man has contributed most in terms of increasing emissions due to the burning of fossil fuels to create electricity. CO_2 occurs naturally in freshwater and seawater, in some rock formations and in the soil. CO_2 is not toxic, explosive or flammable.

The Carbon Cycle

Taking a step back, the element of carbon, one of the components of CO_2 is naturally present in the Earth's atmosphere, water, soils, rocks, plants and animals. All of the carbon present in the Earth today has been here since the birth of the solar system, and it moves in a cycle, from one physical place and form to another. The amount of carbon in the cycle does not change it is simply exchanged between one store and another – land, sea and air. The human activity of burning fossil fuels changes the balance of this system, meaning more carbon is present in the atmosphere than the land or sea phases, and this in turn contributes to the greenhouse effect.

The Challenge Ahead

There are several options for changing the effect we are having on the climate; we can change our fuel generation practices for renewable or low-carbon options, we can increase fuel efficiency, so we use less to generate the same power, and we can prevent CO_2 from being released to the atmosphere by deploying CO_2 capture and storage (CCS).

Over the longer term, low carbon technologies and energy efficiency improvements provide the biggest and best chance for change. However if we do nothing while we wait for these technologies to be developed to the stage of readiness, so that they can replace fossil fuels in the energy generation mix, we will have passed the point of no return, and climate

change will be insurmountable and the way in which we live will be changed forever.

We need to develop and deploy CCS technologies in the short to medium term in order to reduce the amount of carbon that we emit. The technology of CCS means that we can continue utilising fossil fuels while alternative fuel technology is developed, without releasing the CO_2 into the atmosphere.

The impact of insurmountable climate change would include social, economic and environmental effects, and could include impacts such as: spread of diseases, displaced communities, food shortages, extreme weather events, water shortages, drought and much more.

Summary

There are many options for reducing greenhouse gas emissions and all will be needed in order to prevent insurmountable climate change. The use of CCS does not mean that other options will be neglected or not researched and developed, all the options will be needed and CCS has the potential to make a big impact, relatively early. That is why more action is needed to deploy CCS projects around the world; it can make a difference quickly while other technologies are developed and brought to maturity.

Information Sheet 2: A Brief History of CCS and Current Status

This information sheet aims to provide a brief history of the development of CO_2 capture and storage (CCS), and describes the different types of project. The important thing to take from this information sheet, is that although CCS is technically a relatively new technology, what CCS does is use existing, well proven technologies in new and innovative ways; the various parts of the process have been used extensively in other processes for decades in industry.

The Beginning...

The basic idea of CCS – capturing CO_2 and preventing it from being released into the atmosphere was first suggested in 1977; using existing technology in new ways.

CO_2 capture technology has been used since the 1920s for separating CO_2 sometimes found in natural gas reservoirs from the saleable methane gas.

In the early 1970s, some CO_2 captured in this way from the a gas processing facility in Texas (USA), was piped to a nearby oil field and injected to boost oil recovery. This process, known as Enhanced Oil Recovery (EOR) has proven very successful and millions of tonnes of CO_2 – both from natural accumulations of CO_2 in underground rocks and captured from industrial facilities – are now piped to and injected into oil fields in the USA and elsewhere every year.

Different options – different projects

Gas Processing

Gas processing facilities, which extract natural gas from underground fields, often have to clean the CO_2 from the natural gas in order to be able to sell it. These facilities therefore have to capture the CO_2 before they have a useable commodity.

Power Plants

Power plants that burn fossil fuels don't have to capture the CO_2 in order to produce electricity and the capture process will actually cost slightly more overall. So capturing CO_2 from power plants is purely done for emissions reduction reasons.

EOR

EOR projects have a use for the CO_2 captured in the earlier processes; this gives the CO_2 a value in monetary terms. The CO_2 is often extracted from the oil field along with the oil, but as it was expensive to purchase, this will be separated and can be used again to produce yet more oil. Eventually, when all the oil has been produced, the CO_2 can be left (stored) in the depleted oil field – permanently preventing that CO_2 from being released into the atmosphere and contributing to the greenhouse effect and global warming.

Where is CCS in its development?

With so much going on, and at a fast pace, it is very difficult to get a clear picture of how many projects are ongoing around the world. As of the end of 2012, there were 5 large scale CCS projects in operation around the world, with 3 operational full chain (with capture and storage) pilot projects also ongoing. However there are 23 large-scale projects being developed that have secured funding and if these continue to progress to large-scale operational projects, the future development could rapidly increase in pace. The Global CCS Institute has a good handle on developments and their

website www.globalccsinstitute.com/projects/browse gives a current picture for those interested.

Summary

It is clear that for CCS to make the maximum contribution to emissions reductions, the pace of development and deployment needs to increase substantially to get projects up and running in time to meet global targets. CCS has the potential to make a big difference to greenhouse gas emissions, but action is needed swiftly to allow the impact to take effect before temperatures rise, and the cost of battling climate change goes up.

Information Sheet 3: Matching Sources to Stores

The aim of this information sheet is to look at one of the constraints on CO_2 capture and storage (CCS). In theory it sounds simple; capture CO_2 from power plants, store it in underground storage formations.But what if there aren't any nearby? Is there enough storage in the world? This sheet will answer these points.

What if There Are No Storage Options Nearby?

If there are no suitable storage formations nearby, then the captured CO_2 can be transported (albeit at a cost) and has been extensively for other purposes. Information Sheet 6 deals with transport in more detail, but for now we will simply state that captured CO_2 can be transported to suitable storage sites.

Is There Enough Storage?

In simple terms; yes. There is a lot of uncertainty of the actual amount of storage available, as many reservoirs and formations have not been thoroughly characterised and explored, but best estimations suggest they would operate satisfactorily. There are wildly varying estimates, from extremely conservative to extremely optimistic, but as more exploration continues, the range is reducing, and even at the lower end of the potential storage available it is sufficient to store emissions for long enough to enable other clean energy technology to develop to a stage where fossil fuels would not need to be relied upon. Many areas of intensive activity would be suited to networks where numerous capture facilities link up and the combined CO_2 is then stored as a single operation.

Some studies have shown that just one storage option, storage in saline formations, has great potential; in the USA, this option alone could store the equivalent of 100 years of CO_2 emissions at current levels. Oil and gas field storage would add yet more to this. Some regions in the world would struggle; others would have a surplus of storage potential, so the issue of transport is a key one, and one that will be dealt with in more detail in the Information Sheet on Transportation of CO_2.

Matching CO_2 Sources and Storage

So we know that there is enough storage around the world, but how does that match up to the locations where the emissions are produced?

Broadly speaking, all regions of the world have potential for storage. Estimates range from the USA having 77% of its subsurface showing a good chance of storage potential, through Europe with 57% and India with 43% so some regions will have more options available than others, and some regions may struggle to store their emissions for longer periods of time. Again, this is closely linked with transport – the cost of transport obviously goes up with the increased distance, and also regulations will come into play as there are strict rules governing the transport of CO_2, especially over national borders. This is addressed more in Information Sheet 12.

Summary

All regions have the potential to conduct large scale CCS, although some countries may struggle to find sufficient storage sooner than others. These are the situations where trans-boundary transport of CO_2 will be vital, and this is something that will need to be clarified by legislation sooner rather than later. Climate change is a global problem, and countries will need to cooperate over storage resources to overcome the problem.

Information Sheet 4: Capturing Carbon Dioxide (CO_2)

In order to store CO_2, first we need to capture it. There is a lot of research being undertaken both into improving existing processes, and developing new methods of capture, but currently there are three main methods of CO_2 capture which capture the CO_2 either before combustion (burning) of the fuel, after it, or by combusting the fuel in a different environment, and these are described below.

Post-Combustion CO_2 Capture

Post combustion capture, as the name suggests, takes place after the normal combustion process has taken place, i.e. after the fuel has been burnt to produce electricity. Post combustion capture takes place in the chimney of a power station, also known as the 'flue'.

A chemical (or solvent) is washed through the exhaust gases, and this chemical effectively removes the CO_2 from the exhaust gases. This chemical, now containing the captured CO_2, is collected at the bottom of the flue and the CO_2 can be removed for transport and storage, while the chemical can be re-used.

First examples of this exhaust gas cleaning have been used since the 1930's, and because the capture takes place after combustion and after the electricity has been produced, no changes need to be made to the power station other than adding the capture system to the end of the process. This makes post combustion capture particularly suited to power stations that are not due to be replaced, and are still operating as relatively new power stations.

Pre-Combustion Capture

Again, the name of the process suggests where the capture takes place; pre-combustion capture takes place by removing the CO_2 from the raw fuel.

The fuel is subjected to a chemical reaction which converts the fuel into a gas mixture made up of hydrogen, carbon monoxide, and oxygen. A second stage reaction converts this into hydrogen and CO_2. The CO_2 is removed, and the hydrogen is combusted with air to produce electricity. The only waste product to come out of this process is water.

This is a very clean process, and also eliminates many other emissions. It is a more expensive option, and as the combustion process is significantly altered, it is less applicable to existing power stations, and is much better suited to new-build stations.

Oxyfuel Combustion

The third option is different in that instead of burning fossil fuels in air, which conventional power stations do, the fuels are burnt in oxygen. This means that the waste products are CO_2 and water which are easily separated.

Again, this process is more suited to new power stations, but can be fitted with minor changes to existing power stations. The main costs associated with this option are based around the supply of oxygen – this is done by removing the other components of air in a special process before the combustion process, and this is relatively expensive.

Summary

While all three options are viable, the choice remains dependant on the location, the need to fit the process to an existing power station or build a new one, and the availability of equipment and chemicals needed for each different process. All three are being tested, developed and demonstrated, and all have a part to play in emissions reductions.

Information Sheet 5: Costs of CCS

It is understood and accepted that CO_2 capture and storage (CCS) is one of many options to mitigate the effects of climate change, however it is one of a few that have the potential to offer deep cuts in emissions. There remain some questions and uncertainties over the costs involved, and this information sheet aims to address these costs, and put them into context.

Why is CCS Expensive?

All new technologies, or new applications of existing technologies are expensive at first, and then reduce over time. Think of buying a mobile phone: when mobile phones were first available, the handsets were extremely expensive, but over time, as the technology becomes more established and widespread, newer handsets are developed at a cheaper cost. CCS can be seen to operate in a similar manner. First demonstrations will cost more, but once established, the ongoing costs will not be as high.

For the first developments the costs will be recognisably higher, but over time, as the technology is modified, improved and generally streamlined, these costs will reduce. The initial costs will more than likely be swallowed either by the energy company, or covered by government grants or subsidies. It should also be noted that some sources suggest the costs of not deploying CCS could be up to 9 times higher through increased insurance costs due to more severe weather events, increased costs of food production and other impacts of unmitigated climate change.

What Are the Costs?

Quite simply, the costs involved in CCS either apply to capture, transport or storage. Capture costs are incurred by the physical machinery and equipment needed to capture the CO_2. A one off cost at the start of a development and the ongoing costs for the actual capture; i.e. the chemicals or additional elements used in the capture process (solvents in post-combustion capture, oxygen in oxyfuel combustion and steam in pre-combustion capture).

These costs vary; the oxygen is produced using some specialist equipment, so this is primarily an up front cost, the solvents in post-combustion capture can be re-used to a certain degree, and the steam production for precombustion capture is the primary ongoing cost for this method.

Transport costs are simple to predict as gas transport by pipeline, truck or ship is already carried out all around the world, and the costs of transporting gases over distance are known. There is a possibility of a cost reduction in this part of the chain as pipeline infrastructure reuse is a possibility; using gas pipelines that transported natural gas from a gas field to a processing facility to transport the captured CO_2 to a storage formation.

Storage costs are less simple to predict; drilling of new injection wells is a costly process, possibly minimised by converting existing production wells (in the case of oil and gas field storage) into injection wells. Although a great deal is known about the drilling of wells, observation, monitoring and exploration of potential storage sites can add substantially to the cost of a project. As time goes on and more is known about large-scale storage, these costs will be expected to reduce.

What Do We Know About Costs?

To a certain degree, we don't know a great deal about firm costs, this is because there isn't a large-scale capture and storage project in operation. Many projects are underway at smaller scales, and this is an area that is under constant development.

Some Europe-wide initiatives are in place to share data and information as it becomes available, and as an example, the UK government carried out extensive initial work in determining the feasibility of a proposed project in Scotland.

The project was cancelled, but the information has been made publicly available to any parties looking at similar projects.

Summary

While firm data is currently unavailable, or unreliable for costs, it is clear that there is a great deal of knowledge and experience that can be applied to CCS. It is hoped that as more information becomes available, the variations in cost estimates will reduce, and a clearer picture will be developed. What is clear is that CCS will cost money, however this will likely not impact greatly on consumers and the costs of not deploying CCS would likely be much higher.

Information Sheet 6: Transporting Carbon Dioxide

Transport is a necessary stage in the Carbon Dioxide (CO_2) capture and storage (CCS) chain as it is not common for power stations to be built in close proximity to potential storage formations, especially as many storage options are off-shore. Pipelines and ships are therefore needed to transport the CO_2 from the source to the storage area.

Existing Pipelines

CO_2 has been transported via pipelines since the 1970's, predominantly in relation to Enhanced Oil Recovery (EOR). As described in another Information Sheet, EOR is an expanding industrial activity, where CO_2 is used to produce more oil than conventional methods would otherwise manage. As EOR is conducted more extensively, pipeline networks are being built to facilitate this, and in 2013 there are almost 6000km of CO_2 carrying pipelines in the world, mainly in the USA.

Another potential benefit is that the existing pipelines that are currently used to transport oil and gas from where they are produced could be re-used to transport the captured CO_2 to storage formations.

Transport via Pipelines and Ships

In many ways, the transport element of CCS can be viewed as the simplest – there is a vast amount of experience in terms of transporting gas via pipelines and ships, and the technical side of this part is quite straightforward. Costs vary depending on location, terrain and method of transport. Depending on the length of transport needed and the likely length of time that the CO_2 will be transported to a specific location will affect which is the more economical

option: pipes or ships.

Pipeline Networks

Although predominantly associated with power stations, CCS can also be applied to some industrial processes, and it is often the case that industrial sites that have high potential for CO_2 capture are found in the same region. This provides an opportunity to simplify the pipeline or transport aspect, as the captured CO_2 can be merged and transported as one, rather than each capture plant having its own dedicated pipeline. This can help to reduce the costs of transport infrastructure, and the costs of transport itself.

It is anticipated that where several storage formations are found in close proximity that there could be similar networks at the other end of the pipeline, where CO_2 can be diverted to one storage formation or another, after sharing the pipeline that transported the CO_2 from the capture facility.

Summary

Transport is likely to be the simplest element in technical terms of CCS, however concerns exist over routes and the appearance of pipelines. It is anticipated that pipeline routes will likely follow existing 'corridors', alongside existing pipelines to minimise impacts, however this may not always be possible, and each case would need assessing on its own merits.

Information Sheet 7: Naturally Occurring Carbon Dioxide

Natural Carbon Dioxide (CO_2) reservoirs exist underground in normal circumstances, and these naturally occurring stores of CO_2 have securely held the CO_2 in place for thousands, or even millions of years. These natural CO_2 stores have been extensively studied, and the knowledge gained has been incredibly useful in estimating the storage potential and learning about trapping mechanisms for CO_2 capture and storage (CCS). The knowledge gained from this allows scientists to predict the behaviour of stored CO_2, and gives the ability to perfect monitoring technologies that can then be applied to CCS.

Natural sources

CO_2 is found in two main types of location; sedimentary basins where water containing CO_2 becomes trapped, and in volcanic areas, where CO_2 is released from the magma (molten rock) as the pressure underground changes. Where

naturally occurring CO_2 is found in sedimentary rocks, like those that hold oil and natural gas, these stores are secure, with no pathways or routes for the CO_2 to escape. Such stores have existed, securely holding natural CO_2 for millions of years. One particular example is a geological structure deep underground in Mississippi, USA, which holds an extremely large quantity of CO_2, significantly larger than would ever be considered for a CCS project. This CO_2 entered the geological storage formation 65 million years ago (around the time that dinosaurs roamed the Earth), and has remained there ever since.

Examples such as this are not uncommon, and give clear evidence that appropriate geological structures can contain injected CO_2 for the periods of time required for CCS to effectively mitigate climate change.

Although extremely rare, sometimes naturally occurring CO_2 can leak upwards through the subsurface and release to the atmosphere, usually at a slow rate, with no adverse effects to plants or animals in the area. This is part of the natural CO_2 cycle between land, atmosphere and water. These leaks can teach scientists how CO_2 acts in the subsurface, and allows subsurface monitoring and detection tools to be perfected. It is very important to note that CCS sites would be carefully selected to avoid geology that would be susceptible to leaks and that these natural leaks are used as a positive learning experience.

In low concentrations (typically below 3%) CO_2 is harmless, causing tiredness and an increase in breathing rate, but with no lasting consequences. Above this level however, prolonged CO_2 exposure can lead to unconsciousness and possibly death if the affected person is not moved to a location with clearer air. While this is worrying when taken as a single fact, it should be noted that such high concentrations of CO_2 are rare, and would not remain in open areas as the CO_2 would mix with the surrounding air and disperse.

Natural disasters

There have been isolated instances in the past when a large release of naturally occurring CO_2 has lead to loss of life in natural disasters. While this is extremely rare, and in the following example a specific set of circumstances combined to facilitate the disaster, it is important to highlight the event, recognise the circumstances that occurred which lead to it, and recognise that the situation would not arise in the same manner in a CCS project. CCS

sites would be selected in stable areas and safeguards would be in place to alert of any dangers in the unlikely event that something should go wrong.

In 1986, in a place called Lake Nyos in Cameroon, a natural disaster claimed the lives of 1700 people and 3500 animals. Lake Nyos is situated in a volcanic crater, where due to tropical conditions, and stable temperatures, the CO_2 that accumulates in the bottom layers of the lake do not mix and slowly release to the atmosphere. A geological event, possibly a landslide, disturbed the layers of water, releasing the CO_2, which (being heavier than air) flowed down the valleys and into several villages, asphyxiating the locals. Since then, pipelines have been installed to link the lower levels of CO_2 saturated water with the lake surface to prevent reoccurrence.

It is important to note that the incident at Lake Nyos and other similar disasters cannot be used as examples of what could happen with CCS sites; CCS would only be carried out at sites not subject to the kind of geological events that could cause leaks, and monitoring tools would minimise risks of undetected leaks.

Using Natural Sources to Learn

Being able to study and monitor natural sources of CO_2 in the subsurface enables scientists to learn how CO_2 behaves in underground storage formations at depth and pressures similar to those that will be used for CCS.

Studying natural leaks also enables scientists to fine tune monitoring technologies and develop early detection systems that can then be deployed near storage sites.

Summary

A great deal can be learned from natural underground stores of CO_2 and the very fact that these naturally occurring reservoirs have securely held CO_2 for thousands or even millions of years demonstrates the feasibility of CCS. The situations that led to the few isolated natural disasters would not occur in carefully selected storage formations for CCS. For CCS, sites would be carefully selected in geologically secure areas, with little or no volcanic or tectonic (earthquake) activity, and with thorough and rigorous detection and monitoring systems in place with plans for the remediation of any leaks or releases.

Information Sheet 8: Storing Carbon Dioxide (CO_2) Underground

Once the CO_2 has been captured and transported to a suitable storage site, we need to ensure that it will stay underground. There are several mechanisms that ensure the storage is permanent, and this information sheet aims to describe these in broad terms.

Site Selection

The first thing to determine is where to store the CO_2. There are several physical things necessary for this, and the site selection process will ensure that only the best, safest and most secure sites are selected. These sites will have a suitably sized storage formation in which the CO_2 can be injected, with a suitably impermeable cap rock above it to prevent the CO_2 from escaping upwards through the ground. Other factors will be considered during site selection, such as accessibility, proximity to capture plant and ease of transport, but also other factors such as geological stability (not in an area prone to earthquakes), and other technical requirements.

Rock Types

The storage formation, or 'reservoir rock' itself will be permeable so the CO_2 can be injected into it, porous, so there is enough space to store the CO_2, and deep enough that the CO_2 has no opportunity to escape to higher levels, and ultimately the atmosphere.

The cap rock will lie directly on top of the storage formation, and will act as a barrier so that the CO_2 cannot pass out of the storage formation. A good analogy for these two rocks is that the storage formation acts as a sponge, and the CO_2 can be held within it, and the cap rock is like a rubber sheet, not allowing any liquids or gas to pass through it.

Storage Formation Options

Storage formations come in two types – depleted hydrocarbon reservoirs (oil and gas fields) or deep saline formations. The deep saline formations simply hold very salty (brine) water that has no value for anything, whereas the depleted hydrocarbon reservoirs would originally have held oil or gas. Other than that, the basic geology is the same – both will be rocks similar to sandstone, and have lots of little spaces between the grains which the CO_2 will be stored in. The main differences between the two options will be in terms of location, capacity, and how easily the CO_2 can be injected.

Current Projects

Although this will be subject to change, in 2013, there are a number of projects in operation around the world, and in Norway there are two projects operating at a commercial scale, injecting and storing millions of tonnes of CO_2 every year. One of these, the Sleipner Project has been operating since the 1990's separating CO_2 from natural gas extracted from beneath the sea floor, and the separated CO_2 is then reinjected into an overlying formation. The natural gas is then piped to shore for further processing. There is an extensive monitoring project in operation around the injection programme, and much has been learnt about CO_2 and its behaviour when underground.

CO_2 Underground

While the cap rock initially prevents the CO_2 from escaping, over time, other mechanisms come into play.

Residual Trapping

As the CO_2 moves through the formation (because more is injected), some becomes trapped as small bubbles between the rock grains, and is unable to move any further.

Dissolution Trapping

Some CO_2 will be dissolved into the salty water that is in the storage formation. This CO_2 and water mix is then heavier than the normal water, and sinks to the bottom of the formation.

Mineral Trapping

Lastly, the CO_2 can react with the rock grains themselves, forming minerals within the rock. These minerals take a long time to form, but once formed, they effectively lock the CO_2 in place for millions of years.

With these mechanisms in place, and once the capacity of the formation has been reached, the wells are blocked off and sealed, and the CO_2 is effectively contained without any chance of escape.

Summary

The physical process of storage is relatively straightforward, and with the different storage mechanisms that take effect over time, the longer the CO_2 remains in the reservoir, the more confidence there is that it will never escape. Monitoring will still take place to detect leaks and enable operators

to fix them, but as time goes by, storage can be relied upon more and more as permanent.

Information Sheet 9: Effects of Carbon Dioxide (CO_2) Leaks Onshore

Whilst everything will be done to ensure leakage does not happen at any stage – capture, transport or storage, it is important to recognise that sometimes accidents can happen. Operators will be required to demonstrate that they are aware of the risks, and have a deep understanding of what the potential risks are, and how to deal with them to minimise and remediate any potential hazards.

Leak Sources

It is conceivable for CO_2 to leak from any stage of the process, capture, transport or storage, but all the risks can be managed to minimise and ensure swift detection and remedial action to remedy the problem.

Dangers and Environmental Impacts

CO_2 only presents a danger to humans when concentrations rise to over 3%. At this point it can lead to unconsciousness, and death if the casualty is not removed from the source of CO_2. However, the probability of exposure at high enough levels for long enough periods of time is unlikely as wind and air movements would dissipate any CO_2 very rapidly, and the length of exposure would likely be very short, with no lasting effects.

CO_2 is not to be confused with carbon monoxide (CO) as CO is very dangerous – many people will have CO detectors in their homes to detect leaks from their gas boiler. CO_2 is not in the same league, we breathe small amounts of CO_2 every day, in every breath, and it is the main constituent of what we breathe out.

Plants react in a similar manner, with one particular difference of note, and that is that at low concentrations, CO_2 can actively encourage growth and development in plants. Large numbers of commercial greenhouses (particularly in The Netherlands) use CO_2 captured from industrial processes to enhance the growth rate of their flowers which are then sold all over Europe. CO_2 does still pose a danger to plants, and at concentrations over 20%, plant death will occur.

Leakage Risks and Prevention Measures

Leakage from the capture or transport processes would occur on or near the surface, so any such leak would have an immediate and apparent effect, however the leak would also be easily detectable and manageable. Any changes in pressure within a pipeline system would instigate an immediate shut down and rapid repair. Any leaks at the capture process would be taking place in an industrial setting, with rigorous procedures in place for health and safety, and any leak here would also be shut down very quickly.

The larger risk would be leakage from the storage site. Any storage site will be around 1000m below the surface, or more, and therefore detection proves to be a more complex process. However, due to extensive site characterisation and monitoring before and during injection, any changes would be picked up quickly, and should a leak occur, injection would cease while the problem was dealt with. Over decades of oil and gas exploration and production, a vast suite of monitoring technologies has been developed, and site operators would have a large number of monitoring tools at their disposal. Seismic surveying works by sending sound waves into the earth, and monitoring the reflected signal – kind of like an echo. By interpreting the signal that returns, and measuring the time delay and other factors, operators can tell precisely where the CO_2 that has been injected is, and where it is moving. Any leaks from the storage reservoir would be detected by similar monitoring techniques and wells that were causing a leakage 'pathway' can be isolated, blocked and sealed to prevent such leaks reaching the surface.

Summary

While leakage is possible from the different elements of the whole process, operators would be required to minimise risks, operate within safe limits, and maintaining an extensive monitoring programme, with remediation plans in place should something go wrong. Leaks can be detected, isolated and repaired, whilst careful site and route selection will minimise or remove any potential risks to humans, animals or environmentally sensitive or protected plant species.

It is important not to ignore the risks associated with leaks, but it is also important to recognise that the risks are extremely small, and it is a simple matter to remediate them. The chances of extreme or dangerous accidents

are low. Although some gases are flammable, CO_2 is not, so there is not a fire risk from any leakage – CO_2 is actually used in fire extinguishers.

Information Sheet 10: Effects of Carbon Dioxide (CO_2) Leaks Offshore

With most capture facilities being onshore, with the exception being gas processing facilities at sea, the principle offshore leakage potential routes are from subsea pipelines or storage formation leaks.

Leak Sources

Offshore transport of CO_2 would either be by pipeline or ships, with the CO_2 transported as a dense gas or liquid. Any leak would involve the pipe or ship storage tank rupturing, and would need repair to prevent the leak. Pipelines again could be shut down remotely, as with onshore pipelines, but the ship-based leak would be a more lengthy process, however it would also be much less likely to occur. Leaks from sub-seafloor storage reservoir would occur in the same way as onshore storage formations, but the detection and remediation actions would differ.

Offshore Transport

Operators of oil and gas production facilities have relevant experience of transporting high-pressure fluids and gases through seafloor pipelines. The extent of the experience in the offshore environment is less than the onshore equivalent, but the best source of experience and knowledge comes from the Snøhvit gas processing and CO_2 capture and storage (CCS) facility in the Barents Sea (Norway). Here the site operators have been processing natural gas produced from below the sea floor and storing the CO_2 since 2008 without incident, and the operators have contributed a great deal to the knowledge base used in the CCS industry as a whole.

Specific issues faced by offshore transport that do not apply to onshore situations are primarily around material selection and resistance to corrosion. Submersing metal pipelines in salt water adds a complexity and expense to these pipelines not present in onshore transport situations. Ships used for transport of liquids and dense gases are designed for purpose, and use double hulls to prevent leaks even in the event of an accident or running aground.

Leakage Risks and Prevention Measures

CO_2 leakage into seawater could cause the CO_2 to dissolve into the seawater, making it become more acidic which could have a detrimental affects on some sea life. The exact impact would be determined by the immediate environment; the existing chemical makeup of the seawater, the temperature, depth, pressure and the currents in a specific location. Mixing of the affected water and non-affected water by currents would lessen any effects.

The risks associated with leakage from the storage site would be similar to those described above, as the impacts would come into force once the CO_2 reached the seabed and was dissolved into the sea water. Remediation of any leaks from the storage reservoir would be similar to that in onshore reservoirs, although the costs of operating offshore and below the sea would be higher.

Once again, it needs to be highlighted that the probability of leakage from a carefully selected storage formation, deep under the seabed is extremely unlikely. Taking the Sleipner project example in the North Sea, monitoring has shown the CO_2 to have remained safely within the storage formation for many years, acting as predicted by scientific models. The chances of leaks are extremely small but even if a leak did occur, monitoring and remediation options are more than capable of stopping leaks and preventing damage to the environment.

Summary

Again, leakage is possible in offshore storage operations, but every measure would be taken to minimise or remove the opportunities for incidents. The risks remain fairly similar to those of onshore situations, and the monitoring, detection and remediation of any leaks would be similar, but with the added complexity of operating under the sea.

Although the risks are still present in offshore CCS, and although they are more expensive to remediate, the fact remains that the risks are extremely small, and the technologies and abilities to remediate leaks are in place and ready.

Information Sheet 11: Monitoring Carbon Dioxide (CO_2)

At the heart of any permission, license or other regulatory allowance to carry out a CO_2 capture and storage (CCS) project, is the ability to monitor the CO_2 that is injected and verify that it is where it is intended to be. Monitoring and verification continues past the injection stage and will carry on for years after a project has stopped injecting in order to demonstrate storage is permanent.

Why monitor?

For CCS to be categorised as a climate change mitigation option, it has to permanently prevent the emissions of CO_2 to the atmosphere. If CO_2 is injected into a storage formation, then for the operator to be able to class this as stored CO_2, they have to be able to demonstrate or prove that the CO_2 has remained stored securely.

Monitoring techniques have been developed to be able to show where the CO_2 that has been injected has gone, how far it has travelled, and how much is there.

How does monitoring work?

Subsurface monitoring uses pressure sensors, to monitor the pressures within the storage formation. By monitoring the pressure as it increases during injection, if a leak should occur the pressure would drop and indicate leakage. Other monitoring tools will then determine the location and rate of the leak and allow operators to fix it, preventing environmental impacts.

Seismic monitoring is used to create a picture, showing where the injected CO_2 is, both in terms of depth and how far it has spread out within the storage formation. The Sleipner project operating offshore of Norway has used seismic monitoring very effectively. The project has been operating for a number of years and the differences between the repeat surveys show the development of the CO_2 area in the subsurface. This allows operators to verify how much has been injected, where it has travelled, and where it is now. The images from seismic surveys look confusing to an untrained eye, but with the correct understanding, they can provide a wealth of information for the site operators.

Other monitoring techniques are available and are used to verify the same facts about the injected CO_2. Monitoring can also assess the condition of wells

drilled into the storage formation, both old and new, and determine which need remediation or plugging / sealing before an injection project starts.

Surface and near surface monitoring focuses on water systems, air quality and ecosystems in the vicinity of a project. By monitoring the groundwater in an area, the operators can determine if any CO_2 has leaked to the groundwater. Surveys before injection starts are important here as groundwater can contain different levels of CO_2 depending on many external factors, so it is important to know what the original groundwater was before testing to see if any CO_2 has leaked into it.

Atmospheric monitoring tests the composition of the air to determine if the CO_2 levels are rising due to leaks. These tests can be very location specific, so if there is a leak, not only can these methods detect it, but they can also pinpoint it to allow site operators to determine where it is coming from and fix it.

By monitoring changes within ecosystems, both plant and animal, operators can detect if any small leaks are causing changes to the animals and vegetation in the area. Some species can act as early indicators, and can be used to identify any small changes over time.

Summary

With even the most rigorous site selection, and careful injection programme, there will be those who are cautious over the safety of CCS. By utilising and deploying monitoring technologies site operators can offer an extra reassurance that the site is operating properly, safely, and within preordained restrictions laid down by regulators.

By demonstrating that the injected CO_2 is accountable, it is acting as expected, and is where it is expected to be, reassurance can be offered to interested parties and safety can be assured and demonstrated.

Information Sheet 12: Legal and Regulatory Concerns

CO_2 capture and storage (CCS) projects will need to be subject to regulation and laws, and although there are some regional regulations that govern and allow pilot and demonstration projects, widespread and all encompassing regulations have so far been missing. There are numerous legal issues that will need to be addressed in order to draft full legislation that will regulate

the CCS industry, specifically the storage side.

Is CO_2 a Waste or a Commodity?

This question has been answered and it is now known that CO_2 is to be classed as a commodity. There was a genuine worry that should it have been classed as a waste, there would have been issues relating to transport – wastes cannot be transported across international borders, so if CO_2 was classed as a waste, then some regions with less storage potential would have faced difficulties in mitigating their CO_2 emissions.

Permanence of Storage and Site Ownership

In order to be allocated credits under emissions trading programmes, the CO_2 must be permanently stored otherwise there would be no inherent desire of the operators to act to the best of their ability. In order to maximise operating efficiency, credits should only be allocated for confirmed permanent storage. However, the issue then lies in defining permanence. How long does the CO_2 need to stay there to be classed as permanent?

The aim of CCS is to store the CO_2 for thousands of years, but operators will need paying immediately, the issue of repayment in the event of leaks leads to a question of time limits… when does responsibility pass from the operator to another entity and which entity? Operators will not want to run sites where they are liable for many years after they stop injecting – at some point, the responsibility and ownership of the site will need to pass to a local or national authority, and this is debated around the world as to when this happens.

Ownership of Rocks

Another question comes up with the ownership of the pore space within the rocks. Landowners may want compensation, or other monetary exchange if CCS is taking place where the injected CO_2 will be under their land. In the USA, landowners generally own the geological formation under their land whereas in other regions of the world it is owned by other bodies depending on the presence of minerals and other factors. This will need addressing before CCS can take place.

As an example, some regions of the world have modified their laws so that the pore space within a rock formation is owned by the government while the rock and minerals remain the property of the landowner. This allows CCS to take place, but it remains to be seen how this will take effect in practice.

Sub Seafloor Storage

This is a more complicated area; the seafloor up to 12 miles from shore is subjected to the same laws as that country, however in northern Europe there are regulations in place that prohibit the disposal of wastes in or under the sea. This circles back to the question of whether CO_2 is a waste or a commodity.

Regional Laws

Some areas in the world have developed and implemented laws that will allow CCS to take place on an operational basis, providing that strict criteria have been met and safety measures are in place. These laws make some headway against the issues outlined above, but this is an ever-changing and developing area, so trying to define the conclusions in an Information Sheet such as this is not possible.

Summary

Regulations, legislation and laws will be required to successful deploy and operate CCS projects. Many regions are working on this, and some have put these into practice, but there is still some way to go before established legislation permits wide-scale deployment of CCS such as will be necessary to mitigate climate change.

Public Perceptions of CCS

With more and more CO_2 capture and storage (CCS) projects reaching the mainstream media and being reported in the news, public perception is an important aspect of a project. With access to information becoming ever simpler via the internet, it is very important for project operators to be open and honest, but above all proactive in their communications to the public.

Who are the public?

In this instance, the public can be considered anyone who is interested in the project for a variety of reasons. They may be scientifically trained and well aware of the processes involved, or they could be relatively uninformed, but equally interested with or without scientific background and training. This is why public perception is so vital – getting the right information to the people who want it and engaging with local populations from the earliest possible stage.

What do the public want to know?

Why, what, who, where, how; five simple questions that define what needs to be communicated from the operators to the public.

- **Why** – they need to understand the basics and background of climate change, and what unabated climate change will mean.
- **What** – they need an introduction to CCS – how it works, and what is involved.
- **Who** – they need to understand who the companies are, why they are involved, and what their experience and expertise is; essentially why they are suitable operators for the project.
- **Where** – they need to know where the project will operate, to understand if it will impact on their local environment and economy.
- **How** – they will want to know the project details in terms of the specific elements involved, and what the risks, impacts and benefits to them will be from the project.

This demonstrates why it is important to treat public engagement as a new task for every project, because every local population will have specific concerns and worries which need to be addressed on a case-by-case basis.

Misconceptions

There will always be some misconceptions about CCS and CO_2 that will need to be addressed. Many people who haven't had a background in science may mistake CO_2 (carbon dioxide) for CO (carbon monoxide) – CO_2 is relatively safe, and is used in carbonated drinks, the food industry, and in fire extinguishers, CO is very dangerous, can kill and is why we have CO detectors in our homes to ensure that our household boilers aren't leaking. If CO_2 is mistaken for CO, then the resultant objections to a project may prove completely unfounded, but very hard to overcome.

Trust

Following on from effective communications and addressing of misconceptions, trust is an integral part of gaining public engagement and acceptance for a project. If the site operators are seen to be engaging with the local population, hearing their concerns and providing solutions and information, they are much more likely to gain trust and a project is therefore

more likely to succeed. If operators are uncommunicative and do not engage the local populace, then the project will be looked at with more caution and concern, and will have a harder time gaining acceptance.

Benefits

It is worth considering that CCS projects will likely bring economic benefits to an area, creating jobs, both directly and indirectly, boosting the services trades in the area, and possibly bringing more people to an area, boosting house building, sales, rentals and associated businesses. CCS can be a change for good in a community, and this is often overlooked in public engagement practices.

Summary

Engagement with local communities should be actively pursued from an early stage, involving people at every stage of a project, and highlighting the potential benefits to all involved, both directly and indirectly. If public engagement is carried out openly and innovatively, then the chance of project success is much higher. Engage early, engage openly,and engage innovatively.

2013-18 CO2 PIPELINE INFRASTRUCTURE

Key Messages

- New CO_2 pipeline projects require large investments in infrastructure. Re-use of existing infrastructure can lead to substantial savings in investment costs.
- In the US, EOR has been the primary driver for CO_2 pipeline infrastructure development. Most EU projects focus on CO_2 storage within emissions reduction schemes.
- Except for the US, most countries have little or no experience with CO_2 pipelines or CO_2-EOR operations.
- Start-up, routine inspection, shutdown and venting of CO_2 pipelines can differ considerably from natural gas pipelines.
- Pipelines can usually handle the flexible operational needs of both supplier and user. Examples for pipeline networks exist in the US. These hubs have no specific set of rules, as each system has its own standards for CO_2 purity and operating conditions.
- Although CO_2 pipelines are rarely the focal point of public concern, effective communication strategies are a key element for successful implementation of the whole project.
- Currently it is not possible to draw robust conclusions, whether or not the incident rate with CO_2 pipelines would be different from other gas pipelines.
- Little information is publicly available on the costs of CO_2 pipelines.
- The contractor created a reference manual, database and interactive web tool detailing information on 29 CO_2 pipeline projects worldwide.

Background to the Study

Currently there are more than 6,500 km of CO_2 pipelines worldwide; most of them are linked to EOR operations in the United States but there are also a number of pipelines associated with or under development for CO_2 storage. Valuable experience is available from these projects for all phases of pipeline projects: from early design through to operation and decommissioning.

The aim of this study is to collate information from the public domain on existing CO_2 pipelines into a comprehensive reference document. Other objectives are to discuss the similarities and differences between CO_2 and other, especially natural gas, pipelines and to provide an overview. The overall lessons learned from this study should support project developers, decision makers, regulators, and governmental bodies who do not deal with engineering calculations and cost estimates on a regular basis.

The IEAGHG commissioned this study on behalf of the Global CCS Institute. Ecofys was the main contractor with SNC-Lavalin, who has extensive experience in the oil and gas industry, e.g. in US-based EOR operations, acting as a subcontractor.

Scope of Work

The deliverables for this study consist of a reference manual, database, interactive web tool and webinar. The reference manual highlights key design, construction, operational and regulatory learnings. A database, containing more than 100 data elements, complements the reference manual. It covers the following categories, as Table 1 shows:

Category	Sub-categories	Data elements
Pipeline infrastructure	Pipeline Auxiliary equipment Costs	E.g. Route, length, depth of lay, material, diameter, wall thickness Compression and dehydration Design and construction
Operation and maintenance, risk and safety	Operational characteristics Monitoring Safety	E.g. Volume, source, destination, purity, pressure, flow Inspections and monitoring Procedures, corridors and valves
Regulatory regime	Realisation process Restrictions	Spatial planning, environmental impact assessment and permits/concessions E.g. Spatial planning and location
Public concern	Public communication Decision process	Media, publications and health Environmental Impact Assessment

To make access to the collated information easier and more user-friendly, Ecofys implemented an interactive web tool based on Google Maps. It shows the location and routing of the 29 CO_2 pipeline projects investigated in this

study and allows users to zoom in and access a summary of information from the database (see screenshot in Figure 1).

Figure 1 - Interactive web tool (demo version available at www.globalccsinstitute.com/publications/co2-pipeline-infrastructure)

From over 80 CO_2 pipeline projects worldwide, Ecofys carefully selected a subset of 29 projects covering all key regions and operating conditions in a balanced way (see Table 2). More than half of the chosen projects are operational.

	Project Name	Country code[a]	Status[b]	Length (km)	Capacity (Mton/y)	Onshore/ Offshore	Sink[c]
	North-America						
1	CO_2 Slurry	CA	P	Unknown	Unknown	Onshore	EOR
2	Quest	CA	P	84	1.2	Onshore	Saline aquifer
3	Alberta Trunk Line	CA	P	240	15	Onshore	Unknown
4	Weyburn	CA	O	330	2	Onshore	EOR
5	Saskpower Boundary Dam	US	P	66	1.2	Onshore	EOR
6	Beaver Creek	US	O	76	Unknown	Onshore	EOR
7	Monell	US	O	52.6	1.6	Onshore	EOR
8	Bairoil	US	O	258	23	Onshore	Unknown
9	Salt Creek	US	O	201	4.3	Onshore	EOR
10	Sheep Mountain	US	O	656	11	Onshore	CO_2 hub
11	Slaughter	US	O	56	2.6	Onshore	EOR
12	Cortez	US	O	808	24	Onshore	CO_2 hub
13	Central Basin	US	O	231.75	27	Onshore	CO_2 hub
14	Canyon Reef Carriers	US	O	354	Unknown	Onshore	Unknown
15	Choctaw (NEJD)	US	O	294	7	Onshore	EOR
16	Decatur	US	O	1.9	1.1	Onshore	Saline aquifer
	Europe						
17	Snøhvit	NO	O	153	0.7	Both	Porous Sandstone formation
18	Peterhead	UK	P	116	10	Both	Depleted oil/ gas field
19	Longannet	UK	C	380	2	Both	Depleted oil/ gas field
20	White Rose	UK	P	165	20	Both	Saline aquifer
21	Kingsnorth	UK	C	270	10	Both	Depleted oil/ gas field
22	ROAD	NL	P	25	5	Both	Depleted oil/ gas field
23	Barendrecht	NL	C	20	0.9	Onshore	Depleted oil/ gas field
24	OCAP	NL	O	97	0.4	Onshore	Greenhouses

	Project Name	Country code[a]	Status[b]	Length (km)	Capacity (Mton/y)	Onshore/ Offshore	Sink[c]
25	Jänschwalde	DE	C	52	2	Onshore	Sandstone formation
26	Lacq	FR	O	27	0.06	Onshore	Depleted oil/ gas field
	Rest of World						
27	Rhourde Nouss-Quartzites	DZ	P	30	0.5	Onshore	Depleted oil/ gas field
28	Qinshui	CN	P	116	0.5	Onshore	ECBMR
29	Gorgon	AU	P	8.4	4	Onshore	Sandstone formation

- [a]Country codes: AU=Australia, CA=Canada, CN=China, DE=Germany, DZ=Algeria, FR=France NL=Netherlands, NO=Norway, UK=United Kingdom, US=United States
- [b]Legend status: P=Planned, O=Operational and C=Cancelled
- [c]EOR=Enhanced Oil Recovery, ECBMR=Enhanced Coal Bed Methane Recovery

Table 2 - CO2 pipeline projects included in the assessment

The contractor used the following sources for data gathering:

- Project websites
- Environmental Impact Assessments (EIA) / Environmental Impact Statements (EIS)
- Reports and permit applications
- Front End Engineering Design (FEED) studies
- Scientific publications
- Interviews with pipeline owners and project developers

To maximise amount of data and lessons learned, Ecofys included four cancelled CO_2 pipeline projects in the scope of the study (i.e. Barendrecht, Jänschwalde, Kingsnorth and Longannet).

Findings of the Study

Availability of data

The quality, accessibility and level of detail of the data presented in the following sections varied for a number of different reasons:

- Confidentiality / commercial purposes

- Change of pipeline owner
- Lost or inaccessible data
- Lack of digitalisation
- Language

Drivers for CO_2 pipeline projects

Table 3 shows the main drivers for CO_2 pipelines and gives example projects for each category.

Motivator	Comments	Example Projects
Enhanced Oil Recovery (EOR)	CO_2 is used as a tertiary recovery agent to increase oil production in depleting or old oil fields.	SACROC, Monell, Beaver Creek, Boundary Dam
CO_2 reduction targets	CO_2 is stored in deep saline formations or depleted oil or gas fields	Quest, Barendrecht, Jänschwalde, Kingsnorth, Lacq Longannet, Peterhead, ROAD, Snøhvit, White Rose, Rhourde-Nouss-Quartzite
Enhanced Coal Bed Methane Recovery (ECBMR) and Enhanced Gas Recovery (EGR)	CO_2 is used to enhance coal bed methane production from coal-beds or coal bearing formations or re-injected in suitable gas formations (depleted or for EGR)	Qinshui
Use of CO_2 for industrial purpose	CO_2 is transported to greenhouses and used to stimulate growth of plants and crops	OCAP

Table 3 - Drivers of CO2 pipeline projects (adapted from Amann, 2010)

In case of EOR, a project can make a good return and offset the investment costs by using CO_2 to increase the oil production. However, if market conditions change the project may lose its incentive. An example is the Beaver Creek project that was abandoned due to low oil prices during the late 1980s but was revived in 2005.

In certain jurisdictions, revenue may come from generating carbon offsets. Most CCS projects in Europe focus on CO_2 storage as a mitigation option. As this does not result in additional revenues, a financial support system or carbon offset system, like the EU ETS, needs to be in place.

Sources, sinks and hubs

CO_2 pipelines connect a variety of sinks and sources. Figure 2 shows that gas processing and coal-fired power plants are the most common sources for the pipeline projects investigated in this study. Common sinks are oil fields under EOR but also depleted oil and gas fields. These storage sites generally have the benefit of existing infrastructure that can be re-used.

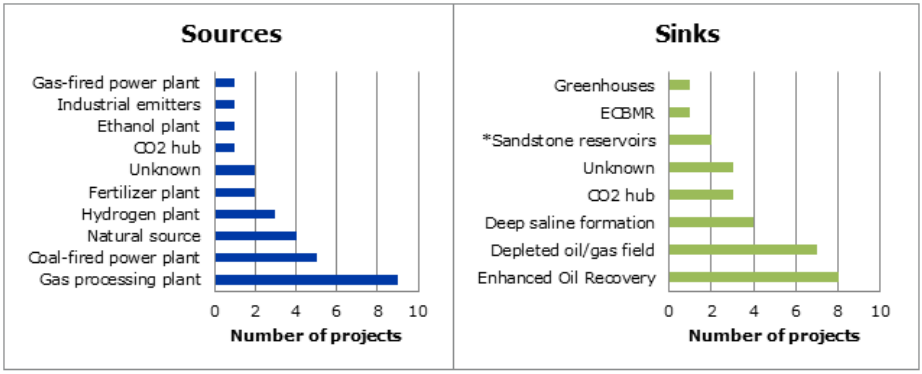


Figure 2 - Sources and sinks of CO_2 pipeline projects

The purity of the CO_2 stream depends on the CO_2 source and, if appropriate, the CO_2 capture technology. In 2/3 of the 29 pipeline projects the purity exceeds 95% and 1/3 of the projects deliver a purity greater than 99%. The main impurities in the CO_2 stream are H_2O, N_2, O2, H_2S and CO.

Where multiple CO_2 sources and sinks exist, a gathering, transmission and distribution network - a hub - may develop. Currently operating hubs are almost all located in the US; examples are the Denver City Hub and the McCamey Hub. CO_2 hubs have no specific set of rules or lessons learned because they are usually developed ad-hoc when CO_2 sources are available and/or a viable market exists. Each hub has its own standards for CO_2 purity, acceptable impurities, pressure and temperature.

Planning, design and construction of CO_2 pipelines

The physical characteristics of the CO_2 pipelines investigated in this study vary greatly. For example, the range in length lies between 1.9 and 808 km. The following Table 4 shows the spread in other characteristics such as diameter, wall thickness, etc.

	Range
Length (km)	1.9 - 808
External diameter (mm)	152 – 921
Wall thickness (mm)	5.2 – 27
Capacity designed (Mt/y)	0.06 – 28
Pressure min (bar)	3 – 151
Pressure max (bar)	21 – 200
Compressor capacity (MW)	0.2 - 68

The inclusion of short-distance demonstration projects as well as commercial, long-distance EOR projects is the main reason for the large variation. The longest pipelines are located in North America and the average length of CO_2 pipelines there is longer than in Europe. Another interesting point is a positive correlation between length and capacity of the pipelines. It seems that longer pipelines have to transport larger volumes of CO_2 to be economically viable.

Technical standards for CO_2 pipelines
The following dedicated standards for CO_2 pipelines currently exist:

- Unites States: CFR part 195
- Canada: CSA Z662
- Europe: DNV-RP-J202
- ISO/TC 265 (currently under development)

CO_2 pipeline project phasing
In many respects, CO_2 pipelines are comparable to natural gas pipelines but there are the following key differences:

- The properties of CO_2 lead to different design parameters.
- In many places CO_2 pipeline projects are first-of-a-kind.
- CO_2 pipelines do not transport a product that people see as directly beneficial.
- Risks associated with geological storage and the Lake Nyos incident influence the public perception of CO_2 pipelines.

Apart from this, CO_2 pipeline projects generally go through the same cycle as other gas pipeline projects. The project cycle typically takes between 3 to 6 years from concept stage to the final investment decision. The actual construction time usually lies between 1 and 4 years depending on the length and complexity of the pipeline.

Pipeline and equipment

Pipelines usually have a service lifetime that exceeds their reason for existence. If the initial design specifications allow for, than in most cases a re-use is beneficial, as this can drastically reduce the overall project costs. Offshore pipelines are a common area for re-use because they have the highest costs of all different terrain types (see Table 6 in section on CO_2 pipeline costs). There are no serious negative technical implications to operate a re-purposed pipeline in CO_2 service, as long as the capacity is lower than original.

Corrosion of the pipeline steel (which is usually carbon steel due to economic reasons) is a serious concern related to leakage and needs to be addressed during the whole project. Most CO_2 pipelines are buried under the ground, so they need both internal and external corrosion protection. The most commonly used method to prevent external corrosion is cathodic protection, sometimes in combination with a coating. Water is the main risk factor for internal corrosion. A dehydration system can keep the water content well below the allowable limit (about 840 ppmv for onshore in North America; offshore European may require below 50 ppmv). CO_2 streams from sources that produce a dry CO_2 gas (e.g. hydrogen plants, gas-processing plants) may not need additional dehydration.

The number and capacity of the compressors depend on the pipeline dimensions, transported volume and phase of the CO_2 stream. The majority of the studied pipelines transport the CO_2 in supercritical phase. To avoid phase change in practice the operators stay clear of the phase transition boundaries.

During operation, a sudden unexpected pressure drop in the pipeline can indicate a leak. For such a case, pipelines are equipped with Emergency Shutdown (ESD) valves to isolate the affected pipeline section. The distance between these ESD valves varies over the pipeline and depends on factors like population density and regulations. The selected CO_2 pipelines in this

study have an average ESD valves distance of 10-20 km.

Flow meters are another important piece of equipment. They provide both a means of accurate billing and early detection of leaks.

In contrast to natural gas, high-pressure CO_2 pipelines are not self-arresting in terms of longitudinal failure and thus require the installation of crack arrestors. Crack arrestors can simply be occasional joints of pipe with greater wall thickness and improved hoop-stress properties. An alternative is the periodic wrapping with non-metallic materials.

Regulatory regime and permitting

Depending on the location of the project and the related regulatory framework, an assessment of environmental impacts might be necessary. The approaches and requirements for this vary from country to country. In general, such an assessment for a CO_2 pipeline is not fundamentally different from that for another gas pipeline.

North American regulations require an Environmental Impact Statement (EIS) when the project is complex in nature and needs consideration and analysis of environmental effects, for example under the National Environmental Policy Act (NEPA) in the US. Opinions of stakeholders and public participation play an important role in North American EISs. According to Directive 2011/92/EU, in Europe an Environmental Impact Assessment (EIA) is required for pipeline sections with a diameter of more than 800 mm and a length of more than 40 km. Most European CO_2 pipeline projects carried out an EIA because the capture and storage facilities triggered it, not the pipeline itself. By and large, there are not many EIAs or EISs that focus specifically on the pipeline part. The Kingsnorth project, for example, carried out an assessment for the offshore section of the pipeline.

In the investigated jurisdictions, CO_2 pipelines are within the regulatory framework of all pipelines that transport gaseous or liquid substances. In the US, CFR 49 Part 195 applies, which was amended in 1989 to include CO_2 in the former "Hazardous Liquid" category. Before this, CO_2 pipelines had to meet codes for natural gas pipelines. Canada has its own regulation for CO_2 pipelines, CSA standard Z662. In Europe, Directive 2099/31/EC on geological CO_2 storage states that the framework used for natural gas pipelines is adequate to regulate CO_2 as well.

The permitting and approval process plays a key role in the timeline realisation of pipeline projects. Securing permits and performing EISs/EIAs usually takes much longer than actual construction. An example for this is the 808 km Cortez pipeline in the US, which took 8 years to complete with only 2 years of construction time. Reason for the long timeline was the requirement for state-by-state approval of the pipeline routing.

Construction of CO_2 pipelines

The acquisition of necessary permits and right-of-way may be more time consuming than the actual construction of the pipeline, so they have to be done in a timely manner. In the US, CFR Section 195.248 prescribes a minimum pipeline burial depth of 1.2 m. After construction, regulations require a test of pipeline integrity. CO_2 pipelines that have passed hydrostatic testing are cleaned and dried to prevent corrosion or premature failure on start-up.

Operation, inspection and Maintenance of CO_2 Pipelines

Regulations require that the responsible operator prepares and follows a manual for each pipeline system. It consists of written procedures for conducting normal operations and maintenance activities but also handling abnormal operations and emergencies. In the US, this manual needs to be reviewed at least once a year.

Limited data was available on the control systems used for CO_2 pipelines. Typically, a SCADA (Supervisory Control and Data Acquisition) system monitors the key operational parameters: pressure, temperature, water content and flow rate. Very small leaks may be hard to detect with this system. The Weyburn project uses a special Leak Detection System (LDS), which monitors for leaks every 5 seconds and displays the related data on a computer screen. In combination with proprietary software, the LDS can determine the size and location of a potential leak. The flow meters integrated into SCADA and LDS help with checking the CO_2 mass balance for contract obligations.

Inspection

To minimise external influences, most pipelines are buried underground but this makes inspection more difficult. Most countries prohibit building activities within a certain range of the pipeline corridor (typically 5 m). In addition, visual corridor inspections by foot, car or helicopter take place

every week.

Most operators use so-called "pig runs" to inspect the inside of their pipelines. A pig can clean the pipeline, measure wall thickness and detect leakage and corrosion. With around EUR 1 million (USD 1.4 million) for pipelines with a length between 25 - 270 km, pig runs are very costly. One reason for this is the low lubricity of CO_2, which poses a great challenge.

Besides the pipeline, inspection of auxiliary equipment takes places on a regular basis as well. This includes compressors, dehydration units, valves, cathodic protection system, monitoring systems and emergency systems.

Safety statistics
For the US, the PHMSA (Pipeline and Hazardous Materials Safety Administration) provides statistics on pipeline incidents. According to PHMSA, there have been 46 incidents involving CO_2 pipelines between 1972 and 2012. The main reasons for these incidents were:

- Relief valve failure
- Weld, gasket or valve packing failure
- Corrosion
- Outside force

Most of these incidents occurred in areas with low population density, so they did not cause any reported casualties or fatalities. In contrast, natural gas pipeline accidents injured 217 and killed 58 people over the period 1986 – 2001. However, it is difficult to make effective comparisons between CO_2 and natural gas pipelines yet because of the huge discrepancy in the number of km of pipeline (550,000 km vs. 6,500 km in the US).

In Europe, no incident reporting or analysis system exists for CO_2 pipelines, so industry gathers statistics and reports incidents on a voluntary basis. The OCAP project reported three incidents with small leakages during operation of the pipeline. Again, no human injuries or fatalities occurred.

Decommissioning and abandonment
Pipeline decommissioning is the permanent deactivation of a pipeline that leaves the pipeline in a permanently safe condition, as prescribed by a regulatory body.

The main reason for decommissioning of a pipeline is that it no longer has a commercial use. Otherwise, well-constructed and well-maintained pipelines often have a lifetime in excess of the design lifetime. CO_2 pipelines are expected to perform as well or even better than other gas pipelines if the operator carefully addresses corrosion issues.

Because the existing CO_2 pipeline projects are relatively young (40 years), there is hardly any information available about large-scale decommissioning activities.

Public Concern

It is important to understand the key drivers of public concern because it can become a serious threat to a project if not handled in time and in a careful manner. During interviews many pipeline operators made clear that the CO_2 pipeline is usually not the focal point of public opposition. Most concerns relate to either the capture (building of a power plant or production plant) or the storage part of the project. In general, there is less public concern over offshore transport and storage than over onshore projects.

The Barendrecht CCS project in the Netherlands is an example where public concern led to the cancellation of the project. The developers of the ROAD project directly used the lessons learned from Barendrecht by training staff to communicate simply and clearly and to address concerns from local residents.

Most projects investigated in this study used websites, public meetings and telephone helplines as means of communication. The range of available information on the websites can vary between the different projects. Some projects (like Saskpower Boundary Dam, OCAP, Lacq) have dedicated websites while others (e.g. Kinder Morgan, Jänschwalde, Kingsnorth) just provide simple generic information. The participation in public meetings varies as well. Most North American pipeline projects have seen only limited interest in public meetings. Reasons for this are the difference in population density and the long-standing oil and gas operations that both lead to a higher acceptance of pipelines compared to Europe.

CO_2 pipeline costs

The following list gives an overview of the key costs drivers for pipelines:

- Piping (type and grade of material)
- Equipment (such as compressors, booster stations, valves, crack arrestors, etc.)
- Trenching (i.e. earthworks, excavation, backfilling)
- Distance
- Diameter
- Terrain
- Labour
- Engineering (e.g. design, project management, regulatory/permitting activities)

For some projects, cost data is publicly available and can be used as a reference to estimate future project costs. Due to commercial reasons, engineering companies sometimes keep the design and construction costs confidential. Table 5 presents actual costs for selected CO_2 pipeline projects that were available from public documents.

Pipeline	Costs for pipeline	Currency	Year	Onshore/ Offshore	International Units
Canyon Reef Carriers (SACROC)	46 million	USD	1971	Onshore	D= 324 – 420 mm L= 354 km
Cortez	700 million	USD	1982	Onshore	D= 762 mm L= 808 km
Weyburn CO_2 pipeline	51 million	USD	2008	Onshore	D= 305 – 356 mm L= 330 km
Quest	140 million	USD[b]	2012	Onshore	D= 324 mm L= 84 km
Qinshui	39.35 million	USD	2006	Onshore	D= 152 mm L= 116 km
Longannet	160 million	GBP	2011	On: 100 km Off: 270 km	D= 500 to 900 mm L= 380 km
ROAD	90 million	EUR	2010	On: 5 km Off: 20 km	D= 450 mm L= 25 km
Gorgon	9 million	AUD	2011	Onshore	D= 269 – 319 mm L= 8.4 km

[a] For pipeline and associated compression stations
[b] Initial estimate in CAD (Canadian dollars). Assumed exchange rate USD 1.00 = CAD 1.00

Table 5 - Actual costs for selected CO_2 pipelines

If data is not readily available, then it is possible to estimate pipeline capital costs using credible sources, like the NETL guidelines (Carbon Dioxide Transport and Storage Costs in NETL Studies – Quality Guidelines for Energy Systems Studies). The related formulas reflect US dollars as of 2011 and require diameter and length as input parameters. The results of the estimation can give a first impression of possible CO_2 pipeline costs but are in no way an accurate estimate. In any case, terrain has the strongest influence on pipeline costs and accounts for the largest uncertainty in cost estimation. Table 6 shows costs for different types of terrain and it is clear that interference with bodies of water increases the costs most.

Terrain	Capital Cost (USD/inch-Diameter/mile)
Flat, Dry	USD 50,000
Mountainous	USD 85,000
Marsh, Wetland	USD 100,000
River	USD 300,000
High Population	USD 100,000
Offshore (150-200 feet ~ 45–60 meters depth)	USD 700,000

Table 6 - Pipeline cost metrics as disclosed by Kinder Morgen

Operation and maintenance costs are not readily available from the investigated CO_2 pipeline projects but again can be estimated by using the following guidelines:

- Fixed O&M costs of USD 8,454 per mile and year (NETL guidelines)
- 1.5% of initial capital costs per year (Wong 2010)
- 3-8% of initial installed capital costs (confidential source)
- EUR 1 million (USD 1.4 million) per pig run (Wevers 2013)

A number of factors differentiate CO_2 pipelines from other gas pipelines when it comes to costing. Some examples are:

- The CO_2 depressurisation characteristics dictate the use of crack arrestors.
- The carbon steel grade needs to be resistant towards brittle fracture because CO_2 can reach very low temperatures when expanded.

- CO_2 suppliers have to deliver at specified conditions which are in general:
    - o 95% purity
    - o Water content depending on region between 50 – 840 ppmv
    - o Temperature and pressure according to single dense phase transport
- Installation of ESD valves to limit CO_2 release in case of leakage.
- Venting procedures need to include provisions for lofting and dispersing released CO_2.
- Gaskets and other non-ferrous materials must be resistant to deterioration in presence of CO_2.

Usually the CO_2 supplier(s) or the CO_2 capture project part is responsible for accounting the costs related to separation, clean-up, compression and dehydration of the raw CO_2 stream.

Expert Review Comments

Six reviewers from industry, academia and other organisations took part in the expert review of the reference manual and submitted useful comments. In general, the reviewers stated that the reference manual has a good structure and provides a valuable overview on CO_2 pipeline transport. Some reviewers asked to increase the level of detail in certain sections (especially regarding operating conditions, impurities and corrosion) and to harmonise the information presented in the two main sections of the report (i.e. lessons learned from existing projects and guidelines for CO_2 pipeline projects). Ecofys addressed most of the comments in the final version as long as they have been within the scope of the study. In some places, Ecofys regarded the addition of more information as not beneficial for the report and established a stronger reference to the database. The review of database and web tool was done by IEAGHG and the Global CCS Institute only.

Conclusions

The purpose of this study was to collect public information on CO_2 pipelines and make it available to project developers, decision makers, regulators and the interested public. The findings of the study are easily accessible in three different ways: through a reference manual, a database and an interactive web tool.

With the exception of the US, most countries have no or little experience with CO_2 pipelines or CO_2-EOR operations. Even for many of the operational projects certain information is not accessible due to commercial or other reasons. This applies especially to costs and auxiliary equipment that belongs to other parts of the process chain, like compressors and dehydration units.

Currently the main driver for CO_2 pipeline projects is EOR. CO_2 transport and storage as part of larger CCS projects can only generate revenues if a pricing or support scheme is in place.

A main result of the study is that CO_2 pipelines are both similar and different compared to other gas pipelines, natural gas in particular. They are similar to some extent, so that the regulations and standards used for CO_2 originate in natural gas pipeline codes. But they are different in terms of the physical properties of CO_2, which results in different design parameters, and the risk perception, which the public usually associates with geological storage of CO_2.

The permitting and approval processes play a large role in realisation of the project timeline. This can take much longer than expected and exceed the construction time by far. The CO_2 pipelines in the US have a 40-year history of operation with no civilian injuries or fatalities. In contrast to Europe, a sophisticated reporting system exists.

Detailed cost information was difficult to find for many projects due to confidentiality. Key factors determining the costs of a CO_2 pipeline are terrain, length and capacity. The primary means of cost reduction is the re-use of existing pipeline infrastructure. Some projects in the EU considered this approach (e.g. OCAP, Lacq, and Peterhead).

Public concern may vary from project to project, depending on the location, population density, type of project, source and sink of CO_2, etc. As public opposition can lead to cancellation of the whole project (as in the case of Barendrecht), effective communication strategies and early involvement of all stakeholders are key elements in addressing such concerns. Although important developments are expected in pipeline technology, e.g. in the fields of corrosion resistance, pigging and crack arresting, it is likely that the main area, where improvement is necessary, will be public acceptance.

Recommendations

The combination of the three deliverables (i.e. reference manual, database and interactive web tool) is a very attractive way of disseminating the results of this study to slightly different target groups and their needs. However, these tools live on being up-to-date. This is why we recommend a regular update of the web tool and database through follow-up studies (every 2-3 years).

We also think it is a good idea to use the results of this study for setting up a Wiki on CO_2 pipelines/transport to deliver information in an easily comprehendible way to the public. Likewise, an extension of the Wiki with other IEAGHG studies on CO_2 transport, capture, storage, etc. is possible.

Although CO_2 pipelines are usually not the focal point of public concern, source and sink of the CO_2 can largely influence how the public perceives them. Because of this, we aim to undertake a study focussing on the public perception on CO_2 pipelines.

2013-01 SUMMARY REPORT OF THE 3RD IEAGHG SOCIAL RESEARCH NETWORK MEETING

In Memoriam of Dancker Daamen

On the 27th of September 2012, a colleague and friend was sadly taken from us during a sailing trip. Dancker Daamen was a leading member of the steering committee of IEAGHG's Social Research Network, was a well respected and liked researcher. His input to the SRN in particular was no small effort, where his active and enthusiastic contributions were hugely appreciated, and he will be sorely missed.

Dancker will be remembered by friends and colleagues as a dedicated researcher, always ensuring his results were sound, before communicating them, and he always aimed to inspire fellow scientists to achieve similar goals. Dancker will leave a hole in the research community.

Introduction

The overall aim of the Social Research Network is "to foster the conduct and dissemination of social science research related to CCS in order to improve understanding of public concerns as well as improve the understanding of the processes required for deploying projects".

The objectives of the Network are as follows:

- Ensure high quality social science research
    - o Elevate reputation and acceptance of social science research
    - o Consistency of research
- Identifying gaps
- Promoting a learning environment
- Building capacity within the Network
- Translate information from studies into tools or applied lessons
    - o Apply insights to actual projects
    - o Interact with technical experts
    - o Communicate results to policy makers
    - o Ensure application is grounded in theory
- Create a clearing house of social science research

This 2012 meeting, the third of the IEAGHG Social Research Network, was held in Noosa Heads, Australia from the 12th to 13th of April. The meeting was hosted by CSIRO and sponsored by the Global CCS Institute, CSIRO Advanced Coal Portfolio, CO2CRC and DPI Clean Coal. Over 40 delegates attended this successful meeting from 8 different countries.

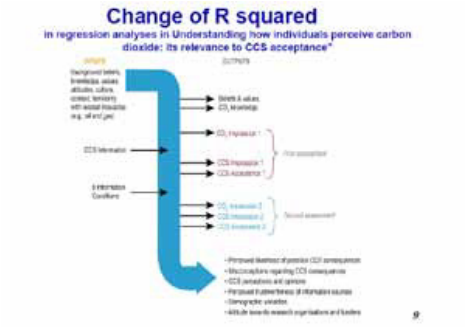
Session 1: Methodologies and Techniques

Peta Ashworth, CSIRO – "Comparison of large group process"

In terms of the description of the process used, this research looked at the views of individuals on climate change/energy technologies and to enable discussion on such topics, facilitating assessment of the impact of the information given. This data collection studied the building of a group identity, trust in presenter/information, knowledge or attitude change in different countries and what influenced such changes. The researchers found that all reported an increase in their knowledge of greenhouse gas emissions throughout the day and there was a recognisable change in the approval of

CCS – Australia and Canada were generally more positive, whereas the Netherlands and Scotland decreased in positivity – demonstrating that there are many different factors influencing this and context matters . The results looking at support for energy technologies showed considerable variation between the technologies.

Kenshi Itaoka, Mizuho Information and Research Institute – Regression and interpretation



Slide Courtesy of Kenshi Itaoka

R squared is interpreted as the ratio of variance explained by a regression model, the total sum of squares around the mean. This method is used mainly for analysis of partial correlation between factors, to avoid interpreting simple correlations incorrectly, and also to find the causal inference. The size of R squared does not generally matter in a social science setting (except perhaps when influencing policymakers), but if the value is low then it should be explained (at least in terms of whether important covariates are or are not included). If R squared is high, this could cause problems in that it could hide the effect of other variables.

To ensure more accurate results when using R squared in a social science setting, it is important to list all potential influencing factors, to check simple correlations, conduct multiple regressions, check the linearity and conduct an SEM (path analysis).

Gerdien de Vries, Bart W. Terwel, Naomi Ellemers, and Dancker D.L. Daamen, Leiden University – "The Dilution Effect in Evaluations of Persuasiveness of CCS Information"

CCS opinion is highly influenced by a number of types of communication – positive and negative. Much of the current CCS communication material contains multiple messages, varying opinions and non-relevant information for forming an opinion (so called 'non-information'). This study investigates whether the inclusion of non-relevant information to relevant information dilutes the effect of the relevant information – the 'dilution effect', an

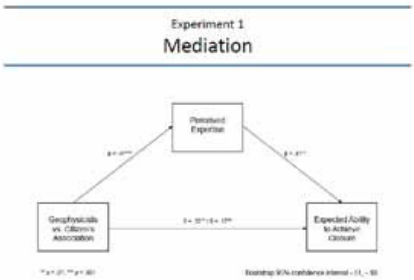
important concept which could influence attitudes.

Using an experimental methodology, a dilution effect was observed when on-information was added to positive highlyrelevant information, but not when positive low-relevance information was added. Subjects in all conditions regarded the highly-relevant material as more relevant than low-relevance information, and low-relevance information as more relevant than non-information.

For positively and negatively framed CCS information, a dilution effect occurs on persuasiveness when non-information is added to highly-relevant information. It seems that this effect does not occur when low-relevance information is added. In public communication strategies, CCS stakeholders should be aware of the dilution effect and must take into account the relevance of the material – non-information could weaken the persuasiveness of their high-relevance information (both positive and negative).

Charlotte Koot, Emma ter Mors, Naomi Ellemers, and Dancker D.L. Daamen, Leiden University – "Source expertise, consensus and the ability to achieve closure"

Public support is important for the implementation of CCS, but public knowledge on the topic is relatively low. There is a motivational need by persons for cognitive closure; the ability to make decisions with certainty and that you feel you can confidently know what your attitude is. This research is looking at factors that influence people to achieve cognitive closure and the precursors (elements of communication that affect whether people are able/less able to say what they think about the subject) of the ability to achieve closure. This research looked at whether people value the expertise of the source to achieve closure and at the general consensus (or non–consensus) of the piece of information.



Slide Courtesy of Charlotte Koot

For both conditions, the consensus was found to also affect the perceived expertise. It seems that expressing consensus (or not) appears to have little

effect on the ability to achieve cognitive closure when the information source is generally considered as expert.

Conclusions

Delegates noted that some recent polling results are actually showing that opinions as to whether climate change actually exists are dropping – there seems to be a real perceived lack of acceptance of the science, in particular when there is a lack of consensus in the scientific community. The early results of the large group process show they may be useful to educate and influence stakeholders on complex processes. It is difficult to form attitudes about complex topics like CCS.

Session 2: Findings Related to CCS, Part 1

Suzanne Brunsting, ECN – "Social Site Characterisation of Potential CCS Sites in Poland and the UK"

Social site characterisation is instrumental to plan, evaluate and approach a way to actively engage local stakeholders in prospective CCS projects. This characterisation is focussed on two sites in Europe and the information publicly available on these potential projects. The results from the two sites were similar in some ways (both in rural areas, small towns, where unemployment is a concern and climate change not a major concern), there was an existing low/very low awareness of the local CCS plans but general high expectations of CCS (largely related to potential job opportunities brought into the area). Any concerns voiced were due to potential leakage, the Polish site test population was concerned with the gas reservoir below the drinking water reservoir and the UK (Scotland) site population voiced concerns with the effect on water purity.

Social site characterisation so far has provided a vast amount of information on what public outreach should consist of and the methods that should be undertaken to carry out such a task. Content should be transparent, should explain CCS in terms of climate change (as awareness is low), give some expectations management, address any known knowledge gaps and address the risks of CCS.

Jonas Pigeon, Universite du Havre – "Social feasibility of CCS projects along the Seine waterway axis"

The research was conducted in the chosen area as it accounts for 20% of the

CO_2 emissions in France (a highly industrial area including many petrochemical companies, an area designated as low carbon). The area sits atop the Paris Basin, an area with suitable saline aquifers for CO_2 storage. In Norway, it was found that the state was very strongly supportive at the beginning but this decreased with time. There are good relationships between technology users, researchers and technology providers. To learn on implementation of CCS in other countries, the researchers also visited Norway and Scotland, where both are supportive of the technology. To conclude, the examples show the importance of actors involved in CCS projects. The understanding of these principles could enable us to improve the design of projects. Taking into account spatial development dimension and social practices related to spatial areas/local identities could provide recommendations for the design of a CCS technological system in the Seine waterway axis.

Amanda Boyd, University of Calgary – "Views and perceptions of Canadian communities to CCS"

Local opinions are critical to projects, but little is known about the effect of an alleged CO_2 leak on opinions. Weyburn allowed us to look into this. The alleged 'leak' situation could be classed as a 'focussing event' which can be used by groups to elevate attention to a problem (it is important to note that a focussing event may not be completely negative). This research was concerned with examining and contrasting views of CO_2 injection in communities (one project with little opposition and one with a cancelled project).

The research looked at two sites in Canada, Weyburn/Goodwater and Priddis (Calgary). Methods used included interviews (group and individual) with community members and key stakeholders, along with observation and attendance at community events/meetings. The two sites are not comparable as the questions were tailored differently for each site. In terms of results, the Weyburn/Goodwater community disagreed with the leak allegations and showed more trust in companies, scientists and monitoring technology. It was noticeable that allegations of leaks had caused major conflicts in the communities. For Priddis, the Weyburn leakage allegations coincided with the consideration of the project, and contributed to its being stopped by landowners concerns. These results show that allegations or a similar negative event can impact development and community acceptance.

This could be a major factor in future developments and it is key to recognise the importance of monitoring at projects and also necessary to prepare communication material to address potential areas of concern, such as a leak.

Bart Terwel, Leiden University – "Initial public reactions to CCS: Differentiating general and local views"

Local opposition might be categorised into 3 categories – anti-CCS sentiments (e.g. due to perceived tampering with nature), anti-process sentiments (e.g. perceived procedural unfairness) and NIMBY (Not In My Back Yard) sentiments. It was found that initial reactions to a local storage project are not necessarily dominated by NIMBY sentiments. The attitudes of "onsite" (but not "offsite") residents were influenced by concern with the risk of storage procedures to local residents' safety. The trust in the government has a significant effect on people's judgements regarding the risks and benefits of the potential project – which will have an effect on residents' inclination to protest. It appears that the initial public reactions to storage projects are unrelated to the concern about climate change (even if the population is aware that it is seen as an important strategy to meet CO_2 emission reduction targets by scientists/ policymakers).

Conclusions

One of the issues that was discussed included the importance of societal conditions – understanding what are important local issues, the importance of societal issues that may impact project acceptance, note that safety risks are important (but not the only factor), knowing that the trust in government will impact outcomes and judgement and the awareness that context is important. The role of various actors is important – the information source makes a difference, the role of trust/credibility is key, we must think how to create a shared vision and must not forget the importance of politicians – they are influential stakeholders. We must consider the impact of the focussing event on the overall positions, in predictability, who buys into the discussion etc.

Session 2: Findings Related to CCS, Part 2

Anne-Maree Dowd, CSIRO & Aya Saito, Mizuho Information and Research Institute – "Understanding how individuals perceive carbon dioxide"

This is an investigation of how citizens of three countries (Japan, Australia

and the Netherlands – 2470 participants in total) perceive CO_2. It attempts to relate individual perceptions of CO_2 to perceptions of CCS and determine how information provided about the underlying properties and characteristics of CO_2 influence individual attitudes towards low carbon energy options, particularly CCS. Regression analyses carried out showed the effects of the provision of information on CO_2 – it was found that providing information describing the characteristics of CO_2 had a generally positive effect on people's opinions on CCS implementation. Information describing CO_2 natural phenomena, like hot springs and including CO_2, seemed to have a negative influence on CCS implementation, as did information provided on the behaviour of CO_2 during the CCS process.

Recommendations from this work suggest that efforts to promote understanding of CCS should include information on the properties (balanced/complete information in this case) and chemistry of CO_2. Information on the basics of climate change, CCS and CO_2 in general may be required by some. Topics deemed important by respondents should be collected and then addressed in communication material. Care should be taken in describing CO_2 natural phenomena and the behaviour of CO_2 in CCS – the information must be open, transparent, correct and complete.

Suzanne Brunsting, ECN – "The influence of knowledge versus perceptions of CCS on public attitudes towards CCS in the Netherlands"

Perceptions are items to which there is no clear right or wrong (e.g. opinions), compared to knowledge which is items that are clearly right or wrong. It is interesting to see if knowledge can predict perceptions of CCS. This research was originally done in 2010 and repeated in late 2011. Results show that the awareness of CCS has increased (where knowledge hasn't), there appears to be a neutral attitude to CCS and there is a lack of understanding of the role of CO_2 in climate change. There are uncertainties in the subject – mainly about the goals/consequences of CCS and CO_2 sources, characteristics and effects.

The model suggests that public communication strategies on CCS (to/for the general public) should focus on education on CO_2 (sources, characteristics and effects) and should debate about the benefits of CCS and the risks of leakage of CO_2.

Bart Terwel, Emma ter Mors, and Dancker Daamen, Leiden University – "It's not only about safety: Beliefs and attitudes of 811 local residents regarding a CCS project in Barendrecht"

This focused on the relationship between beliefs and attitudes towards CCS plans, namely the Barendrecht project in the Netherlands. Questions were asked via telephone interviews and the overall opinion of the project was negative – 86% of respondents thought the project was unacceptable. Participants were asked on the beliefs of the CCS plan (i.e. on helping to combat global warming, potential of the plans to lead to a loss on property value) and on safety (i.e. safety of capture, transport and storage). Questions were also asked on the decision processes/parties involved (e.g. trust, procedural fairness) and on information provided.

The perceived attributes of a CCS plan (perceived safety of transport/storage, likelihood of loss of property value) were found to affect attitudes. A good process (regarding the CCS plan) is important to deal with credibility issues, perceived unfairness of the decision procedure and lack of trust in decision makers. In terms of lessons learned, there are at least two conditions for local support (good attributes and good process), there is a need for credible information on safety as well as effective compensation for losses and there is a need to enhance public trust.

Declan Kuch, Asha Titus, Stephen Webb, University of Newcastle – "Coal Innovation in Action: Using ANT to study Carbon Capture and Storage"

Actor Network Theory (ANT) is a qualitative way of studying the social context and techno-scientific content of CCS – a way of understanding associations between humans and non-humans ('things' that can modify human behaviour). This project aims to understand what makes a good innovation unstoppable, to develop a model of how social and technical aspects of CCS project work together and to understand public perceptions of low emission coal technologies. The appeal of ANT is that it draws attention to the way demonstrations of the technology developed over time and the way networks of power grew between scientists and other actors. It was observed that there were different risk rationalities that organised the working culture, which meant that these different groups would hold different notions on the matter. This is key in looking at how to coordinate between these differing 'appetites' for risk.

Conclusions

The properties of CO_2 should be included in CCS communications as should topics that have been deemed important by the public. Information provided has to be transparent, correct and complete. The perceptions of CCS are more powerful than the knowledge, although knowledge does play a role in shaping CCS attitudes. The public should be educated on the effects of CO_2, and should debate the benefits and risks of CCS. For project success you need good attributes (safety, no loss) and a good process (fair decision).

Session 3: The CCS Ethical Landscape

Philip Boucher, Tyndall Centre – "Mapping Ethical Landscapes of Carbon Capture and Storage"

This study uses and ethical matrix approach, consisting of a list of actors and ethical principles. The issues are then identified in the individual cells, a top-down approach. This ethical landscape method is a data-led analytical structure (the data defines the boundaries and content), uses limited resources (no actual participation and using only secondary data), has coded content (so provides a visual map of the ethical landscape) and has allowed the researchers to identify ethical faultlines (areas of potential ethical contention). The benefits to this methodology is that it requires low resources, is a fast approach to scoping and imitates a bottom-up approach through a data-led structure. However, limitations are that there is no actor validation, no account for heterogeneity and that it is flat – there is no account for power, enrollment or representativeness. This work has a strong potential as a preliminary study. It identifies issues which could be looked at in more depth in an additional study and could be used as a starting point for a two-step participative/deliberative approach. The study was undertaken at various scales and positions ethical framings within broader semiotic regions.

Slide Courtesy of Philip Boucher

Panel Discussion – Philip Boucher, Judith Bradbury, Fabien Medvecky

The features of CCS development can be framed in ethical terms. An ethical matrix can be useful to explore the ethical landscape of a technology,

potentially identifying divisive issues. The CCS Ethical landscape is dynamic and to consider ethical implications we must gain broader and deeper understanding of character and foundations of ethical perspectives – as well as points of convergence and divergence. It is important to consider what motivates us to have the ethical views we do and explore assumptions inherent to these views. Further consideration of intergenerational justice in the climate change and CCS debate is needed. Project developers and social scientists have different roles in the debate. Is there a role for social scientists as practitioners? Is it possible to foster a deliberative process – and is there time for such deliberation?

Session 4, Part 1: From Outside the Circle: Role and Use of Social Science Research and its Application in Other Sectors?

Frances Bowen, University of London – Managerial perceptions of low carbon technologies

How managers perceive climate change and decide when to share information is important, but it is also as important to consider the managerial perceptions of scale (it seems to explain much of the current inactivity in this area). Here, a Canadian oil sands company has been looked at, along with OSLI – the Oil Sands Leadership Initiative, a collaboration of parties in Canada. Oil sand extraction is very energy intensive and there is very little intention to use carbon capture and storage as part of the operation. They are quite open about not wanting to perform CCS on oil sands. Much of the talk about managing impacts in the oil sands revolves around scale, with two dimensions of scale – perception of scale of the issue and perceptions of the scale of the initiative needed to deal with it.

Issue scale perception is the magnitude/extent of impact, the timescale, issue interdependence and solution search effort. Initiative scale perception is concerned with the capital investment and risk, the time horizon, number of participants and boundary clarity. It is interesting to look at how fast you can move depending on the scale of the issue/initiative (smaller tends to be faster). This brings about several implications – one being the dilemma of whether to pursue initiative – small may give incremental, quick, small wins (but inadequate of address the overall problem) and large initiatives may promise a comprehensive solution, but are slow to structure or implement. Another implication may be to speed up climate initiatives – to

do so managers must reduce the perceived scale of the issue and link climate change with smaller scale issues. It is key to manage the PERCEIVED scale.

Kieren Moffat, CSIRO – Coal Seam Gas project

Slides Courtesy of Kieren Moffat

A 'social licence to operate' needs ongoing acceptance from the local community (and other stakeholders), meaningful partnerships between all stakeholders and a set of expectations as to how it will operate. A discourse analysis was carried out to look at a mining councils sustainability reports (in particular the social licence) and consideration given to social psychology (in particular how groups in conflict can improve their relationship). The model of expectation was tested through regression and results show that trust is an important and central variable – the only consistent predictor of acceptance/approval. Trust is a mediator of the relationship between natural/economical capital and acceptance/approval and it mediates the relationship between contact with company employees and negative behavioural intentions. Future work will focus on these relationships and it is important to work out how to facilitate trust in the CCS world.

Makoto Akai, AIST – "Discussion on energy portfolio of Japan under a new myth"

Social responses to the recent Fukushima nuclear accident can be divided into short term (including mass evacuation and rationing of supplies) and mid/long-term (including long-term evacuation and fear of radiation). The main similarities between nuclear and CCS were identified as both having a huge energy infrastructure, both low carbon technologies and both have similar characteristics of risks (in geological storage). Differences included

the importance of the hazard (radiation versus CO_2) and generating profit versus imposing costs under normal operation.

Observations of Japanese society show they have a poor knowledge of politicians on energy issues, there is an emotional discussion on the energy portfolio (e.g. nuclear versus renewables) and arguments put forward by non-expert 'intellectuals' can be particularly harmful to society's opinions. In Japan, it has been suggested that steps should be made in order to improve the social opinion, including improving the energy literacy, restoring public confidence in scientists, experts and policymakers, educate the media to a higher extent and encourage scientists, policymakers etc. to work together with social scientists as practitioners.

Conclusions

Managers are people too, and they are influenced by their perceptions of scale, scale of the issue and scale of the solution. A 'social licence to operate' is needed from local communities. Social science research on CCS is bordering applied, practical studies and heterogeneity is important when tailoring communication. After the Fukushima accident in Japan, the majority of the public now have an attitude opposed to nuclear and governments/scientists are losing the public's trust. It is important to promote improving energy literacy.

Session 4, Part 2: From Outside the Circle: Role and Use of Social Science Research and its Application to CCS?

Emma ter Mors, Bart W. Terwel, Dancker D.L. Daamen, Leiden University – "The potential of host community compensation in CCS facility siting"

Local public opposition is an obstacle to siting various facilities (power plants, prisons etc.), primarily due to the imbalance between costs/risks and benefits. Perhaps offering host community compensation – a form of equity adjustment aimed at correcting imbalances between local burdens associated with potential projects – would address this.

A literature review showed that with compensation, there was a substantial increase in the acceptance of low risk facilities, but it made little difference in the case of high risk projects (could be useful when planning low to medium risk projects with increased safety measures). Several recommendations were made including more research into WHY compensation is effective (or not)

and efforts should be made into increasing external validity (e.g. more onsite research, non-citizen examples etc.). Other factors should be considered, such as the timing of compensation, who is offering the compensation (trust issues) and citizen participation in host fee negotiation etc.

In conclusion, host community compensation is not a final solution for all problems, but it can help to prevent some facility siting issues. More research is needed on these principles to see the effect on public acceptance and research should be undertaken to confirm the potential of this compensation in the specific context of CCS.

Frank van Rijnsoever, Universiteit Utrecht – Practical CCS communication

The team have been looking at the influence of communication frames on the choice for or against CCS and on choice persistence for different population segments. Theoretical approaches include elaboration likelihood model, prospect theory, classification of arguments and random utility theory (RUT). RUT is widely used and looks at utility (the happiness experienced from making a decision) from choice attributes/individual characteristics that are observed plus those that are unobserved. Discrete choice experiments will be used for this research in CCS communication and are based on RUT, giving participants a series of choice tasks and allowing for generalisation and heterogeneity. The researchers will vary attributes through model source to message to receiver. The characteristics of the respondents will be looked at to ensure a representative and fair sample – including involvement with CCS, knowledge of CCS, attitude towards climate change, use of information sources and social demographics.

Conclusions

The purpose of a social licence is to facilitate on-going acceptance from the local community and other stakeholders – trust plays a critical role in the relationship between contact and relational consequence. According to literature, host community compensation can help to prevent or solve facility siting issues. Research is needed to examine why and when such compensation works, also to confirm the potential of host community compensation in the specific context of CCS.

Session 5: Influences to Evolving Energy Complexes

John Cook, Global Change Institute – Website on climate denial/ misinformation etc.

Mr. Cook runs a website looking at misinformation and climate denial – and uses science to address these issues. He has demonstrated that the process of debunking myths can actually backfire, however – as when you try to debunk a myth it can actually reinforce the idea in people's minds – the 'Backfire Effect'. The key in this instance is to reinforce the facts or explicitly warn people before the myth. Even when these backfire effects have been negotiated past, there is still an issue to deal with – when a myth has been 'debunked', a gap is left in the persons mental model. It is important to fill this gap with an alternative explanation (so a gap is created by the facts, then filled by the alternative information).

It has been identified that to make ideas 'stick' in peoples' minds you must make them simple, concrete, unexpected, credible and emotional. The 'Curiosity Gap' refers to the generation of curiosity by opening gaps in a person's knowledge, then filling these gaps – the same process as the debunking method mentioned previously.

Koen Straver, ECN – "Mapping the Dutch media landscape on CCS: Arguments and knowledge transfer"

The purpose of media analysis is to monitor developments in public opinion and to relate with the knowledge of lay people, omissions in knowledge, misperceptions etc. A medialog analysis was carried out – of all national (Dutch) newspapers from May 2009 to October 2011 where the main article topic was CCS, and participants were given a short questionnaire about the article. They found that CCS was mainly discussed from a safety and political perspective, with focus on developments in policy, projects and stakeholder relations. Much less attention was paid to the context of climate change, energy use and the role of CO_2. Little attention was given to CCS for its role in energy transition.

Jean-Philibert Moutenet, INRS – "The evolution of public awareness and opinion on CCS in the context of shale gas exploration in the province of Québec (Canada)"

There is currently a debate on going in Québec on shale gas exploration,

which could have an impact on public/local opinion of CCS. It is important to look at such impacts and in this case Léger marketing surveys were used, with one year between each survey. Respondents had little awareness of climate change (what it is, the causes), knew almost nothing about CCS and had only a partial understanding of CO_2. Respondents were given a short explanation of CCS during the survey.

Slide Courtesy of Jean-Philibert Moutenet

The surveys found that it is not possible to link the increase of respondents against CCS and the increase in security concerns specifically to the shale gas debate that started after the first survey. Other influences (i.e. alleged leaks, political and economical conditions) could have had an effect on the opinions. CO_2 geological storage and shale gas activities share the same techniques and so a layperson could view them as similar activities. It was concluded that the social context in a region where controversial shale gas activities are underway may not be conducive for acceptance of a potential CCS pilot.

Conclusions

Care is required when debunking myths/misinformation and backfire effects should be avoided to prevent reinforcing of the misinformation. The 'stickiness' of correct information should be improved by creating a gap in the understanding and then filling this gap with an alternative narrative. In Québec we saw that significant results suggest a rise in negative views of shale gas with reduced favourability to CCS – leading to interesting implications for the technology. The ECN study showed an overall balanced use of Dutch arguments, but there were more negative than positive arguments in the media (regarding issues such as safety, economy, environment and ethics) and the coverage of climate benefits was positive but infrequent. CCS was found to be mainly discussed from a safety and political perspective – much

less attention was paid to the context of climate change, energy use, the role of CO_2 and implications for this role in energy transition.

Session 6: Collaboration Opportunities

Prof. John Cole, Australian Ctr Sustainable Business & Development "Bridging the parallel universe: making research matter in public policy"

Climate change is an environmental issue that shifts quickly from the science to policy realm and can be seen as a human dilemma – covering many important issues including natural resources, social problems, the environment and economy.

Modern trends seem to be that science is confused with activism, risk communication becomes spin, it is now a matter of beliefs, where simplicity prevails, there is alienation from politics and there is a distrust of science. Science does not seem to be well represented in general programming and newspapers are in decline in the OECD countries but are growing in popularity in developing countries. A key issue is the fact that opinions change greatly due to external influences and lessons learnt from water (recycling projects) have shown us that policy must be 'simple, honest and grounded in reality'.

Kirsty Anderson, Global CCS Institute – "Research priorities at the Global CCS Institute"

Slide Courtesy of Kirsty Anderson, GCCSI

The Global CCS Institute is interested in sharing knowledge, factbased advocacy and assisting projects. In supporting social research, The Institute has a CSIRO-led global research programme, CCS project deliverables, international workshops/meetings, IEAGHG Social Research Network and over 45 social research reports. The Institute also provides toolkits and guides, project/area specific reports and have future priorities geared toward social research. Such priorities include targeted reports and

cultural translation within Asia and developing countries.

Conclusions

A key issue is how to bridge the gap when social science crosses into policy and industry and how to ensure social scientists are heard. More research is still needed, but it is important that previous work is used and applied. A 'knowledge broker' between the scientists and policy makers is a potential solution to ensure that messages are not confused during translation. It is key that communicators should look at their community first.

Session 7: Outcomes and Recommendations

Gaps

Gaps identified during the meeting included areas like energy literacy (expanding perception and knowledge) – here there is a need for broader education on energy including the global need and the broader energy mix, including CCS on gas power. There are gaps in social research in China and a lack of perception and social studies in other non-OECD countries. More needs to be done on the antecedence of trust and the application of lessons learned (i.e. in the translation of these lessons). Further research is needed into the engagement of local people by carrying out more research into site-specific social research. It is important to consider how to create a shared vision between actors in a multidisciplinary team (an example of how to do this may be a toolkit) and how to ensure heterogeneity for the development of communication materials. The uniqueness of CCS should be characterised and intergenerational justice should be considered.

Conclusions

The perceptions of CCS are more powerful than knowledge, but knowledge does play a role in shaping attitudes – it is important to discuss CCS in the broader context of energy/climate change and also provide knowledge on the basics (i.e. properties of CO_2). Key lessons learned are being used and, more importantly, applied – although more social science research is needed. Care should be taken when debunking myths and in particular to avoid misinformation. Host community compensation is not a final solution to siting issues but can be a valuable tool to help prevent (or solve) CCS facility siting issues and controversies. Social science research is similar to geological

research on CO_2 storage (as it is site specific) and more sites are needed to further develop understanding.

Recommendations

The following recommendations were made at the end of the two day meeting in Australia:

- The exchange of information should be encouraged in new research projects
- More sites are needed to ensure detailed and accurate results
- Further multidisciplinary social research should be carried out, bringing other dimensions of social science together on key issues such as risk communication and community compensation
- More applied research is needed on sites with monitoring experience (to assess development of perceptions and attitudes)
- Energy literacy must be promoted
- A platform should be created to capture and share social science research – a potential new responsibility for IEAGHG.

2013-02 BUILDING KNOWLEDGE FOR ENVIRONMENTAL ASSESSMENT OF CO_2 STORAGE: CONTROLLED RELEASES OF CO_2 AND NATURAL RELEASES WORKSHOP

Summary

A workshop on 'Building Knowledge for Environmental Assessment of CO_2 Storage: Controlled Releases of CO_2 and Natural Releases Workshop' was held in July 2012 hosted by Montana State University (MSU) in Bozeman, Montana.

This workshop focussed on controlled release projects. As such, it brought together for the first time most of the world's controlled release projects, ten in number. This created the opportunity not just for sharing of results, but for future sharing of facilities and techniques, opportunities which were taken advantage of during the meeting. The workshop also looked at the Environmental Assessments undertaken for real projects, with details being provided by Shell on the Quest project and its recent approval.

In the area of monitoring, great progress is being made. There are increased capabilities and new experiences offshore. The very realisable capability for large-area monitoring was shown, with the potential capability of leak detection, and work on offshore baselines also being ground-breaking. Exciting developments in onshore monitoring were also presented, including the Process-based technique, for assessing the source of CO_2 found in the near-subsurface.

One of the concluding recommendations was to "Keep up the good work" because gaps identified in the previous two workshops are being successfully addressed. The meeting concluded with a request from participants to become a full IEAGHG Network, called the "Environmental Research into CO_2 Storage Network".

Introduction

The third workshop in an IEAGHG series on environmental impact assessment of CO_2 storage was held in July 2012. The 'Building Knowledge for Environmental Assessment of CO_2 Storage: Controlled Releases of CO_2 and Natural Releases Workshop' was held from the 17th to 19th July 2012 in Bozeman, Montana. It was hosted by Montana State University (MSU) and sponsored by MSU, Southern Company and the Center for Advanced Energy

Studies. Forty-eight delegates attended from 12 countries.

The main focus of this workshop was on controlled release projects with other sessions on environmental impact assessments and Regulations, monitoring, overburden/ mechanisms of migration from deep to shallow subsurface, leakage scenarios and communication of leakage. The third day of the meeting was spent at Yellowstone National Park, with part of the day observing formations created from natural CO_2 seepage.

Session 1: Welcome and Aims of the Meeting

There have been 2 previous meetings on Environmental Assessment of CO_2, but this is the first workshop following approval of a workshop series. Therefore part of the aim of the meeting was to create a set of aims and objectives that the workshop series will work towards. This was explained in this session with the intention to decide on these during the conclusions session.

Session 2: Environmental Impact Assessments and Regulations

This session consisted of a comparison of existing environmental impact assessments (EIAs), an overview and analysis of current relevant EPA rules and an example of successful implementation at a real project. Some main outcomes from the session are that projects proceeding with standard EAs before dedicated regulations have done so successfully and have assisted and educated regulators to enable development of regulations. Dedicated regulations can provide some problems for demonstrations – e.g. EPA Class V vs. VI, PISC 50yrs; there is a need for flexibility in regulations, and/or the ability for amendment; there may be issues over land access for long term monitoring, which will need to be considered; and there will differences in EAs onshore and offshore.

Overview and Comparison of Environmental Assessments for CCS, Jun Kita, RITE

Comparisons across countries show a similar process. First there is a screening followed by an environmental impact assessment (not necessarily needed in some countries depending on the screening) from which an environmental impact statement can be issued. Then follows the key process of the consultation with stakeholders, after which decisions can be made

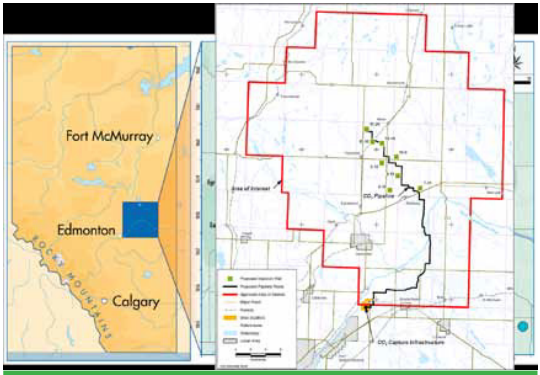
and a monitoring plan put in place. Legal and regulatory frameworks were also compared across countries, differences were noted, but there was not anything that could not be dealt with if necessary.

EPA Class VI Underground Injection Control Rule, Lee Spangler, MSU

More projects will be using the Class VI rule, but some issues have been noted especially in regards to R&D projects. Default post-injection monitoring is 50 years (it is possible to request a lower time), which can be an issue as companies may not be willing to do this on a research project. Financial responsibility can also be a problem for research institutions. Some projects have converted to EOR to be allowed a Class II well permit. There are also some inconsistencies between the reporting rule and the UIC rule regarding language associated with leakage. All R&D CCS projects will have to switch from Class V to Class VI.

Shell Quest Carbon Capture and Storage Project: Environmental Assessment Process and Results, Tara Barnett, Stantec

The focus of this environmental assessment was on the assessment of accidents, malfunctions and unplanned events for the project. When looking at the interaction between the project and environment, valued environmental components (VECs) are identified. VECs identified covered the entire range from air quality and sound environment, to surface and subsurface water quality, to terrestrial and biophysical, and socio-cultural components. The next step was an analysis of what could happen outside of normal operations. For Quest, 9 scenarios were considered and 3 of these were carried forward; including the release of CO_2, formation brine or CO_2 saturated brine from the storage complex or injection wells. Active and passive mitigation methods were considered, including real-time logging of injection rates and downhole pressures and through the selection of the



Quest Project, Tara Barnett, 2012
Location of capture plant, storage site and pipeline route

storage site itself, such as the regionally extensive salt seals over the storage complex. Some effects may persist after mitigation and the significance of this was analysed. The Quest project's Environmental Assessment was approved shortly before the workshop.

Session 3: Controlled Release Experiments

This session contained updates from several controlled release projects, some of which are completed, some in progress and some yet to start injection. There are variations in focus across the projects, from testing detection technologies to specifically determining impacts of CO_2. The number of facilities has proliferated giving a wider range of settings, soil and water chemistry types, flora and fauna and the first marine controlled release has been performed.

Some of the main learnings are that surface detection is gaining broader acceptance; there are challenges in relating / scaling lab experiments with controlled releases; indicator species are being identified and benthic species seem to be particularly sensitive; seasonality and timing can affect impact of leakage

CO_2FieldLab, Dave Jones, BGS

The aim of this project was to determine the sensitivity of monitoring systems to shallow CO_2 migration and surface leakage, test and calibrate migration models in well controlled conditions, upscale results to assess monitoring systems and requirements and propose a monitoring protocol. The injection was into a heterogeneous sand deposit with complex bedding and channels, which are poorly sorted coarse sand, with abundant fines and pebbles.

The main conclusions are heterogeneity in sand deposit deviates the plume path, but is not able to be characterised by non-invasive methods. Electrical resistivity methods (and GPR) sensitive to CO_2, show both increasing and decreasing resistivity. Post-injection data is needed to characterise and build a reliable model. From history matching, both high and low permeability layers can match the location and timing of surface seepage. The next step is to build a reliable model which the geophysical methods can be calibrated against to determine their sensitivities.

The ZERT Controlled Release Site, Lee Spangler, MSU

The ZERT test site has been operational for 5 years and has involved 47 investigators, 31 instruments / sensor arrays and 5 universities, 6 DOE national labs and 4 companies. Some of the main learnings over this time are:

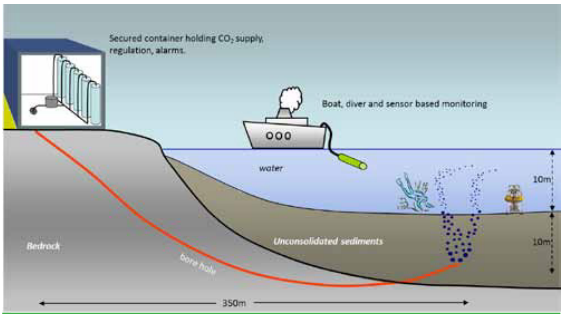
ZERT Test Site; Picture courtesy Lee Spangler Experiments have taken place at the ZERT controlled release site over 5 years. Over this time work has been carried out by 47 investigators from 5 universities, 6 DOE labs and 4 companies using 31 instruments / sensor arrays

- Many near surface methods are quantitative but:
  - Diurnal, seasonal, annual variations in ecosystem background flux affect detection limits
  - Appropriate area integrated, mass balance is a challenge
- Nearly all methods could detect 0.15 tonnes / day release at ZERT site
- Isotopes & tracers have lower detection limits than straight CO_2 flux or concentration
- Scaling, 6 tonnes per day would be detectable over an area 40 times as large
- Surface expression was "patchy" – 6 areas of ~5m radius
- Natural analogues also seem to have "patchy" surface expression
- Will engineered systems that leak have similar properties

The QICS Controlled Marine Release Project, Jerry Blackford, PML

The QICS project is the first offshore sub seabed sediment release project. The aims of the project are to deliver information that can be directly applied and fully understood by policy makers, planners, public bodies and the public with an interest in planned CCS projects; quantify the fluxes and transformations of CO_2 from the storage reservoir to the seafloor ecosystem, into the water-column, and potentially the atmosphere; evaluate the biogeochemical and ecological impacts in the shallow sediment and the water column; and establish techniques for the detection and monitoring of leaks by examining

the spatial and temporal biological, chemical, and physical signatures that may result.



Conceptual Diagram of the QICS CO2 Release Experiment; Jerry Blackford, 2012 QICS is the first sub seabed release experiment. This experiment considers how CO_2 will flow through the shallow subsurface and allows observations of flow in real sediment environment and full scale testing of monitoring techniques.

The CO_2 release phase has now been completed and the project is in the recovery phase. Some preliminary results were presented, which include seismic monitoring showing a 15-20m horizontal spread. CO_2 appeared 3 hours after injection started and a video of CO_2 release shows bubbles and pock marks. Some fauna are thought to have been affected, but this has not yet been quantified and an increase in alkalinity near the end of injection suggests carbonate dissolution.

The PISCO2 Project: Experimental set-up and Perspectives, Fidel Grandia, Amphos 21

The objective of the project is to investigate the effect of CO_2 in soils on different biotopes. Construction for this project started in 2010 and injection is expected to commence in 2013. This will include experiment on lichen, strawberry plants and will consider the kinetics of chlorophyll.

Environmental Impacts of CO_2 Storage: Results from the ASGARD field facility, Karon Smith, University of Nottingham

The ASGARD site has been in operation since 2006 years and its approach has been to inject controlled amounts of CO_2 into soil, test detection techniques, monitor changes in plant and soil conditions and test sensitivity to soil and plant types. This presentation concentrated on the results from the vegetation studies.

The main conclusions from the plant studies noted were that significant effects occur at relatively high levels of CO_2 (above about 10%) and are likely to be highly localised; CO_2 usually damages root development but in some instances stimulates it; the response to CO_2 depends on the plant species

and the stage of development when the leak occurs; monocotyledons appear to be more tolerant than dicotyledons but there is variation between plant species; and some species (e.g. clover) are more sensitive, affecting competition. Other work conducted at the site includes soil gas concentration, soil flux, botanical studies, bacterial studies and the environmental impacts of pipeline leaks.

Potential Impacts on Groundwater Quality of CO_2 Geological Storage: The CIPRES Project, Marie-Christine Dictor, BRGM

Planning for this project started in January 2012, the main objectives of which are to characterise biogeochemical mechanisms that control the degradation of water quality and devise a methodology for monitoring groundwater quality above future CO_2 geological storage complexes. The main expected outcomes are recommendations for investigating the potential risks of CO_2 storage on groundwater quality; identification of the biogeochemical reactivity of CO_2 within the aquifer to estimate the impact on water quality and spatial and temporal distribution of the potential impacts on both chemical and microbiological water composition; and methodological guidelines for implementation of monitoring programmes.

Field Results from a Controlled Release of Dissolved CO_2 into Dilute Groundwater, Rob Trautz, EPRI

The objective of this study is to investigate the potential CO_2–induced mobilisation of metals using a controlled release of dissolved CO_2 into groundwater. Injection of CO_2 has been completed and the project is in the post-injection monitoring phase with planned closure in 2013. Groundwater is produced, into which CO_2 is dissolved, then reinjected to a 50m depth. This is carried out in a closed loop system to avoid contact with oxygen. Measurements were focused on pH and some cations and anions

The results show that on injection there is a rapid increase in cations, followed by a decrease; the same is true for anions but to a lesser extent. Lab characterisation of sediments indicates that trace metals are present. The majority of trace metals (e.g., As, Cu, Pb) remained below their respective method detection levels and it is unknown whether they are increasing or decreasing. Sorption/desorption processes are likely mechanisms responsible for rapid increase-decrease in concentrations. However, elevated concentrations of several constituents were observed at 2 wells implying that

dissolution processes are starting to dominate later in time; and/or the plume front become comes wider as more metals desorb and begin to accumulate and move with the front.

Ginninderra Greenhouse Gas Controlled Release Facility: First Shallow Subsurface CO_2 Release, Andrew Feitz, Geoscience

Australia The main aim of this project is to test atmospheric monitoring techniques. A pre-release above ground experiment was carried out in 2010 and monitored using atmospheric tomography. CO_2 emission rate was determined within 3% and localisation determined within 4%. The first release was March – May 2012 and the initial results were presented. Soil flux took approximately 4 weeks to stabilise and changes were detected in the soil gas after only 4 hrs, 15m from the hot spot. There was considerable lag between surface expression of soil flux and sub-surface soil gas (1m deep).

The next steps will be to process the data from first release; including finishing analyses and look at gas ratios in the soil gas, inverse Bayesian (atmospheric CO_2 using "cheap" point sources) and micro and tracer data. The second release is planned for October 2012, where there will be airborne hyperspectral (dwarf wheat) and in field phenotyping , inverse Bayesian (atmospheric CO_2 using infrared laser source), AUV helicopter CO_2 survey and more geophysics and soil flux surveys. A third release is planned for 2013.

Ressacada Field Lab for the Petrobras CO_2 MMV Project, Andrea Moreira, Petrobras

The aim of project is to test MMV techniques including new (real time) CO_2 monitoring tools to be applied to commercial scale, as well as testing detection limits for near-surface monitoring techniques. The overall goals for Brazil are moving towards CO_2EOR not storage. Brazil does not currently have any target obligations to reduce emissions, but has taken on voluntary targets. Injection is planned to start in 2014.

Hydro-geochemical impact of CO_2 Leakage from CCS on shallow potable aquifers: Vrogum main release experiment, Aaron Cahill, Danish Technical University

The objective of this project is to look at very shallow aquifers and consider the geochemical impact that may take place following a CO_2 leak. The site has fairly pure water with little to no buffering capacity. The pilot field

injection has been completed and the main injection commenced in May 2012. Injection is at 4m and 8m and there are distinct differences observed with depth (between layers).

A sudden increase in electrical conductivity was noted at 8m, while nothing was seen at 4m. A variety of anions and cations are monitored, which can be seen to increase after injection, but again much more noticeable at the deeper wells. The migration of the plume is being monitored and more wells are being drilled as the plume migrates.

Session 4: Monitoring

This session was defined as 3 parts, an overview considering different monitoring methods available; baseline monitoring and sensitivity; and quantification and diffuse leakage. Some of the main outcomes of the session are how the range of methods available has increased. Particularly the ability to screen large areas, i.e. AUV offshore and electromagnetic methods onshore; these methods enable cost and time effective monitoring over a large area, and if an anomaly is detected it can be investigated further.

Regarding baselines; there are several indicators that could be monitored to detect CO_2 leakage in the marine environment, though natural variability means significant effort to characterise the baseline. It is now possible to identify leakage without a baseline using the process-based technique; however, it may still be desirable to use survey style background measurements to establish a pre-injection baseline, as well as continual monitoring to identify potential leaks. Advances have also been made in quantification methods as well as wide area techniques.

Monitoring CO_2 Storage: How Far should we go?, Rob Arts, TNO

An overview of potential monitoring techniques was given as well as the importance of a monitoring strategy, which while specific for each site, aims to show no leakage, though this is difficult to prove. Difficulties in developing a monitoring strategy include consideration of large areas versus more accurate point measurements (will enough area be covered to identify a leak), indirect deep (geophysical) early warning methods versus shallow direct (late) methods as well as the impact of large area methods (seismic) versus benefit. Examples of how this has been done in the CO2ReMoVe and ROAD projects.

Marine Monitoring of offshore CCS Storage – Challenges and Solutions, Ian Wright, Southampton University

There has been much progress in the area of marine monitoring, but there are still some challenges, including issues of what to monitor for, as if there is a leak, CO_2 may be preceded by saline fluids, which in turn may be preceded by anoxic fluids.

Some of the main conclusions include CCS sites with large spatial seafloor extent and overlying ocean volumes (with potentially dispersed and localised emission sources) provide a monitoring challenge; the essential rationale for monitoring will be baseline studies, leakage detection, and flux emission quantification; potential CO_2 leakage may have precursor fluid release of reducing sediment pore fluids ± aquifer brines (each of which has a unique chemical signature); new marine sensor and underwater platform technology is developing to deploy long-term point observing and remotely surveyed monitoring of the critical fluid parameters at the necessary sensitivity and spatial scales for CCS sites (and at relative low cost); seafloor / ocean monitoring can detect both dissolved phase (using chemical detection) and gas phase (using passive and active sonar), but is not yet commercially deployable; chemical and sonar monitoring systems may also provide a tractable and robust method for quantifying leakage loss beyond just detection; quantification of CO_2 loss is probably easier and more accurate at the seafloor.

Conductivity Measuring to Assess Brine Impact, Katherine Romanak on behalf of Jeff Paine, The University of Texas

This covered the use of magnetic and electromagnetic conductivity methods to find brine impacts; a method which has been used successfully to locate leaky wells. The magnetic survey is used to identify potential preferential leakage pathways by identifying the casing of plugged and abandoned wells. EM conductivity can detect salinisation as well as discriminate among salinity source types; the change over time can then be monitored.

These are both airborne methods, therefore able to screen large areas rapidly with generally unrestricted access. This can then be followed up with more focused on-ground monitoring activities. Challenges include, magnetics only being able to detect abandoned wells with casing in place and EM having a limited investigation depth of a few hundred meters, but this is still

potentially useful for CCS and CCUS applications.

Setting the Standard for baseline studies for sub-seabed CO_2 Storage – the CO_2BASE Project, Andrew Sweetman, NIVA

The main objective of the CO_2BASE project is to perform a pilot baseline study on two sites in the North Sea in order to determine best practices for baseline data acquisition; the study will run for 6 years.

It is necessary to understand the natural system, in order to ascertain if any changes are due to CO_2 leakage or part of the natural variability. This project will consider and monitor very shallow biological and chemical processes on the seafloor. This includes animal behaviour on the seafloor and benthic biodiversity; bioturbation shows burrowing to the seafloor, which may indicate potential leakage. Geochemical variability is considered and mixing rates will be determined. Modelling will be used to simulate local current conditions and tracer transport at sites, biochemical processes and sensitivity of local ecosystems to elevated CO_2 content.

Process Based method, Katherine Romanak, University of Texas

This methodology can be used to test for leakage in the absence of a baseline by considering the source of CO_2 based on the ratio of key gases: CO_2, CH_4, O_2, N_2. Background processes are biological respiration (plant and microbial), oxidation of methane, dissolution of CO_2 into groundwater and reactions with soil carbonate and atmospheric exchange. Leakage can cause exogenous CO_2 or CH_4 from a storage formation.

The ratio of CO_2 to O_2 will indicate whether the CO_2 is produced by biological respiration, oxidation of methane, or leakage while the total concentration of CO_2 is not relevant. N_2 that is higher than atmospheric values indicates that CO2 has been consumed in the system (possibly by dissolution into groundwater) whereas N_2 that is lower than atmospheric values may indicate a leakage signal. N_2:O_2 ratios can be used to determine the amount of consumption of O_2, which may occur most vigorously in the case of a methane leak being oxidised to CO_2. This process-based methodology has been tested and proven at a number of sites and can be used as a targeted response tool for unexpected reservoir behaviour, landowner concerns, or observed changes in the biosphere.

Dial and Other Wide Area Detection Methods, Kevin Repasky, MSU

This talk focused on the development of surface monitoring technologies for large area detection of carbon dioxide for ensuring public safety and site integrity. Various methods of CO_2 detection will be needed for carbon sequestration site monitoring, but DIAL (Differential Absorption Lidar) is useful in providing near surface detection over several square kilometres. The methodology works by using 2 closely spaced wavelengths and the light collected indicates the CO_2 density. Fibre sensor arrays monitor the difference between a reference and transmitter array, which provides a cost effective scalable network of point sensors. Hyperspectral aerial imaging takes images at different wavelengths and looks at the brightness; this has been tested on a vegetation plot and can provide large scale coverage.

"No Detectable Leakage": Accuracy and Sensitivity of Storage Monitoring Methods, Anna Korre, Imperial College

Quantifying leakage depends on the methodology being used and in most cases there will be nothing to detect, so it is important to assess accuracy and sensitivity in monitoring. A statistical analysis is needed to detect the signal through the noise. Classic hypothesis tests are vulnerable to false alarms and highly dependent on data uncertainty. A specific leakage model in Neyman-Pearson acceptance testing allows evaluation of probability if correct decision making over whether leakage exists. Extension to multiple leakage models probability of leakage.

Detailed information is needed in the statistical structure of the data and the uncertainties. Accumulation of enough background data may be impractical, but there are still many statistical techniques available. False alarm rates are likely to be encountered with data with very low statistical power to detect leakage.

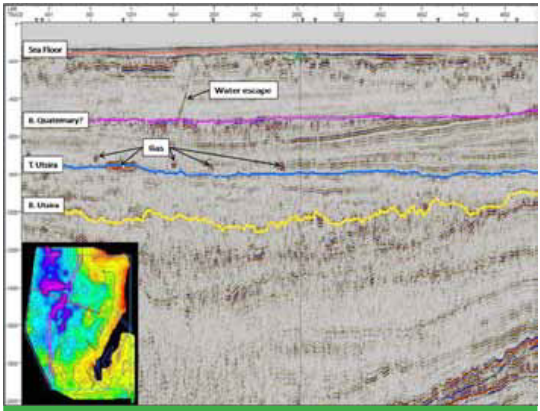
Session 5: Overburden / Mechanisms of Migration from Deep to Shallow Subsurface

To understand potential impacts it is necessary to understand processes and mechanisms of migration through the overburden. Mechanisms are currently poorly understood but there is ongoing research and an idea from this session was to engage with external communities with more knowledge e.g. methane seepage, hydrocarbon, geomechanics.

Seismics are useful to characterise overburden and identify potential pathways and large spatial coverage can be achieved using hydro acoustics. Other learnings from the session include bacterial mats on seafloor can be a good indicator for pathways; monitoring is needed at depth for early detection, as a potential leak may not manifest itself immediately; O_2/DIC flux ratios may be used to identify potential leakage including diffuse leakage and potentially quantify leakage rates; and further research needed in sedimentary systems to understand potential mechanisms and define how analogous natural systems are.

Sub-Seabed CO_2 Storage: Potential Leakage Pathways and Effect on Marine Ecosystems (ECO_2), Klaus Wallman, GEOMAR

This focused on the work carried out looking at potential leakage pathways at Panarea, a site of natural CO_2 seepage and Sleipner, a current storage site. The Panarea site is part of an active volcanic area with fumarolic activities and gas vents; acoustic monitoring has been used to map a large surface area of the seabed and eighty previously unknown bubble flares have been found in the study area.



Quest Project, Tara Barnett, 2012
Location of capture plant, storage site and pipeline route

At the Sleipner site, potential leakage pathways are being mapped with seismic data. There is currently almost no surface monitoring and this is now being conducted as part of the ECO_2 project. Numerous vertical seismic pipe and chimney structures in the sedimentary overburden have been identified; there is methane seepage through abandoned wells, but no detectable leakage of CO_2. Also identified was 3km long fracture 25km north of the Sleipner site, through which there is also methane seepage and no detectable CO_2. It is not expected that CO_2 will be detected at the site as it is separated from the storage site by several thick impermeable layers. The gases continue to be monitored.

Fluid Transfer Modelling from the Basal Cambrian Sand through the Overburden to Useable Groundwater Formations for the Quest CCS Project, Jeff Duer, Shell

The biggest risk on the quest project was considered to be through legacy wells, so modelling was focused on this to determine potential leakage pathways. The talk focused on 4 wells on which cross-flow modelling was carried out.

The main conclusions were that investigation of the legacy wells illustrated that minimal invasion of brine occurred and that the cooking lake acts as a pressure sink. Investigation of the injection well illustrated that minimal invasion of CO_2 occurred. Investigation of a fault leak path illustrated that minimal invasion of CO_2 occurred through a 1 mD leak path 1000 metres from an injection well at 1/3 total field rate. MMV in one of the wells would need to be very close to the leak path to observe fluid invasion, whereas pressure build up can be seen considerably farther quite readily.

Gas Migration over Gas Reservoir in Different Geological Scenarios: Comparison among Geological, Structural and Geochemical Data and Modelling, Salvatore Lombardi, University of Rome

The study of natural analogues, allows understanding of migration mechanisms, pathways, and geological controls that influence the potential for CO_2 leakage. To this end a range of different sites have been compared to conclude that most fluid circulation is controlled by fractures and faults and their features; density, connectivity, and grade of strain localisation, which controls porosity distribution in fault zones.

This can be used to establish criteria for risk assessment and safety strategy. For site assessment, methods developed at natural analogue sites can be used to show if there are any potential migration pathways at a site considered for CO_2 storage. For monitoring, knowledge of where and how CO_2 may leak helps define a monitoring and safety strategy, as well as planning any eventual remediation plan.

Session 6: Leakage Scenarios

This session consisted of talks on considering natural systems to identify potential leakage scenarios and work carried out in the ECO_2 and RISCS projects to identify potential leakage scenarios. Some of the main outcomes

were that natural systems can be used to look at how leakage could potentially occur and what the effects would be, as can be seen with deep sourced hydrothermal fluid leaks. Leaks are improbable but possible, and therefore plausible leakage scenarios need to be developed. To consider leakage scenarios it is important to know flux rates, the duration of the leak and the area and form of leakage.

Hydrothermal Systems and Analogues for Breached Traps and Subsurface Healing: Outcrop and Subsurface Examples and Escape Mechanisms, Dave Lageson, MSU

As some likely sites for CO_2 storage are where naturally occurring CO_2 already exists in the deep subsurface, then it is important to understand the processes that occur in these regions. Many of these systems are associated with magmatic or non-magmatic sources of hydrothermal fluids, making understanding of these high-temp reservoir conditions through surface and core studies essential.

Hydrothermal Breccia pipe – Using Hydrothermal Systems as Analogues or Breached Traps and Subsurface Healing; Dave Lageson, 2012. Surface analogues can be used to study subsurface reservoir conditions.

This study concluded that surface analogues can be excellent laboratories for studying subsurface reservoir conditions; fracture and fault systems are predictable and mappable across many scales of observation; low-temperature hydrothermal brine systems are important diagenetic components of carbonate reservoirs that must be understood for long-term carbon dioxide storage. Key to understanding these systems are detailed, integrated studies involving structural geology, carbonate diagenesis and geochemistry, at all scales of observation.

An Environmental Perspective on Leakage Scenarios, Jerry Blackford, PML

Part of the ECO_2 project is to develop site specific scenarios based on modelling work and initially generic scenarios are needed to enable progress. Factors that are needed are flux rate, duration and area (and form of leakage). Three main categories were identified; worst case leakage, with injectivity on an industrial scale: 5-10 Mt/yr over a short period (~0.5 years); leakage through faults/fracture with several spots on the seafloor; and leakage through an open well (~ 1t/day). From these a range of plausible scenarios can be created.

A particular issue noted was moving from leakage flux to CO_2 dosage. Tidally driven plumes and CO_2 density effects imply that perturbation at any given location is likely to be intermittent.

Development of Leakage Scenarios in the RISCS Project, Dave Jones, BGS

Even though all leakage is improbable at a well-chosen and operated CO_2 storage site, it is important to create a range of leakage scenarios to act as a basis for designing monitoring and mitigation plans, as well as a communication tool and to provide a context for the discussion of project results.

A range of scenarios were developed for the RISCS project by considering marine and terrestrial reference environments. The marine reference environments are cool, temperate, deep; cool, temperate, shallow; warm, shallow; and low salinity. Terrestrial environments considered are maritime temperate; continental; Mediterranean; and generic urban. Aspects of the scenarios include what kind of environments there will be, patterns of leakage (point source, alignments of point sources, diffuse etc), things that could be affected ("receptor classes"). The scenarios will initially be simple descriptions, by are expected to become more complex later in the project.

Session 7: Communication of Leakage – Discussion Session

Session Chair: Katherine Romanak, University of Texas

Panel Members: Tim Dixon, IEAGHG; Travis McLing, INL; Lee Spangler, MSU; Lori Gauvreau, Schlumberger CS; Jerry Blackford, PML

This session started with an opening presentation from Katherine Romanak to introduce the discussion. This focused on using natural analogues and

controlled release projects in public communication and how the analogue used should be relevant to CCS or what is being explained. The other panel members each gave a short presentation, before opening up the discussion to the floor. Tim Dixon talked about how negotiations to have CCS in the CDM were positively affected by the preceding UNFCCC technical workshop, which allowed stakeholders and technical experts from the IEAGHG networks to interact. Lee Spangler talked about how the ZERT site has been used to communicate with the public and regulators. Issues have arisen due to an emotional response, but if the time is taken to explain the situation, this can be resolved. Lori Gauvreau talked about the importance of developing consistent terminology, which the public are able to understand and avoiding terms that can be misunderstood, such as overburden, supercritical CO_2 and plugged and abandoned wells. Jerry Blackford talked about the communication strategy at the QICS project, which has been very successful. All local stakeholders were involved from the start and the point of view taken was not to advocate CCS, but to answer questions related to the science. Travis McLing talked about past experience and how easy it is to get misquoted by the press, especially if they do not get all of the information. Pictures can also be used to communicate, but this needs to be thought about, as this will be the lasting image people take away with them.

The main outcomes of the discussion were:

- Terminology should be consistent and clear to the audience.
- All Projects need a Communication Response Plan
- Open and honest communication is needed with all groups of stakeholders
- Be proactive not reactive
- Information needs to go to the right people, e.g. Technical workshop for UNFCCC negotiators
- Be careful with the press as it is easy to be misquoted
- Pictures are what gets retained – remembered forever
- How analogous are natural systems – what is relevant to CCS

Session 8: Conclusions and Decision of the Aims and Objectives

The meeting concluded with a request from participants to become a full IEAGHG Network, called the "Environmental Research into CO_2 Storage Network". The Network should have the aim of a "A network to build and advance knowledge for environmental research of geological CO_2 storage", with the objectives being to "Stimulate and nurture international collaboration and knowledge sharing to improve understanding for environmental research of CO_2 storage, and to act as a source of technical information".

Key points from the meeting included:

- EIA regulations are not a barrier to projects
- There are now a good number of controlled release projects, providing useful knowledge
- CO_2 release behaviour in the near-subsurface can be unpredictable
- Marine work – very good progress on monitoring and on baselines
- Electro-magnetic remote monitoring of brine appears very useful for 'early' leakage detection
- Environmental Assessments will be substantially different for offshore to onshore, we don't have offshore examples yet
- If leakage does occurs –it will be 'patchy' and in small localised areas, not over a large area
- The Process-based technique is an example of monitoring moving in right direction – able to provide important information where there are no baselines. This technique uses ratios of gases present to determine source of CO_2
- Still need baselines for leakage detection and impact assessment
- Indicator species are being identified, especially benthic and terrestrial plants
- Seasonality and timing can effect leakage impact
- Broader acceptance of near-surface monitoring then in 2008

Research needs or gaps identified included:

- Need for deep subsurface release experiment
- Understanding overburden processes
- More on brine intrusion – industrial analogues
- Bringing in new research communities
- Challenging to find small leakage spots
- Need more wide area monitoring techniques and proven: need for high spatial resolution
- Need to understand how analogues compare to CCS sites

The recommendations from attendees included:

- Keep up the good work! – gaps identified in the past are being addressed
- Consistency in terminologyData sharing in between projects, and engaging with other research communities
- Further meetings could be focussed on:
  - Transport mechanisms through the overburden and surface expression and natural attenuation
  - Remediation – possibly in conjunction with the risk assessment network
  - Biological impacts
  - Groundwater impacts
  - Comparison of environments: systems assessment

2013-03 SUMMARY REPORT OF THE 2ND IEAGHG JOINT NETWORK MEETING

Introduction

The Joint Network Meeting co-ordinates all four of the geological storage networks: Risk Assessment; Monitoring; Modelling; and Wellbore Integrity; and the Environmental Impacts of CO_2 Storage Workshop Series. The 2nd IEAGHG Joint Storage Network meeting was held from the 19th to the 21st of June 2012 in Santa Fe, New Mexico, USA. It was hosted by Los Alamos National Laboratory and sponsored by Sandia National Laboratories, Los Alamos National Laboratory and Schlumberger Carbon Services. Sixty-eight delegates attended, representing 11 different countries.

The aims of the meeting were to:

- Ensure the Networks are working in the most efficient way without duplication or gaps,
- Identify cross-cutting issues and their consequences; requiring input from more than one network,
- Set the framework for the future direction of the networks.

The 3 day event consisted of 2 main sessions. Session 1 considered how far we have come, and included reviews from the IEAGHG CO_2 storage networks on developments in their own areas, and lessons learnt from CO_2 storage projects on cross-network issues previously identified, followed by breakout discussion sessions to consider lessons learnt. Session 2 was highly discussion based and considered where we should go next for all the networks. This included sessions to identify R & D knowledge gaps and reviewing the current networks to see how they can be used to meet the needs of the R & D and wider CCS community. The third day consisted of a meeting held by NRAP in the morning and a field trip based around the local geology and Chimayo natural CO_2 release site in the afternoon.

Session1: How Far Have We Come?

IEAGHG Network Development

Network Progress since 2008, Tim Dixon, IEAGHG

Some recommendations from the previous Joint Network Meeting have been followed through, including the creation of the modelling network and commissioning of studies related to technical gaps identified. Expertise from the networks has been able to be drawn upon for peer reviews including the Otway peer review in 2009 and the US EPA VEF in 2008. They have been useful for regulatory developments including the UNFCCC, where three of the networks addressed the issues for CCS in CDM and some network members played a significant role in the 2011 Technical Workshop in Abu Dhabi, which went on to influence negotiations of CCS in the CDM towards their successful result.

The Risk Assessment Network, Charles Jenkins, CSIRO and Hubert Fabriol, BRGM

Over the past Risk Assessment meetings some of the main topics addressed include: risk communication, which requires a common language and the importance of building trust; regulatory development, where it is important to take an active role in addressing new and emerging regulations, including provision of information for regulators; risk assessment methodologies; risk profiles, for which knowledge is improved as more information is available from demonstration projects; impacts, for which further understanding is needed and is an active area of research; risk and incident management and monitoring. There is further work needed regarding corrective measures.

It was highlighted that it is important to know who the audience is when talking about risk assessment and particularly for quantitative risk assessment. The network has also taken a role in the identification of 'emerging risks' that are thought to be increasingly important, such as the potential effect on groundwater and induced seismicity.

The Monitoring Network, Kevin Dodds, BP AE and Sue Hovorka, University of Texas

The Monitoring Network meetings have covered a wide range of technologies as well as how different techniques can be used together to see the full picture. Much learning has been taken from demonstration projects,

particularly regarding history matching, which needs to be carried out throughout the project allowing accuracy of prediction over time. Emerging and evolving regulations have been taken account of during the meetings and it is important to maintain communication with the regulators.

An issue highlighted is that monitoring needs to be able to cover the different goals of showing climate change mitigation, show that resources are protected and to account for carbon credits. It was also noted that the detection threshold can be site specific and determining quantification is an active research area.

The Modelling Network, Neil Wildgust, PTRC and Jeremy Rohmer, BRGM

The Modelling Network has had 3 successful meetings since its conception at the last Joint Network Meeting. The meetings have highlighted knowledge gaps and complex issues needing to be dealt with by modellers, including modelling the complexity of the subsurface which includes complex hydrofacies architecture, fracture networks and information from core flooding. There are also issues related to history matching and the impact of model uncertainty. This is of particular importance as it is part of the iterative process as more monitoring results are available and can affect what is required regarding regulations.

The Modelling Network web pages have also been used to host Statoil's Sleipner benchmark model, which is available to all members of the Network.

The Wellbore Integrity Network, Bill Carey, LANL and Stefan Bachu, AITF

The Wellbore Integrity (WBI) Network has also had 3 meetings since the last joint meeting and 4 meetings prior to that. The main considerations have changed over time, with the starting point looking at whether materials survive CO_2 injection, changing to frequency of well leakage, defects and geomechanical impacts and more recently the focus has been on EOR.

Wellbore integrity is also related to the risk profile, potentially causing a risk increase in the long term, due to the breakdown of materials. Some other issues considered are cement stability in CO_2, steel corrosion, design of CO_2-resistant cement, best practices in well completions, well abandonment practices, detailed modelling of fluid-wellbore interactions, field-scale modelling of wellbore performance and remediation technologies. The largest uncertainty and risk are old abandoned wells in the area of review as

the state of completion may not be known.

Environmental Assessment workshop series, Lee Spangler, MSU and Franz May, BRGM

This workshop series, started as an ad hoc workshop in 2008, Defining R&D Needs to Assess Environmental Impacts of Potential Leaks from CO_2 Storage, which was then followed by another workshop in 2010, Natural Releases of CO_2: Building Knowledge for CO_2 Storage Environmental Impact Assessments. The next workshop and the first since approval of the workshop series will have a focus on controlled release experiments.

Much work has been carried out in this field and the network has helped to highlight knowledge gaps and areas where research and experimentation is needed. Research areas include how flux rates in natural settings relate to potential leaks, impacts under different situations – some of which is being considered in controlled release experiments and monitoring methods.

Lessons Learnt from CO_2 Storage Projects

Review of Large Scale Projects, Angeline Kneppers, GCCSI

The Global CCS Institute continually tracks the status of large scale integrated CCS projects (LSIPs) worldwide. The Institute identified 73 LSIPs around the world, including 15 currently in operation or in construction. In terms of recent progress, since 2009 the strongest early movers are still in progress and those in the early operational or construction stage are projects mainly in North America (mostly EOR), Europe (mostly saline aquifers) and China (enhanced coal bed methane, or ECBM).

The general needs to accelerate the deployment of CCS fall into three categories – stoppers, delayers and enablers. Stoppers may include long-term investment environment, financial security (i.e. CO_2 price, subsidies etc.), liability and public perception. Delayers include factors like the speed of funding allocation, technical gaps in approval/acceptance processes, infrastructure planning and slow/reluctant supportive policies, legislation and frameworks. Enablers for the deployment of CCS include the reuse of infrastructure, use of CO_2 for EOR or EGR, efficient use of existing knowledge and international collaboration on all of these issues.

Key lessons learned include knowing that there are no technical barriers to the storage of CO_2 (with sufficient knowledge/experience). More data is needed from operational projects and the data required for site assessment should not be underestimated (5 to 10 years lead times from screening to injection). CO_2 disposal requires the same attitude, approach and capability to that of a major petroleum development. It is key to note that it is most likely that significant financial investment may be required prior to project sanction.

Ancient cliff dwellings exploiting geological erosion at Bandelier National Monument

Migration from the Primary Store: A Cross network challenge, Max Prins, Shell

An important question for any CCS project is how to detect migration from the primary store. This work was carried out at the Longannet to Goldeneye project– and had a problem statement of 'how do we determine if we can detect migration from the primary store?', looking at where it is likely to occur, where it can occur, at what rates and what volumes can be detected. In terms of risk assessment, a full bow-tie analysis was carried out and safeguards identified. The bow tie results lead to identification of threats and potential

migration paths – particularly important is the timing of migration. For most scenarios the system will stay hydrostatic (for approximately 1000 years) as the CO_2 cannot be driven out. For the volume at risk you take each well then calculate the mobile CO_2. To look at the rates of migration, significant modelling is required. For leak detection it is key to have an integrated approach – through networks including wells, risk assessment, monitoring, modelling and environmental.

Cross cutting issues research – Carbon Capture Project Phase 3, Kevin Dodds, BP AE

The CO_2 Capture Project (CCP) has been in place since 2001 and the 3rd phase is due to be completed in 2013. CCP3 is looking at areas including assurance R & D (wellbore integrity, subsurface processes, monitoring and verification (M & V), optimisation), field trialling and stakeholder issues. In wellbore integrity, a key study is the field acquisition of cement in wells. Key findings were that the cement was carbonated, the interface erodes (where the cement does not) and there was evidence of calcite precipitation. In subsurface processes, capillary entry pressure and impurities were looked at (physical and chemical effects like rock alteration), along with the impacts of these processes on storage and injection.

In storage optimisation, all site data was looked at with the process of coming to a conclusion as to the viability of the project. This was applied to a number of sites (including In Salah) and this will be developed further into optimisation and economics, whilst addressing a range of CO_2 assurance issues. A retrospective assessment of M & V was carried out, assessing the suitability of monitoring for sites and addressing issues related to the sensitivity of monitoring (sitespecific). Modular borehole monitoring (MBM) was looked at in detail, with a final idea to look at all options and create a guidance document for general reference. CCP3 trialled MBM deployment at the Citronelle site (USA), carried out through casing resistivity tests at the Otway project (Australia) and completed trials on borehole gravity at the EOR and storage site at Denbury Cranfield (USA). Stakeholder issues are being looked at in a contingency study to inform the relative effectiveness of monitoring technology to detect and characterise types/modes of leaks – more work is planned on this in workshops to be held in 2012 and 2013.

Recent research developments from the IEAGHG Weyburn-Midale Project, Neil Wildgust, PTRC

The Weyburn-Midale research project has two key deliverables – a technical best practice manual (BPM) and an issue of the IJGGC journal. The BPM will cover characterisation, performance predictions, geochemical monitoring, geophysical monitoring, performance validation, well integrity, risk assessment and community outreach.

The study area here has a huge amount of pre-existing information – meaning data management is an issue. The migration scenarios assumed certain wellbores leaked at a certain rate and a natural analogue study was also carried out – results showed that despite the CO_2, there is limited evidence of any major reactions of porosity etc. and as the use of the 3D seismic information was successful, they are able to show that it is an effective tool at this site for mapping the CO_2 in the reservoir. However, it is more problematic to look at the CO_2 saturation – so it is important to have a model to constrain the interpretation. Seal integrity and fracture mapping is an important issue, where they found a reasonable match for core samples. In passive seismic modelling there was a lot of useful information on geomechanics. The leakage allegations in 2011 generated a lot of bad press, but soil gas monitoring results disproved these allegations. The wellbore integrity field testing programme is a key research issue and permeability testing of the cement sheath confirmed the effectiveness of the cement. When looking at risk assessment and geological storage, the geosphere and biosphere risk was focussed on. The containment risk profile showed that well cement and leakage through the wellbore is a key risk scenario, but such risks actually demonstrate acceptability.

Key Messages from operational storage sites – Findings from the CO_2ReMoVe Project, Henk Pagnier, TNO

The main objectives of the CO_2ReMoVe project are to develop/test technology for predicting, monitoring and verifying geological CO_2 storage, to test procedures and technologies at a unique set of large scale and pilot sites, to demonstrate that CO_2 can be stored in a safe and effective way, and to develop best practice guidelines for M & V. the project is involved with a unique set of injection sites, for example Sleipner, In Salah, Snøhvit, K12-B, CO_2SINK and RECOPOL.

The project aims to address several questions, the first being whether CO_2 can be stored in a safe manner. Evidence suggests that it can be stored safely and effectively with no leakage to the biosphere. Monitoring of site performance can deviate from single predictions – so you must establish acceptable deviations or demonstrate convergence between the model and measurement and the acquirement of robust baseline data is essential for effective performance verification. The second question focusses on whether storage is practical and affordable. A limited portfolio of monitoring tools is needed to provide assurance at a given site and a much wider range of monitoring techniques was investigated than a commercial project is likely to use – allowing a higher degree of flexibility. Another question considers if some procedures/requirements can be standardised – CO_2 storage standards should not be technology prescriptive; there is no 'one-sizefits-all' monitoring programme. In conclusion, CO_2ReMoVe has unprecedented access to several industrial and pilot scale sites, has developed, deployed and tested multiple tools and integrated monitoring strategies to address regulations.

The Illinois Basin – Decatur Project: Updates and Recent Experiences, Randy Locke, ISGS

This project is a demonstration of carbon storage in a saline reservoir at the Decatur site in Illinois, USA, where 1 million tonnes of anthropogenic CO_2 will be injected over 3 years – alongside a comprehensive 7 year monitoring framework (with the verification well completed in May 2011). The focus of the project is the Mount Simon Sandstone, with CO_2 injection in the base of the section and as of the 16th June 2012, 184,000 tonnes had been injected.

For early implementation stages of projects, it is important to integrate new field data into models and communicate changes in model predictions (i.e. rates of CO_2 migration) quickly so that necessary adaptations can be made. The Decatur project has a comprehensive monitoring programme involving 20 different technologies and methods. Successful efforts in the project include site characterisation, permitting, drilling, reservoir modelling, engineering, risk assessment, public outreach and baseline monitoring.

The Lessons Learned about cross-network issues from MRSCP and Mountaineer Projects, Neeraj Gupta, Battelle Battelle Carbon Management is involved with many CCS efforts and other projects, where the focus has

recently been shifting to EOR and commercial oil and gas. FutureGen is a commercial scale oxycombustion project with pipeline transport and storage in the Mt Simon Sandstone. The AEP Mountaineer project has injection wells in 2 formations (approximately 37,000 tonnes injected so far), with an extensive monitoring programme. The Michigan Basin II injection test is leveraging the existing EOR infrastructure and overall testing indicates rates of 600 metric t/day (or higher) could be obtained here in the formation.

Breakout Session 1: Lessons Learnt

Risk Assessment Network

Risk assessment is the central part of a project – it defines how work is done. Risk communication was not one of the original Network objectives, but throughout all meetings it was a common theme that communication is key – it is important to talk to more people, both inside and out of the usual parties. A lot of useful work has been done in this Network but is perhaps not getting out there enough – the question is how to facilitate this. The need is there to converge toward a common language. It has been observed that NGOs are often neutral on the technical aspects but participate more to the regulation discussions – consequently their position can, and does, change. Where we are at the moment, we are at the stage where we have new regulations, new projects almost permitted etc. – so soon shall see if risk assessment has satisfied the regulators, which will then tell us about where we need to go.

Monitoring Network

The regulatory environment is currently maturing and in this process it has become clear that there are still things to be done. A lot more progress needs to be made in quantification and the role of risk processes in monitoring integration has been recognised and strengthened. A key achievement is the contribution of multiphysics and recognition of the value of this; where different types have been brought together (i.e. Weyburn). A baseline terminology used expertise to interpret changes that occurred and the importance of public perception has been frequently addressed.

Wellbore Integrity (WBI) Network

This Network has covered a range of topics including the mechanisms, magnitude, frequency and impact of CO_2 leakage, self-healing of wells,

modelling of well leakage, risk assessment, monitoring of well integrity, remediation of wells, best practices and regulatory agency interactions. Slow, low-rate leakage is the main problem for CCS and it is not likely to be the injection wells that are a problem, but the existing wells. The risk profile for projects should reflect the potential for long-term deterioration of wells and the movement of plumes to encounter leaking wells. Cement is key to reducing wellbore integrity issues – if the cementing is good (in terms of the role of centralisers and in design, quality and placement), the well is most likely to perform as expected. Certain cements have the ability to self-heal (in some circumstances). The Network also identified key risk factors potentially leading to well failure.

Environmental Impacts

This workshop series is now starting to 'define more refined', specific questions. Much work has been done in looking at the response of systems (soil, plants, microbial etc.) to the high CO_2 environment, for example in indicator species. We know that there are some systems available to study – but how analogous are these to CO_2 storage? The knowledge of pathways is essential for impact assessment – the relation of CO_2 discharge points to groundwater flow systems and tectonics. Major rock constituents can impact groundwater chemistry and it is important to acknowledge that impacts are not only caused by CO_2 but also from associated brine and formation fluids. It is key to engage other communities, but we have learnt that they don't often understand the environment they are communicating in – and it is critical to take care when trying to communicate environmental impacts.

Modelling Network

Modelling has made a lot of progress in the last 4 years, and specific improvements that have been made in the Network include the greater emphasis on 3D now rather than 1D and 2D. A lot of work has been done on improving core flooding in lab experiments and matching that to modelling floods (with increasing success in extrapolating the small scale up to basin scale). More detailed models have emphasised the importance of heterogeneity and there is now a better understanding of processes, along with achievements made in coupling processes. More complex problems have also been addressed and accounted for – i.e. impurities and well leakage – and there is now a larger number of available tools and higher standards

of technology. Experimental data leads to improvements in models, but it is important that there isn't an expectation to provide fully integrated models (simplified can also be very useful). More models are now available but there is a danger in this – poor parameter input will demonstrate inaccurate results. In calibration and prediction, there has been good history matching in several cases and the new data has provided an opportunity to evolve and improve the models. It is important to meet the expectations of the regulator when it comes to matching – what is a good match?

Session 2: Where do we go next?
Part 1 – Identifying R & D Knowledge Gaps

This session was introduced by Franz May who talked about the 6 discussion topics selected by delegates out of a possible 10 derived by the Steering Committee. These were then discussed in breakout sessions, where the instructions were to discuss knowledge gaps and identify needs of the R & D and wider CCS community, discuss how networks can assist in meeting needs of the R & D and wider CCS community, identify areas requiring input from more than one network and discuss if there is a need for networks or ad-hoc workshops in other key areas.

Breakout Group 1: Uncertainty in simulations forming parts the permits (e.g. risk assessment, reactive transport in storage reservoirs). Model updating (history match) consequences for validity of operation license?

Knowledge gaps identified were issues specific to CCS as this is a wider issue and relevant to other industries, from where lessons can be learnt, such as the oil, gas and nuclear industries. Specific CCS knowledge gaps identified were wide spatial scales (e.g. pressure-impact zones), time dependency: e.g. temporal evolution of risk profile and public perception. A second knowledge gap identified was model uncertainty; it is not only a matter of knowledge gathering, but also how to adjust/re-do model concepts in the light of new knowledge, which is an iterative process. There needs to be a balance between sophistication, number of parameters, increase of number of uncertainty sources and the question to be asked is: what is enough? And how to integrate model uncertainty in the permitting process? The third knowledge gap identified was related to communicating uncertainty on the results/knowledge to the public and regulators; communication approaches may differ depending on the background of each audience.

Needs identified were for a need for systematic / robust approaches for an iterative link between statistical-based procedure, risk assessment, monitoring, verification, possibly in the form of a best practice guide with in-built flexibility for reservoir specific issues. There needs to be systematic sensitivity approaches: from the model, identify key parameters and form an iterative process with the characterisation phase. When dealing with uncertainty, the potential consequences should be considered in the mitigation plans. Uncertainty treatment approaches exist, but there is a need for validation through application. There is also the need to better understand the needs of the public and regulators.

This topic would require input from the risk assessment and monitoring networks, and potential future workshops identified are 'Communication with wider stakeholder (public/regulators) group on handling Uncertainty' and 'Lessons learnt from the application of different approaches' (e.g. In-Salah).

Breakout Group 2: Completeness of observation and quantification of leakage, especially in shallow and surface monitoring

Several knowledge gaps were identified, including what the definition of a leakage should be; does it include brine and hydrocarbons and should it be redefined in terms of potential impact, which by definition can already be measured though receptors must be defined – it is noted that this does not address the issue of carbon credits. Leakage could be qualified as 'detectable' or 'significant' and current regulation requirements will change with technology. The 99% sequestration criteria in the US is fundamentally impossible to meet as it is not possible to "prove" that the CO_2 is in the reservoir.

Attribution (interpretation of monitoring data) may not be adequately understood; integration of diverse data sets may be necessary as is determining the source of the leakage, such as through wells, fractures, caprock, spills and migration. Determining when the baseline is adequately characterised is an issue.

Monitoring issues include uncertainty of off-shore monitoring methods and approaches. Monitoring at depth, while expensive, may allow remediation before impacts occur in the shallow subsurface.

Needs identified are work on attribution, involving determination of the origin of potential leakage in complex and realistic situations from CO_2, brine and mobilised hydrocarbons, which could involve testing on analogue sites. New theoretical and analytical methods of attributing leakage need developing as does determination of the most effective monitoring methods for each site – learnings from controlled release sites are essential. Other identified needs include determining the variability of aquifer response to CO_2 – passage of fronts, buffering capacity, metals and understanding how a laboratory characterisation of drinking water aquifer (core samples) relates to likely impact of CO_2; understanding differences between confined and unconfined aquifers, development of methods that can monitor large areas effectively. Collaboration was suggested with new work on methane leakage attribution and work on off-shore gas detection.

Networks that could provide input to this topic are Environmental Impacts, Monitoring and Wellbore Integrity.

Breakout Group 3: Corrective measures plan/remediation plan

When looking at corrective measures on deep reservoirs, the first stage is recognising the problem, then characterising it (through monitoring), then thirdly to set up the specific actions.

Knowledge gaps identified were distinguishing between deep reservoir and shallow aquifers; in the reservoir the plume may not where as predicted (it is necessary to take into account the real reservoir complexity), resulting in pressure increasing above the allowed limit, well failure and leakage from unknown flow pathways (e.g. bubbles coming out at the reservoir).

There are various solutions, including pressure management and changing the flow direction and relative permeabilities (using chemical treatments, biofilms etc.), but a major issue is related to cost with respect to the impact. There are also knowledge gaps related to caprocks, where there may be a fracture or linear structure (e.g. sand channel), it may be possible to inject a gas cap over the CO_2 with a different wettability – more research is needed into this.

Further research is needed into breakthrough technologies, it is important to know the effects of injecting exotic species in the reservoir.

It was suggested that regulators need to have the same level of expertise as the operators to understand what they are told about, which is a role that the networks can help in.

A workshop based on this topic was thought to be useful, though there is a current IEAGHG study looking at mitigation of unwanted CO_2 in the subsurface, so a well-timed workshop could be when this is due to be published. Any workshop should attempt to attract people from industries with the appropriate experience. Networks that would provide input to this are the risk assessment, monitoring, wellbore integrity and modelling and environmental impacts networks.

Breakout Group 4: Monitoring Plan – site specific and based on risk assessment and potential migration pathways

Knowledge gaps identified were the relationship of geophysical data to actual CO_2 and geological parameters; site specific calibration will be needed in each case. Detection vs quantification is an issue and how accurate it is possible to be; there may also be non-quantitative key indicators showing escape. Better understanding is needed of physical and chemical transport processes (e.g. if secondary pooling is common, seismic could be effective for leakage monitoring).

There is no general recipe and it would be useful to see how existing projects have needed to adjust monitoring plans.

Another knowledge gap is how much monitoring is needed due to a mismatch of the generally accepted risk profile and knowledge profile. Integration of various monitoring purposes represents a challenge and the regulatory environment is part of site specificity.

Needs identified were what monitoring is needed to improve the initial model and what model outputs are needed to define risk assessment, as well as what environmental consequences are of greatest concern. It was concluded that a workshop drawing from all networks on this subject might be useful.

Panoramic view of the local geology including the Bandelier Tuff
Photo Courtesy of Randy Locke

Breakout Group 5: Groundwater Protection

Knowledge gaps identified were addressing the site specific nature of groundwater protection as there is no one prescriptive answer for each site; how to integrate and apply knowledge from various research techniques to predicting impacts; how to assess the outcome of exogenous fluids entering a shallow aquifer; with the need for complete hydrogeochemical characterization, how is effort managed with respect to reward; how are natural impacts or those from other industries separated from those induced by CCS activities; what is the nature and extent of migration of fluids (brine and CO_2); to what extent will a release enter and impact an aquifer (intermediate interceptors, buffering) and how is this monitored; and how are the contaminants of concern determined.

A workshop on this subject based on one particular site was suggested.

Breakout Group 6: Link between monitoring results and (mandatory) operational consequences (e.g. thresholds, conditions for site abandonment)

A trigger was defined as something that merits attention, but is not necessarily an event that needs to be dealt with; it is a deviation from the model and needs to be continuously reassessed (iterative assessment of trigger and range).

Challenges/knowledge gaps identified were risk and their analysis and how this can be quantified; how monitoring is defined to address perceived risks (e.g. uncertainty, resolution, quantification); how monitoring is tied to the operation (safety protocols of normal operations vs. what can be addressed through monitoring); what is an acceptable deviation from the model; and process/systematic way of going through uncertainties as you move forward.

Needs identified were categories of monitoring to set trigger boundaries; triggers of the operation need to be defined, as well as how significant it needs to be; there should be continued improvement of existing monitoring technologies and development of new tecnologies; and risk driven research (still requires definition of the risks and the process). A workshop focusing on how more mature industries deal with this issue was suggested.

Ad hoc session on Induced Seismicity

In addition, a session was included at short notice in order to discuss the Zoback paper in PNAS on induced seismicity, published that week. Many of the attendees had read the paper but some had not. The discussion was considered useful, and in addition the group agreed to produce the following statement:

> *The topic of induced seismicity and the Zoback paper was discussed by the international gathering of experts at the IEAGHG Joint Network Meeting, and the majority agreed: "Induced seismicity is important to consider for CO_2 geological storage and has already been the subject of extensive research and risk assessment for current CCS projects. There is not sufficient information available to justify the conclusions drawn in the last sentence of the abstract of the paper by Zoback".*

Part 2 – IEAGHG Storage Network Review: Meeting the needs of the R & D and wider CCS community

Breakout Session 3: IEAGHG Storage Networks: Future focus and direction

In the light of the previous information and discussions, breakout groups met to agree details for future issues, topics, and activities for each of the Networks. The following summarises their recommendations.

Environmental Impacts, Lee Spangler

Discussions formulated new ideas and directions for the network. Important areas recognised include the understanding of processes, fluxes and the relation to impacts, the issue of near surface expressions, a greater focus on brine and mobilised substances is needed and more information should be drawn from industrial analogues. This information has to be suitable, however, and it is key to put this into the correct context. Issues come up against include communication (it was suggested that a good route would be through those who write about science for the public), the correct naming of the workshop (as it is treated as a Network) and as meetings are only every 18 months, this can prove challenging. For the future, this group should look at network needs and continue to generate joint proposals (i.e. the first workshop initiated the RISCS project).

Wellbore Integrity Network, Bill Carey

This Network has a huge relevance to CCS – it is the link between the reservoir and surface, it drives risk and monitoring, is a rich modelling subject and is a source of environmental impacts. New topics that could potentially be looked at include existing oil and gas practices (i.e. design of cement/casing), leakage potential, monitoring of abandoned wells, security of long-term well abandonment and the impacts of fracking and seismicity. Network interaction with other IEAGHG groups is difficult (all meetings in disparate locations) – perhaps a way to deal with this is to have a concurrent session meeting of all networks, with an end plenary session. Expertise (and membership) of the WBI Network is localised so holding meetings on a geographical basis is hard – filling the agendas has been somewhat challenging, utilisation focus in the US and Canada is increasing the importance of this topic, but progress has been somewhat slow with a difficulty in involving industry. Potential alternatives to the existing Network could be to hold meetings

every 2 years, to have joint meetings with the other Networks, to distribute WBI tasks between the other Networks, or to consolidate meetings into ones based around topics/themes. If the WBI Network was to be halted, we would lose industry participation in a key area. There is an important connection between EOR and CCS that is kept strong by this Network and some research areas and operational focus areas would be lost.

Modelling Network, Neil Wildgust

Key issues within the Network include the challenge of calibration of models with monitoring data, EOR and depleted gas fields are important (i.e. residual oil zone etc.), as are impurities and the concept of scale. The current format for this works well in providing an outlet to share technical information, but perhaps there could be more online material and the workflow for model updating should be validated (perhaps by holding a joint meeting between the modelling and monitoring groups). The Modelling Network is rather focussed on reservoir modelling, but keeping the title of the group is important as it is allows for broader talk topics if required. It is valuable to rotate the Steering Committee each year and would be useful to collaborate more with the other Networks. It would be useful to get more expertise from those involved in EOR modelling and to look at the storage aspects of EOR.

Monitoring Network, Sue Hovorka

The role of the IEAGHG Networks are to have international updates, to be a small enough forum to have interaction within the group, to have frank technical discussions and to benchmark one project against another. It is important to encourage cross-network interactivity – but we need this interaction without sacrificing depth, which could be done by having back to back meetings, with overlapping sessions, to have a topic-driven workshop (performance assurance is a cross-cutting theme that could be expanded upon as such), or by having ambassadors from one network to another. The priorities within this particular Network include field implementation, demonstrations and applications, to promote best practice (via examples/ lessons learned) and encourage new people to the community.

Risk Assessment Network, Charles Jenkins

This is the 'umbrella' group of the Networks and is conscious that it should be influencing more, for example with NGOs and regulators – and provide a more explicit engagement policy. The Network needs to prioritise what

should be achieved in the short and long term, to be involved in ISO TC 265 and to look at how uncertainties affect the outcome of risk assessment. It mustn't be forgotten that risk management includes monitoring and corrective measures, so a joint meeting with another Network would be valuable and a strong idea was to change the name of the Network to Risk Management. The Network is conscious that many in the group are not risk professionals. The previously published terminology report was useful and it was suggested that this could be updated and disseminated. A common theme in discussions was that the Network (and all others) should have more of an existence in between meetings – perhaps via webinars or another online medium.

Part 3 – Outcomes and Recommendations

Plenary Discussion: Outcomes and recommendations of the 2nd Joint Network Meeting

The aims of this second IEAGHG Joint Network Meeting were to ensure the Networks are working in the most efficient way (without duplication or gaps), to identify cross-cutting issues (and their consequences) and to set the framework for the future direction of the Networks. The common needs recognised throughout the workshop include systematic iterative links between risk assessment (including monitoring and WBI), monitoring, verification and best practices, dealing with uncertainty, consequences and mitigation plans, and defining criteria, thresholds and acceptable deviations from trends. Many suggestions were made during this plenary session, including the strong potential of holding smaller, more focussed, topic-based meetings in the future. The Monitoring Network proposed organising a special session in other international conferences (e.g. Pittsburgh, Trondheim, GHGT), although these meetings are extremely busy as it is and perhaps do not have the time or space for such a session. The Steering Committees could come up with a list of meetings for which associating with would be a useful exercise. The usefulness of combined meetings was discussed – CO2CRC have agreed to host the Monitoring and Environmental Impacts Networks in 2013 as a combined meeting – and since this Joint Network Meeting, Statoil have confirmed they will host the Modelling and Risk Assessment Networks next year.

The discussion looked at how interdisciplinary CCS is and that some publications are missed – it would be beneficial to have an information resource, an archive of papers to cover all disciplines. Issues such as journal copyright policy would have to be considered, but IEAGHG will look into the possibility of such an archive.

The future of the Wellbore Integrity Network was discussed in depth. Although interest and attendance has been reducing, and IEAGHG does not have the resources to continue as it is, its members were keen to keep this as a dedicated Network. IEAGHG will look into this issue further and discuss with Network members in order to make a decision on this Network.

An increased operational focus was suggested involving more operators attending future events. This could include those working on demonstration projects. There also needs to be a standardisation; where tools/techniques have now been developed, there needs to be consensus on what to use globally (e.g. method for CCS capacity analysis) and then where applicable, deploy as a global standard via ISO. This can be discussed in future network

Franz May examining the CO2-rich well at Chimayo natural analogue site (CO2 and brine leakage into an aquifer)

meetings. It would also be useful to adopt a common terminology, in order to improve communication to the outside world.

The main recommendations from this meeting were to have more Network to Network collaboration, hold virtual meetings on 'hot topics', hold topic-based workshops (i.e. performance assessment, remediation), change the name of the Risk Assessment Network to Risk Management and to refresh more often the Steering Committee members.

No matter how the Networks move forward, it's essential that they keep their character. It would be valuable to ensure activity is maintained between meetings in all Networks – 'hot' topic-based or not – to keep momentum going and it could be valuable to hold additional small/focussed meetings linked to others (consulting via the Steering Committees to do so). All agreed that interaction of all Networks with the Social Research Network is important and recognised the value of holding combined meetings. A third Joint Network Meeting is a possibility for the future and a literature archive or alerting system will be looked into. IEAGHG will reflect on all of these recommendations from the meeting and look at how to act upon these in the best way for all.

An overall conclusion that can be drawn from the meeting is that, with a maturing regulatory environment, the technical knowledge and methods now exist in the area of storage so that there seem to be no significant technical barriers to projects meeting the requirements from the fairly stringent regulations in place in many regions. The IEAGHG Research Networks have contributed to this move from research to application. And finally, the Research Networks are highly appreciated by their members who wish them all to continue.

2013-06 4TH IEAGHG NETWORK MEETING AND TECHNICAL WORKSHOP ON HIGH TEMPERATURE SOLID LOOPING CYCLES

Introduction

The IEAGHG High Temperature Solid Looping Cycles Network emerged from the preceding International Workshop on In-situ CO_2 Removal (ISCR) and aims at bringing together researchers and developers of CO_2 capture technologies that operate at high temperatures in cylindrical processes using either circulating or fixed beds of solids.

Within the last few years drawbacks of the conventional amine-based CO_2 capture systems have spurred interest in solid looping processes. Since then the technology has advanced considerably and several pilot plants have been build and brought into operation, e.g the 1.7MW pilot plant at La Pereda in Spain and the 1MW pilot plant at TU Darmstadt in Germany. Progress has been made in particular in carrier/sorbent development as well as in process design and integration. In Calcium Looping, for instance, the use of spent sorbent to produce cement has been demonstrated.

The fourth meeting of the IEAGHG High Temperature Solid Looping Network was held from 20th to 21st August 2012 at the Xijiao Hotel in Beijing and was co-organised by Tsinghua University. Beijing was chosen as the location for this meeting to make the network more accessible to an international selection of participants, especially from Asia.

Although the number of attendees for this meeting was slightly down at about 48, there was a full two day programme with 31 presentations, 10 posters, a plenary discussion and a visit to the "Key Laboratory for Thermal Science and Power Engineering of Ministry of Education" at Tsinghua University.

The Technical Programme consisted of four sessions in total. Three sessions were related to progress made in Calcium Looping in the fields of sorbent development, H_2 production and reactor and process design. One session was reserved for Chemical Looping Combustion and presented advances in carrier development as well as some new process concepts.

Introductory Presentations

Introduction to the Department of Thermal Engineering, Tsinghua University – Ningsheng Cai, Tsinghua University

Thermal engineering is one of 4 departments in the Mechanical Engineering school which is itself one of 16 schools at Tsinghua. It is home to 1 national and 15 key state laboratories. Today the University has links with 205 other universities in 68 countries. Thermal Engineering has 4 key laboratories including those researching IGCC and CO_2 Utilisation and reduction. Work on CCS is undertaken from lab to pilot scale. There is international collaboration with BP, Mitsubishi and Toshiba.

Introduction to the Low Carbon Energy Laboratory – Quiang Yao, Tsinghua University

This laboratory was set up in 2008, has a budget of $130M p.a. and staff of around 800. It co-operates extensively with major companies and US DoE laboratories. It undertakes policy studies in many areas and a key aim is to bring the results of research to the international market but with a strong focus on China. Research resources include 4 nuclear reactors. Recently SEED projects have been set up to research Geoenergy, Biofuels, use of low grade energy resources and bi-phasic sorbents for CCS.

Introduction to the IEAGHG Network on High Temperature Solid Looping Cycles – Mike Haines, IEAGHG

The status of solid looping technology for both combustion and CO_2 capture was compared with that of competing technologies. The need to better understand the strengths, weaknesses and opportunities for the technology was stressed. The history of the meetings including the 4 earlier ISCR gatherings was reviewed and the recent use of mainly European locations noted along with the importance of making the network meetings accessible to an international selection of participants. This year participant numbers were slightly down at about 48, although there was a full 2 day programme of papers and posters. Economic restrictions on travel and the biennial chemical looping combustion conference in Darmstadt at the end of September have undoubtedly restricted attendance.

The Old Gate at Tsinghua University

Session 1: Calcium Looping – Sorbent
Chair: Paul Cobden, Energy Research Centre of the Netherlands (ECN)

The Synthesis of Ca-based, Al2O3 Stabilised Sorbents – Christoph R. Müller, ETH Zürich

Formulations of 80-20 to 90-10 Ca:Al give better sorption performance up to 75% better than typical natural Rheinkalk. The key to good performance appears to be making a very thin layer of CaO on the Al2O3 support. To increase porosity of the structure resorcinol/formaldehyde was used to make a carbon shell. After precipitating Ca/Al the carbon is burned off leaving 5µm spheres with high porosity. In real tests the decay of activity was much slower than natural material. Uptake capacity increases up to a limit of about 93% Ca after which it drops dramatically. For practical use the fine material would need to be pelletized and work on a suitable process is on-going.

Synthesis of CaO-Based Sorbents by Spray-drying – Wenqiang Liu, Huazhong University of Science and Technology

The aim of this work is to create separate ultra-fine CaO particles and separate them with an inert solid in a matrix. Of 4 mixing methods, dry mixing, suspension mixing of insoluble particle, sol mixing (one component soluble) and wet mixing (both components soluble) the wet method was chosen. Use of acetates, lactates, propionates, formates and citrate tetrahydrate were studied. The support was MgO and formulations in which 20µm particles surrounded 100µm CaO particles were produced. Both oven drying which is slow and energy intensive and spray drying were used and the latter shown to produce effective sorbents. The optimum capture capacity was found to be with 82% CaO. Performance was better than literature reports for natural CaO. However a method to pelletize the powders still needs to be developed.

Nano CaO-based Adsorbents Evaluation by a Circulating Fluidised Bed System – Su Fang Wu, Zhejiang University

Use of nano particles has the advantages of high reaction rate, durability and low attrition. Batch CO_2 sorption tests in a fixed bed and circulating fluid bed reactors were carried out. The tests showed low attrition (<3.5% in ASTM test) with 30nm particles. Batch tests were carried out to measure the breakthrough of a stream containing 7.7% CO_2. In a fixed bed reactor there is 100% capture until about 40% of the bed capacity has been used. Because of the mixing a CFBR always shows some breakthrough but can reach up to 99% absorption.

CO_2 Capture Using Lime Mud from Paper Mill in Calcium Looping Cycles – Rongyue Sun, Shandong University Lime mud originates in paper making and consists of a mixture of NaOH and $CaCO_3$. Disposal to land fill is becoming increasingly difficult. Both the caustic and chlorine content can be reduced by water washing. Cyclic absorption tests were carried out for both prewashed and unwashed lime mud. Prewashing was found to greatly reduce loss of capacity after 100 cycles. It was also found that a prolonged first cycle of 9-12 hours greatly increased capacity particularly for unwashed lime mud. Also the effect of prolonged carbonation in the 20th cycle was tested. Measurements show that surface area decreases over time but overall pore volume was increased with a reduction in small pores offset by an increase in larger ones.

Sequential Capture Characteristics of CO_2 and SO_2 by Ca-based Sorbent – Zhao Zhenghui, Cranfield University

The capacity for SO_2 of partially spent lime after duty as a CO_2 sorbent has been investigated using simulated flue gas. The capacity for CO_2 was found to drop by a relatively small amount typically by 20% after 40 cycles of carbonation. The spent lime is withdrawn from the carbonator where the temperature is lower to avoid cooling. Tests were performed in a bubbling fluidised bed reactor on 3 different sorbents.

Rate Equation Theory of Gas-Solid Reaction Kinetics for CaL and CLC - Zhenshan Li, Tsinghua University

The reactions of CLC air reaction and CaO looping carbonation were studied. Both reactions show a fast followed by a slow phase. No theory currently describes the complete process. Reaction products develop through a process of nucleation and growth. There is also migration of products between the islands which grow after nucleation. A model has been developed which is based on fundamental properties of the chemical reaction and surface diffusion. The model fits the measurements well and most notably the fitted coefficients appear to be able to account for experiments at different temperatures without adjustment lending considerable weight to the validity of the model.

The Effect of HBr and Sea Water on the Reactivation of Ca-based Sorbents – Belen Gonzalez, Imperial College

Doping with HBr was found to greatly improve the activity and reduce the rate of activity decay of limestone (Havelock). The doping did not however appear to alter the reactivation effect of steam. Measurements showed changes in pore size distribution as a result of the doping. Further tests were carried out using sea water as the dopant and activity improvements were also measured. Questions were raised with regard to the possible effect of dopants and or support materials on acceptability of waste sorbent into cement making.

Session 2: Calcium Looping – Hydrogen Production
Chair: Ningsheng Cai, Tsinghua University

H_2 Production by CFB Ca Looping Coal Gasification – Shiying Lin, Japan Coal Centre

Results of simulations and tests on a H_2 production process using low temperature (700-850°C) gasification of coal at 20 atm combined with a calcium looping cycle were presented. In the full process the H2 is consumed in a solid oxide fuel cell. The decomposition temperature in the calciner was found to be somewhat less than theoretical, 930°C at 6 atm, 1000°C at 20 atm. The material circulation is sufficient to supply heat to the gasifier as long as the gasifier temperature is not too high (< 750°C). Up to 20% CH_4 remains in the product gas and is reformed before H_2 separation. The H2 is consumed in a fuel cell and waste heat from this can be used either to make steam and heat feeds or as a heat source for reforming the CH4. The latter gives a higher cold gas conversion efficiency. An overall efficiency of 76% was calculated in the simulation.

H_2 Production from Biomass with Chemical Looping Gasification Technology – Qinhui Wang, Zhejiang University

This new H_2 from biomass process has been patented. Simulations show H2 purity of 60% can be obtained when operating gasification below 850°C and at a pressure of 10 bar with a sawdust feed. Experiments have been conducted at 4 bar and 680°C and were able to produce 67% H_2 with a CaO to carbon ratio of 1.2. Optimum pressure for the process is thought to lie between 10 and 15 bar.

H_2 Production from Biogas by Sorption-Enhanced Steam Methane Reforming – Julien Meyer, IFE Norway

The design of a plant under construction at Lillestrom, Norway, was described. The aim is to produce H_2 from landfill gas for delivery at 700 bar, storage at 1050 bar to allow H_2 vehicles to drive between Oslo and Stavanger. A double fluidised bed system will be used. Of note is the use of indirect heating in the regenerator through Inconel U tubes. Space between tubes is > 50x particle diameter so that no fluidisation problems are expected. Design fatigue life of the heating tubes is only 1000 hours although with regular inspections up to 5000 hours may be possible. H_2 purity will be 99.999% achieved through use of a Pd membrane.

The Effect of Impurities on Cyclic Stability of Sorption Enhanced Water Gas Shift – Paul Cobden, ECN

The 6 fixed bed SEWGS pilot plant at ECN was described and plans for a larger 2MW demonstration unit. A number of tests have been carried out on the effect of impurities H2S (500, 2000, 25000 ppm), COS, NH_3 (2000 ppm) and HCN (200 ppm) on three different promoted hydrotalcite sorbents. H_2S and CO_2 breakthrough have been observed at roughly the same time. COS was not detected as it was found to hydrolyse to H_2S. HCN undergoes partial hydrolysis and breaks through slightly more quickly than CO_2. However the sorbents are fully regenerable. Dual Fluidized Beds System for H_2.

Production with CO_2 Capture Based on CaL– Wang Dong, Southeast University

The design of a novel compact chemical looping coal to H_2 production process was described. A feature of the process is the carry through of char to the calciner to act as fuel. The process features also an absorber section above the main carbonator/gasifier bed in which residence time and contacting for further CO_2 absorption is provided. A 2kW hot bench scale has been constructed but has still to be tested.

Session 3: Calcium Looping – Reactor and Process
Chair: Carlos Abanades, CSIC

Experimental Validation of Post-combustion Ca-Looping in a 1.7 MWt Pilot – Borja Arias, CSIC-INCAR

La Pereda pilot plant is a 1.7MW unit processing a stream of the flue gas from a 50MW CFB power plant at La Pereda in northern Spain which has been built in the EU FP7 funded project "CaOling". The feed flue gas is taken from downstream of the ESP and pressurised with a fan through the unit. The captured CO_2 is recombined and the exhaust rerouted to the main power plant flue duct. The calciner is equipped for both air and oxy-fired combustion. The unit was hot commissioned in January 2012 and ran for 800 hours on coal combustion in air mode. There have then been 160 hours of CO_2 capture with the calciner working in air fired mode with no sorbent agglomeration problems. Limestone used has a nominal particle diameter of 110 micron. A brief period of oxy-fired operation has been undertaken but is not yet reported. Initial tests were carried out to analyse the influence of the main parameters affecting the carbonator performance. The effect of the inventory of CaO in the carbonator and the reactor temperature were shown.

Steady states with CO_2 capture efficiencies over 90 % were obtained in the La Pereda pilot plant during these tests. SO_2 captures efficiencies above 95 % in the carbonator were reported.

Effect of Steam and SO_2 on Pilot-scale Capture of CO_2 Using CaL – Alissa Cotton, Cranfield University

The effects of steam and CO_2 on 3 kg batches of CaO sorbent pre-calcined at 900°C have been measured in a 25kW thermal test unit. With a synthetic feed of 8% CO_2 a capture efficiency of about 80% is achieved. Modifications to improve this rate are planned. CO_2 was found to decrease porosity and reduce carbonation capacity. Raising steam content to 20, 30 and 40% progressively improves CO_2 capture capacity. SEM images of fully carbonated material under 40% steam indicate increased porosity. Work on analysis of trace elements was also presented. Levels of up to 10 ppb were detected. In some cases elements were only released when there was a larger inventory an effect which cannot yet be explained.

The Effect of Inert Solid Accumulation in Post-combustion Ca-Looping Systems – M. E. Diego, CSIC

The impact of the accumulation of $CaSO_4$ and other inert solids on the CO_2 capture efficiencies and the overall CaL process performance was analysed. For this purpose, three variants of a 1000MW coal fired power plant with capture using limestone sorbent were modelled. One was a PC unit with no FGD, the second a CFB unit with desulfurisation and the third a power plant with desulfurisation and with a sorbent regenerator. The CO_2 capture efficiency was calculated for the three systems for different make-up flows and coals used in the calciner. The increase of the feed of ashes and SO_2 to the system leads to a lower CO_2 capture efficiency due to the sulphation of the active CaO and the reduction of the inventory of active CaO in the carbonator. The results showed the first case to need a large make up of 50% due to the sulphation of the lime. Even when an effective reactivating step is included in the CaL process, there is a need for a minimum make-up flow of limestone to avoid the effect of inerts.

Fully Integrated Simulation of a Cement Plant with a CO_2 Capture CaL - Dursun Can Ozcan, University of Edinburgh

The optimum location for the carbonator was determined to be the outlet of the 3rd preheater in the cement process where CO_2 concentration is higher

than at the tail end (30% v 22%) and the temperature of 600°C matches that needed for carbonation. The clinker rate was kept constant and some limits were placed on the purge rate of sorbent to limit power generation to that required overall. Results so far indicate an energy consumption of 2.3 – 3.0 GJ/ton CO_2, lower than for a commercial amine process but further work is required to confirm this.

Comparative Second Law Analyses of Endex and Conventional CaL – Rowena Ball, Australian National University

Exergy analyses were carried out over the control volumes of an Endex-configured looping sorption process, in which the exothermic reaction supplies heat directly to the endothermic reaction and calcination is achieved by pressureswing, and a comparable conventionally configured system. It was confirmed quantitatively that in conventional CaL the most costly step by far is regeneration of the CO_2 from the sorbent. The Endex process was found to have a second law efficiency advantage of 40% over the conventional process, achieved largely by a significant reduction in the cost of the regeneration step. The gain is offset by an increase in the cost of the separation step, but this increase is relatively modest. The Endex process is a good candidate for thermodynamic optimisation because entropy generation is spread relatively evenly over its subprocesses. The capital cost of an Endex plant may outweigh some of the operating costs savings given by superior thermodynamic performance.

Optimisation of CaL for Power Plant and Integrated with a Cement Plant – Matteo Romano, Politecnico di Milano

A model of a USC power plant with full heat integration and cryogenic CO_2 clean-up was developed. A detailed model of the carbonator was implemented in Matlab. Efficiencies for varying make up to coal ratios were determined. Equipment costs were estimated in the model using exponential laws. Results indicate a cost of CO_2 avoided of €30–38 per ton. A similar analysis was performed for a cement plant producing 3600 tpd of clinker. Critical parameters are the purge rate and the amount of purge which can be used to substitute raw feed. Indications are that costs could be as low as €28 ton CO_2 avoided.

Cold Model Test of 3 Fluidised Bed Reactors Combining CaL and CLC – Hongming Sun, Tsinghua University

The process modelled uses three fluidized bed reactors (air reactor, calciner, fuel reactor) to realise the combination of calcium looping and chemical looping combustion. Heat balance in calciner is achieved by supplying transferring heat from air reactor to calciner via oxygen carrier which is mainly FeO/Fe2O3, and CaO solid flux is prohibited in the loop between air reactor and calciner. The characteristics including bed hold-ups and residence times were all modelled and agreement was found between conditions in the cold flow model and the theoretical model. The process feeds blast furnace gas to the fuel reactor (carbonator) and uses coke oven gas to fluidise the material in the calciner and appears to have the potential for low energy demand.

Session 4: Chemical Looping I
Chair: Stuart Scott, University of Cambridge

Performance of CaO/CuO Based Composite – Changlei Qin, University of Queensland

The presentation described the performance of a CuO/CaO composite for a combined Calcium & Chemical Looping process. Addition of steam, thermal pre-treatment of the CuO and use of MgO as a precursor can all help to prevent agglomeration and accelerated loss-in-capacity. However, as Cu is an expensive material, minimisation of Cu losses through efficient recycling plays an important role in the future development of these composites.

CuO-based Al_2O_3/CeO_2-supported Oxygen Carriers for CLOU – Christoph Müller, ETH Zürich

Compared to conventional CLC processes CLOU allows for an efficient combustion of hydrocarbon fuels without a prior gasification step. Due to their high O_2 capacity and fast decomposition reaction Cu-based carriers are most promising. The best performance was achieved with $CuMgAl_2O_4$ which showed a high and stable O_2 capacity close to the theoretical value. The chosen support material and the preparation method have a strong impact on morphology and thus can be used to influence the capacity and agglomeration characteristics of the carrier.

Effect of Volatiles in Coal on CLOU – Daofeng Mei, Huazhong University of Science and Technology

An investigation of sol-gel derived $CuAl_2O_4$ supported CuO revealed a steady release of O_2 over time and stable cycles of oxidation and reduction for this CLOU carrier. The presence of volatiles can promote the carbon conversion but at the same time the combustion efficiency and the CO_2 capture efficiency are decreased. It is therefore important to choose a reasonably low-volatile fuel for CLOU processes.

Use of Manganese Oxides Combined with Iron – Henrik Leion, Chalmers University of Technology

The presentation introduced iron-manganese oxides as promising O_2 carriers for CLOU. Generally, the gasification step in CLC is known to be quite slow, whereas the CLOU reactions proceed much faster. The carriers have the advantage to allow for complete conversion and for a magnetic separation. In addition, the Fe/Mn ratio can be used to tune the characteristics of the carrier, such as the activation at different temperatures. Once the particles are stable enough, the experiments will move to a continuous closed system.

Session 5: Chemical Looping II
Chair: Henrik Leion, Chalmers University of Technology

Chemical Looping H2 Production Using Fe_2O_3/ZrO_2 – Wen Liu, University of Cambridge

Because pure iron oxide loses reactivity very quickly it is often stabilised with Al_2O_3. However, this support material is known as problematic as it can lead to deactivation. So ZrO_2, which is inert and thus does not influence reduction kinetics and thermodynamic equilibrium in a negative way, seems to be a good alternative support material. The experiments showed that this carrier allows for a stable and high-purity H_2 production in Chemical Looping.

Pressurised Chemical Looping Combustion of Coal with Iron Ore – Shuai Zhang, Southeast University

The objective of this study was to prove the feasibility of coal-fuelled pressurized CLC in a 100 kWth pilot scale unit and examine the potential of iron ore as a low-cost O_2 carrier for commercial coal-fuelled CLC. The challenges in CLC of coal lie in the low operating temperature which makes a coupling with power generation systems difficult, and the slow gasification

rate. Tests in the 100kWth dual fluidised bed reactor revealed an increased CO_2 capture efficiency and carbon conversion at higher pressures. Hence pressurised Chemical Looping processes may be a feasible and promising option but on the other hand higher cost for pressurization and equipment issues have to be considered.

Gasification and Reforming of Solid Fuels in the Presence of Iron – Stuart Scott, University of Cambridge

For Chemical Looping Combustion solid fuels need to be converted to the gas phase through gasification. When using Fe_2O_3 –based carriers it was observed that these agents remove the mass transfer resistance in the gasification process and thus lead to an enhancement of gasification rates. Moreover, they will effectively combust the volatiles.

Investigation of Chemical Looping H_2 generation with CO_2 Capture – Shiyi Chen, Southeast University

In Chemical Looping H_2 generation which uses iron oxide as a carrier the gaseous fuels cannot be fully converted due to thermodynamic limitations. The presentation introduces a new fuel reactor in which a higher conversion can be achieved. It is also intended to send the high temperature gas product to a SOFC for electricity production.

H_2 Production from Bio-Oil Aqueous Fraction– Changfeng Yan, Guangzhou Institute of Energy Conversion

Steam reforming of bio-oil aqueous fraction coupled with CO_2 capture showed higher H_2 yields and concentrations than traditional steam reforming. H_2 production reaction with calcined dolomite revealed the highest H_2 yield among all carriers investigated. Calcined dolomite loaded with K_2CO_3 improved H_2 productivity by 20%.

Posters

New Progress on Calcium Based Catalyst/Sorbent Materials by SE-SMR – Asunción Aranda, IFE Norway

IFE has developed and patented a novel mixed CaO/calcium-aluminate sorbent with optimum properties for SE-SMR: long-term chemical stability, sufficient sorption capacity and high H_2 yield. Currently "all-in-one" particles including the catalyst are under development to overcome mixed sorbent issues like attrition and segregation with promising preliminary results.

Reactivity Improvement of Iron Ore in CDCL – Daofeng Mei, Huazhong University of Science and Technology

Natural iron ore is a cheap and readily available material and thus a promising O_2 carrier. However it exhibits low reactivity. Ores doped with other metal elements were tested for reactivity first in Hydrogen in a temperature programmed reactor and then with coal in a fluidised bed test reactor. Small improvements in reactivity were observed with Cobalt proving the most effective dopant.

Understanding the Effect of Inert Support on Reactivity Stabilisation for CaL – Zhenshan Li, Tsinghua University

The introduction of inert support materials into CaO particles can drastically improve the cyclic reactivity due to the inhibition of sintering. This study used a simple model to analyse how the Zener pinning force between CaO and support particles might explain this effect on the sintering resistance. The results were validated against literature data and showed agreement. The analysis suggests that there is a critical size of CaO particle beyond which further growth can be completely inhibited by the support, although there is also a mechanism by which encapsulation of the support particles can remove this inhibition of growth. These results are important in gaining a more fundamental understanding of synthetic sorbent performance.

$Ca(OH)_2$ Superheating: A Means to Improve the CO_2 Capture Performance of Lime – Robert Holt, IRL New Zealand

This poster describes IRL's Reactivation Process for CaL, which has three stages: hydration of spent lime in steam, annealing in CO_2 and finally dehydration. During annealing in CO_2 $Ca(OH)_2$ becomes superheated compared to the equilibrium decomposition temperature. The process restores the attrition resistance towards that of the raw limestone. It is proposed to apply the process to a slipstream of the circulating sorbent adjusting this to control the activity of the sorbent to an optimum. This Reactivation Process is proposed as a stand-alone system, with the steam for hydration internally cycled from the dehydration to hydration stages. An average capture activity of 40% is predicted from TGA measurements with repeated reactivation operations after every 7 CO_2 capture cycles. The system offers the potential for average capture activity to be a design parameter set from 20-50%.

Techno-economic Study of the Zero Emission Gas Power Concept (ZEG) – Julien Meyer, IFE Norway

The ZEG concept, which is a combination of SE-SMR to produce H_2 and a SOFC producing electricity as well as providing the heat for the sorbent regeneration, has been compared with a more conventional pre-combustion reference case. The results show that the ZEG technology shows a positive and relatively high NPV for most price scenarios even when there is no revenue from the captured CO_2.

Effect of Sorbent Type on the SEWGS Process in a Fluidised Bed Reactor – Yang Liu, Tsinghua University

This work investigated SEWGS based on CaL with natural sorbents for CO_2 captured from a blast furnace (BF) gas. Because of its relatively high N_2 content BF gas is not amenable to oxy-combustion capture. In natural sorbents both CaO and MgO act as a catalyst. It was observed that once the CaO is covered by $CaCO_3$ product, the MgO, which remains uncovered and thus stays catalytically active, can still continue catalysing the WGS reaction.

Sorbent Enhanced Steam Gasification of Biomass – James Butler, University of British Columbia

Preliminary breakthrough experiments in a BFB together with some cyclic tests have been carried out on biomass gasification with CaO for CO_2 capture. Removal of CO_2 during biomass gasification increases the yield of valuable product gases by shifting the equilibrium towards the desired products. When CaO is used as a sorbent, the formation of $CaCO_3$ also provides the majority of the heat required for gasification. Although the study found a slightly decreased quantity of tar when CaO is present, the overall generation was still quite high due to the low gasification temperatures and thus remains an issue in gasification.

Elevated Temperature PSA Technology for Pre-combustion CO_2 Capture – Shuang Li, Tsinghua University

The study investigated the application of layered double hydroxides (LDH) in a PSA for post-combustion CO_2 capture in IGCC plants. $K2CO_3$ promoted LDH showed a good cyclic stability and a higher CO_2 capacity than non-promoted LDH, even under elevated pressure.

A Novel Ca-Ni-based Hydrotalcite-supported catalytic CO_2 sorbent for SE-SMR – Marcin Broda, ETH Zürich

A new bifunctional catalytic sorbent, containing both the Ni catalyst and the Ca-based sorbent, was synthesised and investigated. The bifunctional catalytic sorbent produced a larger amount of high-purity H_2 than the other sorbents examined which were mixtures of catalytic material and limestone. The good performance is attributed to the fact that both Ca and Ni are co-precipitated as nanoparticles on a spinel matrix. Because the CaO particles are very small much of the carbonation reaction occurs in the initial fast phase.

Kinetics of Nano CaO Reactions with CO_2 – P. Q. Lan, Zheijiang University

The authors developed a gas-solid reactive adsorption model to describe nano CaO reaction with CO_2. The results of experiments were analysed using the model for nano CO_2 which had undergone multiple pre-treatments. They determined that the reaction time and the conversion in the rapid reaction regime are reduced by pre-treatment.

Plenary Discussion
Moderator: Mike Haines, IEAGHG
Panel: Paul Fennel, Stuart Scott, Henrik Leion, Carlos Abanades, Dennis Lu, Paul Cobden

The initial question addressed to the panel was aiming at an evaluation whether science or technology will be the driving force for future development and deployment of CaL, CLC and CLOU. Stuart Scott responded that the point of science is to support the technology. It is not possible to go for a certain technology without a detailed scientific understanding of it.

Paul Fennel clearly stated that both elements are of great interest for the scale-up of CaL and CLC.

Henrik Leion and Dennis Lu also subscribed to this view by underlining that both cannot be separated and that the scientists need to be involved in the process of development and deployment at all times.

However, Henrik made the remark that the CLC community had suffered from focussing too much on the science part and thus a correct balance between science and technology is needed.

In contrast, Carlos Abanades pointed out that technology has to be the real driver and needs to be ready for deployment. Technology should enable the process to be operated efficiently and be simple at a large scale. It is important that fundamental research is useful and applicable.

Paul Cobden explained that in the future CO_2 capture may become the most important driver. Nevertheless, the science has to be done to make the technology cheaper and more efficient.

The next question posed was related to the comparison of CLC with pressurised oxyfuel combustion.

Dennis answered that high pressure is favourable for many processes and this also applies for CLC.

Mike pointed out that an exergy analysis may be important here and that there is still a high penalty because of the ASU. Oxyfuel combustion may become a competitor once the efficiency of the overall process increases.

Henrik raised concerns over the cost of pressurisation of flue gas in general which led Stuart to the conclusion that only pressurised CLC should be compared with pressurised oxyfuel combustion, as both are 2nd generation technologies.

Finally, the question regarding the eco nomics of the solid looping technologies was raised.

There was a broad consensus among the panel members that all CaL, CLC and CLOU have the same problem of not being economically feasible yet.

Stuart said that as researchers we can also provide value by providing fundamental understanding of the various physical and chemical processes which take place. It is sometimes hard to say whether an oxygen carrier is better or worse as we are not considering the full economic implications of the benefits/costs. We should be looking to understand mechanisms and causes since this general knowledge will help move the technology forward.

Mike responded that more publications comparing the performances of the different processes are needed. However, one has to be careful when doing cost analyses for different locations, as they may not be suitable for comparison without constraints.

Carlos pointed out he thinks it should not be too difficult or take too long to come up with a first cost estimation using rules of thumb. It is important for new concepts to first believe in the concept itself, then do the necessary research and finally go on to the economics. He also stated that the transformation between heat and electricity is well established and can be used as a basis. In addition it is crucial to gain sufficient data to identify and exclude the non-feasible processes.

Dennis added that similar reactor types and process technologies already exist, so it would be a good idea to approach engineering companies when starting a techno-economic evaluation.

Meeting Conclusions

At this meeting further steady progress is evident in formulation and testing of sorbents, integration of both CLC and CaL processes with an extending range of industrial processes and in the emergence of encouraging first results from larger scale testing of the process in MW scale demonstration units. A better understanding of the science behind sorbent performance is needed to make the search for better materials more effective. There is also an emerging need to develop a set of credible techno-economic performance figures for the technology to justify further and potentially increasing R&D expenditures as phase in which larger demonstration units are required is entered. Finally the environmental performance of the processes needs to be assessed more rigorously especially as this may represent a considerable advantage over competing systems.

Offers to hold the next meeting in Canada or Cambridge (UK) were gratefully received. After considerable debate the meeting proposed to accept the offer from the University of Cambridge (UK) for the 2013 meeting. A decision on whether to hold a meeting in 2014 in view of the plans to hold the biennial CLC conference somewhere in Europe around the same time will be made at a future date. One alternative is to move to biennial meetings.

All participants agreed that this meeting had been most successful and expressed their sincere thanks to the staff at Tsinghua University for their hard work and excellent organisation.

2013-14 SUMMARY REPORT OF THE IEAGHG COMBINED MEETING OF THE MODELLING NETWORK AND THE RISK MANAGEMENT NETWORK

Introduction

At the 2nd IEAGHG Joint Network Meeting, held between 19th and 21st June, 2012 in Santa Fe, it was decided to hold combined meetings of the Networks. The first such combined network meeting was held in Trondheim between 10th - 13th June 2013. It combined the Modelling Network and the Risk Management Networks and was hosted by Statoil, and sponsored by Statoil, SINTEF and CLIMIT. This combined meeting brought together 60 international experts in the field of modelling and risk assessment and management of CO_2 geological storage. The meeting was chaired by Tim Dixon of the IEAGHG and Philip Ringrose of Statoil RDI.

The three day event consisted of a day dedicated to modelling applications; a second day covering a variety of risk management issues and a final day where topics involving both topics were discussed. The meeting was preceded by visits to the SINTEF research facility in Trondheim and the CO_2 pipeline test facility at the Statoil Rotvoll site. During the visit to SINTEFF delegates were shown lab-scale development of new solvents for CO_2 capture and an oxy-fuel combustion test rig.

During the introduction session Tore Andreas Torp of Statoil received an award in special recognition of his lifetime contributions and achievements in progressing greenhouse gas reduction from fossil fuels through carbon dioxide capture and storage. The award was presented to Tore by Tim Dixon on behalf of John Gale, General Manager IEAGHG.

Day 1: Modelling

Session 1: Modelling

How Risk and Modelling are embedded into emerging Regulations: USA EPA and UNFCCC CDM, Tim Dixon, IEAGHG

The IPCC Guidelines for Green House Gas (GHG) Inventories methodology for CCS, shows the importance of monitoring and risk assessment linked with modelling. This concept is reflected in subsequent regulations, such as the US EPA Class VI wells and GHG reporting rules. For Class VI regulated wells there are minimum criteria and risk assessment is core. The criteria are driven

by the necessity for the protection of drinking water, which can be potentially affected by the migration of brine and CO_2. Risk assessment is based on site characterisation and modelling which becomes an iterative process as more data becomes available from monitoring. The identification of potential leakage pathways will always be a challenge as sites are selected on the basis of security of storage, therefore modelling is an approximation and should be seen as qualitative.

The networks have contributed to the United Nations Framework Convention on Climate Change (UNFCCC) when information was needed to progress CCS as part of the Clean Development Mechanism (CDM). Modelling and risk assessment are now included in the Modalities and Procedures for the CDM. There is a recent consultation out to clarify some aspects of the modalities and procedures and procedural matters, some of the UNFCCC proposed solutions cause concern, such as a quantitative criteria for history matching, hence IEAGHG proposes to add:

"History-matching will inevitably show some deviations between predicted and actual behaviours. Whether these constitute a 'significant deviation' should be based upon a risk assessment and expert judgement, and will be specific to the project and the site. Therefore it would be wrong to assign a generic quantitative value across projects to define a significant deviation". The delegates specifically commented that a significant deviation does not necessarily mean unsafe if the phenomenon can be understood and its impact known.

[An expanded version of this statement was subsequently submitted by IEAGHG to UNFCCC].

Development of Standards for CCS, Jørg Aarnes, DNV

There are several reasons for developing standards, including the promotion of an industry standard, harmonisation of regulations, the provision of a transparent basis for independent verification, and offering assurance and transparency to stakeholders.

Guidelines already exist but standards make these into a discrete set of requirements which should be easy to follow. The proposed scope includes the establishment of requirements and recommendations for onshore or offshore geological storage of carbon dioxide to promote environmentally

safe and long-term containment of carbon dioxide in a way that minimizes risks to the environment and human health. The guidance should cover all phases of a project from initial design through to construction, operation, monitoring and closure. It is also recommended that management documents, risk management procedures and community engagement form part of each project. Guidelines should be primarily applicable to saline aquifers and depleted hydrocarbon reservoirs, but not preclude its application to storage associated with enhanced oil recovery (EOR).

Risk modelling should describe a proposed monitoring plan. The proposed risk management plan should also describe the proposed analysis or data acquisition to achieve risk reduction and mitigation measures.

Session 2: Modelling Toolsets

Sleipner Benchmark Dataset and Model Comparison, Sarah Gasda, University of Bergen

The Sleipner Benchmark dataset is taken from the uppermost layer (layer 9) of the Utsira Formation and has been made available to members of the IEAGHG modelling network by Statoil. Injection into the Utsira Formation began in 1996 at ~0.9Mte/year. 14 Mte had been injected up to 2012. Statoil has been monitoring the progress of the CO_2 plume with seismic, CSEM, gravity and seafloor mapping surveys. The plume has now extended over a diameter of 3 km. The reservoir model was calibrated on actual mitigation observed from previous years and then used to predict future migration patterns. When higher temperature and low densities where applied to the model it showed a better match with monitored results. Formation heterogeneity can also greatly affect flow and uncertainty in formation composition and is considered in some models.

38 people have downloaded the data; most have not yet carried out significant work but have found it useful to test simulations. Four research projects have reached a stage whereby their work can be compared. The differences in the models are thought to be related to the flow mechanisms. A number of the models assumed that density changes are the main influence on flow. This is an uncertainty factor related to the temperature changes of injected CO_2. In some cases models can produce a better match to the observed data.

The disparity between modelled and actual migration patterns depends

partly on different types of model and reservoirspecific characteristics which can create uncertainties. The model also needs to be calibrated on the right criteria. The subtleties of modelling need to be appreciated by regulators to ensure that modelling criteria are not prescriptive.

SIMSEQ – Model Comparison Study for Geologic CO_2 Storage, Curt Oldenburg, LBNL

The dataset used in this model comparison study is taken from the Cranfield injection site in Mississippi. In this example CO_2 was injected into the Cretaceous Lower Tusculossa Formation at a depth of 3,300m. The site is part of an EOR field which has a strong water divide and CH_4 dissolved in formation brine. There is one injection well and two observation wells. Six conceptual models have been applied to the site.

There are 15 participating teams. Modelling by six teams has now been compared. There are a wide range of predictions because of different modelling techniques, coupling methods, approaches for multiphase behaviour and interpretations of site data. Sim-SEQ aims to address model uncertainties and examine what causes the differences in predictions made by different modelling teams. An example of differences in a modelled prediction is the arrival time of CO_2 which differs amongst all the models. The arrival of CO_2 has been observed more rapidly than the predicted migration rate. Model predictability needs to include more site-specific parameters including the influence of CH_4 on CO_2 flow. The far-field production, and injection, has revealed preferential flow paths within the reservoir. This quantitative model comparison illustrates that model conceptualisation plays a significant role in deciding outcomes. To improve the model prediction mode site specific parameters are necessary (e.g. relative permeability, entry pressure, residual saturation etc). Ongoing activities include iterative model refinement using observation data, quantitative model comparison and uncertainty analysis, reactive transport modelling, integration with NRAP and extension to other storage sites. It was concluded that some models are based on homogenous assumptions and do not take account of heterogeneity within the reservoir. Reservoir models are also tailored to maximise oil and gas production whereas the timeframe for CO_2 injection and retention is far longer.

Goldeneye dynamic modelling: key approaches and learning, Owain Tucker, Shell

This project is one of the two in the running for the UK's first proposed commercial scale project. It is a depleted gas field designed to receive 2 Mte/ CO_2 year over a 10 year period from Longannet power station, which was cancelled. It will now come from Peterhead gas power station. . Modelling is essential to predict the plume evolution of both mobile and immobile CO_2. It is also important to be able to detect migration patterns within hydraulically connected formations. An analytical approach is important to identify model parameters that can be used to calculate the theoretical CO_2 capacity especially if it is lower than the original reservoir capacity. Full field models allow the extent of geological variability to be incorporated.

A phased approach was used to define and understand physical processes. Each subsequent, and more complex model, was compared to check consistency with simpler models. These included analytical solutions, simulacrum model, full field model, regional model and coupled models.

The key conclusions reached from this study are that a phased approach is useful to understand the physical processes. The validation of physical processes with simple simulation models proved useful. Screening for key sensitivities was followed by the exploration of relevant dynamic variations in full field simulation. It is important that models are built to answer specific questions which needs to be kept in mind throughout the modelling process.

Session 3: Geochemistry and Impurities

Identification of Major Issues related to fluid rock geochemical interaction when modelling CO_2 geological Storage, Joachim Tremosa (on behalf of Pascal Audigane), BRGM

Potential impacts of geochemical reactions are effects on: the sealing integrity of caprocks; clogging or opening of the pore rock structure; chemical effects of leakage through faulted/ fractured systems; impacts on groundwater; and the effects of impurities. These effects have been examined using modelling, lab experiments and observation of natural analogues.

Chemical reactions have been identified as playing an important role in both the efficiency and security aspects of storage. Mineralisation as a trapping mechanism, is relatively minor in sedimentary rock, but becomes significant

mechanism in mafic and ultramafic rock containment sites.

Homogeneous shale/clay caprock appears not to be impacted by CO_2 acidification and diffusion. However, heterogeneity matters especially for features such as mircocracks, fractured rock, faulted systems or near wellbore zones. These weak points remain difficult to simulate.

Numerical modelling can be used to simulate processes over long time scales and the evaluation of coupling processes ncluding fluid-rock interactions on fluid flow properties. Modelling can also be used to evaluate mechanical and sealing integrity of caprock, fault stability and wellbore cement stability. Actual numerical codes have limitations. These include redox processes, high salinity formations and high CPU time which are difficult to incorporate into numerical codes highlighting the need for additional improvements. Mobilisation of trace metal elements, organic compounds and brine concentrations will also have an effect on CO_2 behaviour. Data calibration from demonstration and pilot sites, as well as lab experiments, can improve database content.

Modelling of leakage scenarios enables the characterisation of cement, and clay or shale alteration, to be included. The quantification of leakage rates, and the predicted chemical quality of impacted groundwater, should be improved.

Geochemical Modelling of CO_2 Storage in Saline Aquifers: Examples from Ketzin, In Salah and Snøhvit storage sites; Joachim Tremosa, BRGM

Saline aquifers are choice targets for CO_2 storage, but their salinity differences can have a significant impact on the chemical behaviour of a system which is rarely considered in geochemical modelling. The salinity can affect speciation within the brine and interaction between solute species. Different solution activity models (Debye-Huckel, B-dot model and Pitzer formalism) were considered for each of the three case studies. Overall there was better agreement found for Pitzer databases, although there are still limitations with regard to deviations with temperature and brine composition. Pitzer databases are currently incomplete and contain incoherencies for different species and temperature conditions. The uncertainties in the databases can strongly affect the results of geochemical simulations of CO_2 storage in deep saline aquifers.

Simulating Geologic Co-sequestration of Carbon Dioxide and Hydrogen Sulfide in a Basalt Formation; Diana Bacon, PNNL

This study considered the effect of co-sequestration of CO_2 and H_2S which is what would happen if impurities were not removed. The STOMP-COMP simulator used includes the ability to vary the number of components, vary the compositions in each phase, and is applicable to deep as well as near surface saline reservoirs.

Basalt is expected to be very reactive and H_2S is the most reactive component of the stream. In the simulations, most of the mixture reacted within 30 years with the remainder mostly dissolved. On injection the pH decreases from 9 to 5 and after 30 years it returns to near neutral. There are very similar results for pure CO_2 and a 99% CO_2 / 1% H_2S mix.

The simulation work indicates that basalt formations are a viable option for long term storage of CO_2. Both CO_2 and H_2S are rapidly mineralised. Porosity changes near the wellbore would be relatively small for a pilot-scale injection. The amount of H_2S (1%) injected does not impact on the proportion of CO_2 mineralised but causes variations in secondary minerals.

SO_2 related mineral reactions in Buntsandstein sandstones during CO_2 storage - a geochemical modelling approach, Susanne Stadler, BGR

The COORAL study looked at the effects of impurities over the whole CCS chain. This presentation focused on the impact of impurities on storage formations. The formation considered in the study is the Bunter sandstone formation in Germany which has a relatively high salinity. Pure CO_2 was compared to a 99% CO_2 / 1% SO_2 mix.

The presence of SO_2 favours the precipitation of ankerite at the expense of hematite; and there is more intense feldspar dissolution and related clay mineral precipitation. Less CO_2 is trapped in carbonates due to anhydrite precipitation; however, in the project scenario no significant differences in porosity and permeability changes can be seen when the CO_2 and CO_2+SO_2 models are compared.

Session 4: Modelling Leakage

Process Modeling of Wellbore Leakage for GCS Risk Assessment, Curt Oldenburg, LBNL

Well integrity is a primary concern for leakage from CO_2 storage sites and models have been developed to understand processes that lead to loss of integrity. Different concepts are used for different well leakage scenarios such as using porous media and open-pipe flow conceptualisations of flow. Drift flux models can be used to simulate non-isothermal, multicomponent, two-phase flow in open pipes or annular gaps coupled to a porous media reservoir.

For each concept coupling reservoir, and wellbore processes, it is necessary to understand the variation in the bottomhole pressure and the use of mobile saturation in the reservoir. There are a number of risks to take account of including: the diffusion of CO_2 into cement; the cathodic reactions induce by carbonic acid; and gas exsolution and decompression cooling caused by the release of CO_2 from a supercritical phase both of which can affect upward leakage.

Modelling Scenarios for Low Probability CO_2 Leakage, Richard Metcalf, Quintessa

A well chosen and operated CO_2 storage site is unlikely to leak, however, cautious and realisitic scenarios and models are necessary to understand and communicate risks. Stakeholders often request 'worst case' scenarios, however this is often not useful in demonstrating, understanding or putting together mitigation plans. What is required is expert judgement which is necessary for assessing the combined significance of quantitative and qualitative uncertainties. The identification of features, events and processes (FEPs) that can be represented in scenarios is also required. The specification, representation and allocation of model parameters needs to be clear to ensure that the significance of modelling results can be communicated.

This study used a 'top-down' approach, whereby the big issues were considered and details added. An example was presented from the RISCS project of one of the 'cautiously realistic' scenarios. In this case there is a localised release to soil as a result of wells/ faults/ fractures, leading to high concentrations of CO_2 in the near surface. In this scenario a realistic flux rate

shows relatively low impacts comparable to natural variation which is similar for fluxes ranging over several orders of magnitude.

Modelling CO_2 leakage through faults, Rajesh Pawar for Elizabeth Keating, LANL

Fault-leakage scenarios need to be considered as there is always the chance that faults could be undetected by subsurface characterisation and, even if existing faults are benign flow barriers, CO_2 injection could potentially lead to changes in fault permeability.

Estimating CO_2 fluxes in leakage scenarios can be based on studies of natural systems or multi-phase flow simulations based on measured or assumed fault architecture, reservoir pressures and CO_2 saturations. Risk assessment calculations assumed CO_2 mass flow rates along faults are much greater than natural CO_2 mass flow rates along faults in highly active systems which may not be possible. Many natural CO_2 release sites are emitting approximately as much CO_2 as would be deemed 'acceptable' by IPCC standards. These sites are worthy of further study as analogues. Ongoing work suggests unintended and significant caprock breaches by fault activation would not release the majority of stored CO_2. The presence of faults could add to the risk which highlights the necessity for accurate site characterisation.

Geomechanical and Hydraulic Modelling of Faults for Stage 2C Injection at the Otway Project, Charles Jenkins, CSIRO on behalf of Eric Tenthoray

This study modelled the splay fault near the Otway injection project to investigate the minimum mass of CO_2 that can be detected seismically. Secondly if the plume were to reach the fault would it be reactivated; and thirdly if CO_2 were transmitted through the fault, how far would it be transmitted.

Fault stability modelling considered scenarios for both strong and weak fault conditions. For a weak fault, more than 1MPa is needed to move the fault, which is unlikely as this is a small injection into permeable sandstone. Shale Gouge Ratio Modelling, used in this study, determined the degree of clay smearing on different parts of the fault. The model showed that the fault is sealed to some extent by clay smearing. Leakage up the fault was modelled as there are several permeable formations above the storage horizon. CO_2 migration is more likely to migrate into permeable saline aquifer horizons

rather than up the less permeable fault zone. Modelling simulation shows CO_2 transgression across the fault. This opens the question as to how much CO_2 could cross the fault. In conclusion, modelling indicated that fault reactivation is not possible under the Stage 2C injection scenario and upward migration of CO_2 through the splay fault will be very limited. Faults could act as barriers or conduits for CO_2 migration. This is a potential area for future research.

Session 5: Uncertainty in Modelling

Effect of stress field uncertainty on Modelling geomechanics and seal integrity for CO_2 storage sites, Laura Chiaramonte, LLNL

Knowledge of the stress field is necessary to understand and calculate caprock integrity as well as fault and fracture reactivation; which can cause induced seismicity and potential leakage through created pathways in the overburden. Stress field data can be determined from the orientation of wellbore fractures, earthquake foci, shear velocity anisotropy and hydraulic fracture orientation. The stress uncertainty in the Snøhvit storage site is a good example of a site where uncertainty was lower than expected. The stress uncertainty differed by up to 90° compared to the reported SHmax.

The strong stress uncertainties lead to difficult predictions. Faults are fairly stable under "most likely" stress state: SS & NS SHmax. Caprock failure would happen before fault reactivation. Under these conditions it is unlikely that a theoretical sub-seismic fault could act as a flow barrier; and faults are ~ 30% less stable with EW SHmax, where several segments are close to critically stressed levels.

Combining downhole data to reduce modelling uncertainties in the CO2CRC Otway Project, Charles Jenkins CSIRO on behalf of Jonathan Ennis-King

This experiment created a region of residual CO_2 around the well followed by an injection of 150t of pure CO_2, followed by injection of formation water pre-saturated with CO_2. Heating tests and residual saturation and wells tests, with noble gas tracers, were conducted before and throughout the experiment with additional tests using reactive ester tracers and dissolution tests. Different techniques were used to test trapping depending on the distance from the injection well. Site data was used to validate models. The CO_2/H_2O distribution in the wellbore was variable. Temperature readings were also variable due to heat convection.

The experiment successfully injected CO_2 and drove it to residual saturation. Uncertainty in formation characterization is reduced by analysis of baseline tests and matching far-field and near-well properties. Uncertainty in wellbore fluid distribution is reduced by combining data from multiple P-T gauges, DTS and RST logs. Pressure analysis gives Sgr 15- 19%, noble gas tracer analysis gives Sgr 11-20%, and RST gives Sgr ~ 20%.

Pressure uncertainty and the Implication for Risk, Karl Bandilla, Princeton University

The probability of leakage will depend on the presence of potential leakage pathways and a sufficient driving force. Potential leakage pathways consist of faults and wells, where there is uncertainty in subsurface leakage pathways. The area of review can be reduced by an order of magnitude by using brine producers to lessen the pressure increase and therefore the area where leakage may potentially take place.

Uncertainty in basic parameters may have large impacts on risk and active pressure management. For example, optimal permeability for injection declines with depth. Saline could be re-injected into other formations but this approach would require a large number of wells to manage displaced saline fluid.

Uncertainty in modelling raised some important issues. A large number of variables need to be taken into consideration. To overcome uncertainty data acquisition is necessary to build high levels of confidence for large-scale CO_2 storage. To reduce uncertainty investment is required, an approach analogous with reservoir appraisal in the oil industry. However, oil and gas have commercial value, which can be quantified relative to production costs, whereas CO_2 is a disposal cost fixed by regulation or other mechanism.

To reduce uncertainty it will be necessary to hone in on critical areas to understand reservoir characteristics and CO_2 migration. Even with multiple data sources, modelling may not be able to adequately predict CO_2 behaviour. Information for risk evaluation may not be adequate or it may be in the wrong format. Models may not be fit for their intended purpose especially as the field becomes more mature. Maintaining essential data will be critical for reservoir management.

Session 6: Modelling Conclusions

The understanding of CO_2 storage is improving but there is still a knowledge gap, for example, the roll of faults in migration. The use of models, especially their predicted outcomes, can provide useful insights. Models can be used to reduce uncertainties and prompt questions about migration, leakage and reservoir management, however, models are not necessarily good for predicting CO_2 migration behaviour.

Modellers need to communicate the validity of the conclusions that can be drawn from their use and not the technical complexities that are associated with this approach. Regulators need to understand why certain approaches are taken and how modelling can be used to predict outcomes. They should be discouraged from becoming too focused on unsophisticated problems that are perceived but unlikely to occur. Regulators could be trained in modelling so that they understand complexities better. This approach could include a comparison of a range of scenarios and comparison with other long-term environmental disposal initiatives such as waste water and radioactive material.

Day 2: Risk Management

Session 7: Projects and their Applications of Methodologies

Quest and Goldeneye risk assessment – focusing the monitoring and additional safeguards on key areas, Owain Tucker, Shell

Quest is a fully integrated saline aquifer CO_2 storage project which included injection into basal Cambrian sands below hydrocarbon potential and faults. This is a multi-barrier site but monitoring helps to ensure containment. Risk management ensures a systematic evaluation of passive safeguards, for example, avoiding seismicity. All potential risks need to be reviewed by checking whether previous events like leakage form previous water injection events have occurred. The monitoring programme is based on a plan to detect injection / leakage from a series of monitoring techniques.

Risk assessment for Quest and Goldeneye was not centralised and the teams independently used the same Bowtie assessment technique, although this approach was slightly differently in each case using different packages, but with the same idea. Each team looked at passive and active safeguards.

They used passive safeguards to look at potential migration pathways and then built active safeguards. There was a systematic evaluation of passive safeguards to determine how effective each is and whether a backup active safeguard is necessary. An active safeguard must have detection, decision logic, and a control response in order to be valid. The combination of active and passive safeguards further decreases the potential for leakage.

Monitoring techniques are being evaluated to determine their effectiveness with support from the UK's Energy Technology Institute. There is also a cost-benefit consideration. For example, seismic can effectively cover a large lateral area and different layers within target formations but it is an expensive technique. Monitoring tool responses need to be independent to be effective. As more information becomes available from different tools risk needs to be reassessed such as with InSAR. At the Quest site there is a deep monitoring well close to the injection site to detect factors such as induced seismicity.

A key conclusion from this work is that demonstration is essential. Goldeneye has held gas in a reservoir for 50M years so CO_2 could be held for 50M years, but gas extraction changes the reservoir characteristics. There are subtle changes caused by extraction and reinjection which need to be evaluated, tested and communicated. This is another example where it is essential to outline what is involved with CCS.

Mapping of Norwegian CO_2 storage sites- how risk is approached, Eva Halland, Norwegian Petroleum Directorate (NPD)

Storage atlases for the Norwegian North Sea and the Norwegian Sea have been produced with one on the Barents Sea in progress. The biggest risks that have been identified are economic and political but this project focuses on geological risks. NPD have access to all offshore data and have mapped down to 3,000m, concentrating on deep saline formations, water filled structures, abandoned hydrocarbon fields and producing fields.

21 saline aquifers have been explored. Capacity estimates are based on pressure build but exclude water extraction. The main risks are from potential leakage points, faults, fractures and old wells. Risk assessment for each potential site covers reservoir quality and seal quality. The potential effects on adjacent petroleum provinces were also evaluated. No geochemical data has been included. A characterisation system was created to rank reservoir

quality for storage. If all the best sites were selected and there were a series of mass injections they would all become part of a regulation programme.

Risk Management Process for the SECARB Anthropogenic Test, Jørg Aarnes, DNV

This is a full chain project involving capture from a coal fired power plant, transport along a 12 mile pipeline and storage into a deep saline formation. This project involves different companies involved in different sectors of the power generation – storage chain who all have different concepts of risk. For example, a risk assessment for a power plant will be more quantitative, whereas the oil and gas industry needs to be able to deal with greater uncertainty. There needs to be a collective recognition of opportunities and risks that can impact on integrated operations. Coherent plans for effective risk management, plus transparent and traceable documentation, will be required.

Significant and tolerable risks were defined which have been reduced. 70 actions were recorded initially: 53 were closed; 19 are in progress; and 7 are active. The top ranked risks were initially related to permitting, injectivity and containment, modelling and monitoring, reliable operations, pipelines and wells. By May 2013, after the project had been operating for 9 months, these risks had been greatly reduced. The top remaining risks are: possible loss of containment; reliability of operations; post-injection MVA; and closure. Some of the key challenges on the project have been the permitting process, which has been more lengthy than expected, and execution of contracts between organisations. One of the most important lessons learnt was that communication between partners is essential from the start.

Applying the MANAUS Risk Assessment Methodology to Fault leakage scenarios, Yann Le Gallo, GeoGreen

The aim of this project was to develop a common operational methodology and risk management for CO_2 geological storage within the context of French regulations. It considered surface installations, different elements of the geological system, and the well system. A functional analysis according to several criteria in space and time was also performed. An example of a leakage event along a fault was presented which included the possible causes, consequences and targets. The iterative risk analysis included preliminary risk assessment and analysis, detailed risk analysis, scenario

and risk evaluation, risk mitigation actions plus probability and uncertainty assessment. In this case pressure propagation across a fault is difficult to predict and therefore there is a need to know how reservoirs will respond in order to quantify the risk. The influence of key drivers on CO_2 migration and pressure propagation was investigated using commercial modelling tools. AS an example the probability of pressure propagation along and across the fault was computed to enable risk quantification.

Session 8: Mitigation and Remediation

Impacts and input from Environmental Assessment meeting, Tim Dixon, IEAGHG

Understanding potential environmental impacts of CO_2 leakage is particularly important for any risk assessment of a CO_2 storage project. Some of the main outcomes of the last network meeting were that Environmental Impact Assessment (EIA) regulations are not proving a barrier to projects. EIAs are different for offshore compared with onshore and there are a good number of controlled release projects and associated knowledge. There has been significant progress with marine projects including the collation of baselines and monitoring (AUVs).

CO_2 release behaviour is not always as expected. If leakage occurs it is patchy, and in small spots, but not over large areas. Onshore electro-magnetic remote monitoring of brine can be used for 'early' leakage detection. Process-based techniques for monitoring are moving in right direction and less baseline data are needed; however, baselines for leak detection and impacts are still required.

Indicator species are being identified, especially benthic and terrestrial plants. Seasonality and timing can affect leakage impacts. There has been a broader acceptance of near-surface monitoring.

CO_2 emission monitoring from the sea floor has been carried out at shallow depths of ~1m but not at 300m where CO_2 solubility is much higher. Plymouth Marine Laboratory (PML) is able to obtain seafloor samples, including a 1m column of water, at these depths. A CO_2 release at 1,000m has been undertaken by Montreay Lab in the US. Controlled releases of onshore CO_2 have also been tested. Heterogeneity within marine sediments can cause unpredicted dispersal of CO_2 gas releases which can be difficult to detect and

could be missed in future monitoring programmes.

Methodologies and Technologies for Mitigation of Undesired CO2 Migration in the Subsurface, Niels Bo Jensen, IRIS

The aim of this project was to review the state of knowledge of novel and standard mitigation and remediation practices, and associated costs, and to review current mitigation plans in place on past, present and future CO_2 geological projects. Migration pathways considered can be man-made (e.g. wells) as well as natural (e.g. caprock defects, faults/ fractures). Mitigation measures were categorised as: interventions on wells; fluid management techniques; breakthrough and novel technologies; and remediation measures on potential impacts. To select the most suitable action the maturity, efficacy and the cost of the mitigation measures need to be considered. This is highly site specific and situation dependent. When actual projects are considered the mitigation plan needs to be integrated with the risk assessment and monitoring plans. These plans need to be designed by experts and reviewed by stakeholders especially as there are diverse formats which are dependent on regulations.

Brine Extraction and Pressure Management, Charlie Gorecki, EERC

The aim of this project was to develop an understanding of realistic CO_2 storage water extraction rates and volumes. It also identified appropriate treatment technologies, and potential applications for the beneficial use of extracted water; and analysed the economics of water extraction plans implemented at different case study sites. An assessment of the global regulatory environment and the identification of potential obstacles as also performed.

Some of the main observations are dependent on site-specific geology and injection scenarios. Increases of 4% to 1,300% in CO_2 storage capacity have been observed. In most of the scenarios, CO_2 plume movement was observed with water extraction. This resulted in larger plumes in terms of areal extent but also increased storage capacity. Generally, reservoir pressure is reduced by around 10% to 20% with extraction, depending on the site and the scenario. The influence of water extraction on pressure and free-phase CO_2 plumes was observed in each of the storage–extraction systems. However, for the purposes of reservoir pressure and plume management, water extraction is best applied to reservoirs with low structural control.

An injection - extraction combination is required to achieve high CO_2 quantities (150 mt/y). Careful selection is therefore required to optimise CO_2 injection and simultaneous brine extraction. Site-specific conditions are highly influential. This exercise has shown that at some sites, for example, at the Teapot site the water source could be treated and used as coolant water for the power plant. At Ketzin the salinity of the formation water is too high and the only option is reinjection. District heating and Lithium extraction are other possibilities. The modelled extraction flow rate at this site needs to be four times greater than the injection rate for CO_2 to manage the reservoir pressure.

Using the water for beneficial use is highly dependent on the end users and the climate and in most cases it is not likely to be economical. To achieve pressure reduction by a significant amount the quantity of extracted water is usually higher than the quantity of injected CO_2. This phenomenon is attributed to the heterogeneities within the storage formations.

Advanced Risk Mitigation Strategies for Active CCS Projects, Sallie Greenberg, ISGS

The Decatur project is an active CO_2 storage demonstration in the Illinois basin. 1Mt/CO_2 has been injected over three years into the basin's Mount Simon Sandstone which has highly variable porosity and permeability properties. The risk assessment included a large number of variables and refinement of potential risks to cover pre-injection and injection monitoring above and in the reservoir. Heterogeneity within the reservoir affected the CO_2 migration. The shape of the plume was pancake shaped not a predicted pumpkin shape. Modelling had underestimated the rate of plume development. 75,000 te of CO_2 were injected before the plume was detected by seismic. The plume is controlled by the reservoir's pressure boundary and very porous sand channels within the reservoir.

A second project will have two wells about a mile apart. The team responsible for this second phase have developed a compliance plan that includes crisis management and media interaction. Staff have been given training in crisis management linked to the project. Active plume management based on detailed reservoir characterisation is also planned.

Session 9: Risk Communication

Communication of Geological Risk, Svein Eggen, Gassnova

Public understanding of risk is often complex, based on many factors, and often based on misconceptions from media images. Even if a risk assessment is perfect from a technical perspective it does not mean that the public will agree with it.

Communication needs to be simple but not overly simplistic and should be based on facts and evidence. Is it important not to strengthen peoples' misconceptions. Myths need to be replaced with facts and if possible explanations should be presented in a way that aligns with peoples' worldviews. Projects should also be described within the wider context of climate change. An important part of communication is the trust of the communicator, therefore choice of communicator is important.

CCS Risk Communication in the Canadian Prairies: Who Cares? Tim Dixon, IEAGHG on behalf of Neil Wildgust, PTRC

The Aquistore and the Weyburn-Midale projects have been associated with a false allegation of leakage. This experience shows the importance of baseline data in communication. Ensuring clear communication between projects, and the engagement of scientific experts who can address issues quickly is also vital. Key stakeholders need to be identified and contacted about any planned course of action before a projects start. Contacting individuals in the media is essential, especially journalists who understand and write clearly about science, ahead of the release of any results. There also needs to be a thorough understanding of the wider repercussions of potential incidents.

One of the main lessons from both projects is the importance of understanding the views of the local people and communication with them from the start of the project. Consultation with local communities about risk, and what can be controlled, is therefore essential. Local monitoring can help to re-assure the local community, however, the myth of leakage is difficult to shift even when disproved.

The Hugin Fracture, Anne-Kari Furre, Statoil

In the summer of 2011 a 3km long sea-floor fracture feature was discovered in the middle of several producing or postproducing sites 25 km north of the Sleipner CO_2 injection site. This discovery was part of the ECO_2 project

and formed part of the work package to 'identify potential pathways and the likelihood of leakage from storage sites through the sedimentary overburden'. Statoil have access to pre 1996 seismic data where the fracture is visible. Channel features can be seen on timeslice data and the fracture is thought to be part of an extensive system of sub-glacial channels and tunnel valleys. The escaped fluids from the fracture are a mix of dissolved methane and glacial water. There is no indication of CO_2 leakage from seismic data which suggests that the feature is not connected to the Sleipner field.

Gas seeps are widely known throughout the North Sea, but this is the first time that they have been observed directly at this level of detail on the sea floor. The discovery of the Hugin fracture will be useful for testing and the development of cutting edge monitoring technology.

Public communication of CO_2 storage site risk, Jens Hetland, the European CCS Demonstration Projects Network

This presentation gave an update of the European Energy Programme for Recovery (EEPR) initiative as well as the lessons learned from it. Within the EEPR project six Front End Engineering Designs (FEEDs) have been completed; although there has been no Final Investment Decision (FID) and two projects have been cancelled.

Perceived risks differ from actual risks. There is a necessity to convince the public of the urgency to progress CO_2 abatement. With renewable energy it is easier to communicate the benefits, but with CCS there are uncertainties. It is not always clear that renewables also have limitations, for example, the large surface area required for wind energy.

Public perception and issues vary between different countries. For example in Italy the link between CO_2 and climate change needed to be explained. The timing of communication is important otherwise misconceptions can be generated.

For example a seismic survey for Compostellia in Spain was commissioned for CCS and not oil and gas exploration.

Engagement with the public must ensure that the audience is understood and listened to. Projects must ensure that stakeholders have a reasonably good understanding so that they will not be surprised about specific

developments at a later date.

Projects should help stakeholders to contextualise risks. The project leaders must address stakeholders concerns, for example, why the Rotterdam Capture and Storage Demonstration (ROAD) project went offshore; and why the proposed Don Valley project provides options for stakeholders. The use of experts as messengers for a project may be important, subject to communication training. Communication experts were not trusted in these projects.

Info-graphics can be a good tool, but they should be checked for accuracy and include comparative scales that can be easily understood. The use of terminology is also important and should be consistent, for example the use of CO_2 and carbon dioxide interchangeably should be avoided. The significance of CO_2 should also be explained.

Session 10: Risk Management Conclusions

There needs to be more debate and public discussion about mitigation with examples from other industries. Comparable examples such as gas storage would be helpful although gas is a valuable commodity. Internal communication, particularly planning ahead and simulating a major incident can provide significant dividends for teams directly involved in CCS.

There is genuine benefit from real projects, for example the controlled release of CO_2 which revealed unexpected behaviour. In this instance the pattern of gas emissions has provided a better understanding of gas migration and release in a natural environment. Learning from projects provides valuable information for future planning and it provides a better understanding of the processes the govern gas injection, migration and release. Full-scale industrial demonstration is essential.

There are competing methods of risk assessment. How risk assessment is presented to the public is crucial especially conveying uncertainty and the long-term retention of CO_2 in storage. Risk assessment methodologies need to be fully auditable. Criteria for risk assessments also need to be unambiguous so that monitoring and auditing can be transferred to different organisations and individuals especially given the timespans involved. Regulation is another factor that needs to be considered as it may force different types of

risk assessment.

Mitigation measures need to be immediate to contain problems.

Examples of successful CO_2 storage, especially where there has been public engagement, need to be publicised. Public acceptability will be necessary especially for onshore sites. Public ignorance of energy and related environmental issues, such as CO_2 emissions, needs greater explanation. Setting an annual energy budget is as a means of emphasising the importance of energy supply and demand. The risks measured against the benefits of CCS are not always clear.

Session 11: Risk Management Case Studies

In Salah CO_2 Storage Project: Lessons Learned, Phil Ringrose, Statoil (In Salah JIP project team)

The initial plan at In Salah was to inject 1Mt/yr into a depleted gas field in a Carboniferous sandstone reservoir 20m thick. The actual injection was 0.5Mt/yr. 4Mt CO_2 has been injected significantly below design capacity. The CO_2 injectors are around the periphery of the field. Injection began in 2004. The site has been subject to extensive monitoring to ensure that there was a good baseline. The use of shallow observation wells for microseismic monitoring were integral to the project. 3D seismic surveys were conducted in 2004 and 2009. This is expensive but essential to track the CO_2 plume. InSAR surveys (Interferometric Synthetic Aperture Radar) have also been conducted. The technique works very well in dry rocky regions such as this part of the Sahara. The surveys are highly sensitive and can measure uplifts of mm scale at the surface. An uplift of cms has been detected between the reservoir and the caprock. Methods were selected using a cost-benefit analysis. Seismic acquisition, though very expensive, was vital for many operational decisions. It was implemented at the start of the injection programme whereas InSAR was started mid-project.

Velocity pull down features were predicted and hydraulic fracturing caused by CO_2 injection. Microseismic monitoring was able to differentiate between different modes of mechanical deformation. Monitoring was also able to detect events related to CO_2 injection. To fill the reservoir to capacity (with a permeability of 1 – 10 mD) CO_2 would have to be injected at fracture pressure or higher. Project monitoring, particularly from InSAR data, revealed

an unexpected rise in pressure and surface deformation. Geomechanical modelling was able to show a fracture at the top of the reservoir which extended into the caprock. In June 2011 the decision was taken to suspend injection when this feature became apparent. The caprock integrity was not jeopardised and the fracture served to increase storage capacity. Even though the technical risks were considered low injection was not resumed. The political risks associated with the perceived risk to a potable aquifer above the storage formation outweighed other considerations.

Important new surface monitoring methods and good baseline data, including that generated from satellite InSAR, has been especially valuable. Monitoring programmes need to be adapted during operational phases and should be part of the Field Development Plan. Risk assessments should be conducted as part of regular operational and monitoring strategies

Injection strategies need to be linked to detailed geomechanical models and related stress fields within the site.

Snøhvit: Injecting and storing 1 Mt CO_2 in the fluvial Tubåen Fm, Olav Hanson and Douglas Gilding, Statoil

The Tubåen Formation was initially identified as the storage reservoir for CO_2 from the Snøhvit field. This is the lowest and most permeable formation closet to the Snøhvit field. The formation consists of three main sands with interbedded shale. This gas field contains ~5% CO_2 which was reinjected at a rate of 80te/hour (equivalent to 2,000 reservoir m3/D). Gas production started in August 2007. Injection commenced in 2008 and was terminated in April 2011. There was a pressure drop as gas was produced and CO_2 reinjected. A comparison of volumetric flow from 4D seismic monitoring showed 80% of injected CO_2 flowed into the higher permeable sandstone (3,500 mD). Seismic monitoring has shown that reinjection has been safe and it has verified the storage, but there has been a revised injection strategy.

Injection of CO_2 into the lower reservoir caused the pressure to increase to a level close to the fracture limit. Injection was stopped and gas was extracted to reduce pressure. CO_2 injection was resumed but into the shallower and more extensive Stø Formation, which was identified as a backup reservoir. 1.6 Mt CO_2 has been injected to date and monitoring has continued. Part of the planned mitigation was not to exceed the injection pressure threshold. There

is only one injection well which limits the injection rate and CO_2 injection is above the gas producing horizons.

Session 12: How Risk Information Informs Modelling – and Vice Versa

Quantitative risk assessment approach by NRAP: making probabilistic predictions utilising numerical models, Grant Bromhal, NETL and Rajesh Pawar, LANL

This project focused on the development of reduced order models (ROMs) and their linkage to (integrated assessment models) IAMs. Sensitivity analysis is used to identify key variables that control component behaviour. The developed ROMS are then validated against simulations.

A science based quantitative risk assessment approach for geologic CO_2 storage sites is being developed. IAMs that can be used to quantify risk profiles for CO_2 leakage related risks have been developed. A systems modelling based approach, and the behaviour of system components, are captured through abstractions from detailed process level simulations. Developed risk profiles are being used to answer questions related to CO_2 storage site feasibility and longterm effectiveness. IAMs can be used to help quantify uncertainty and identify most sensitivity parameters for leakage. For low wellbore spatial densities, wellbore cement permeability is the most important factor. This effect is independent of sandstone or carbonate aquifers even if their underlying processes (flow and chemical reactions) are taken into account. For higher wellbore spatial densities other factors, such as the shallow aquifer porosity and permeability, had a more significant effect.

Higher confidence in modelling should be possible with long term modelling which will be necessary to predict CO_2 behaviour over 1,000+ years. Modelling will also be needed for leakage prediction. With increased heterogeneity it is difficult to predict CO_2 movement. Evidence shows CO_2 plumes move further and faster than predicted. Uncertainty therefore needs to be incorporated into projections. The range and type of errors that are to be expected need to be identified.

The use of models can lead to uncertainty but greater data acquisition will help to verify predictions. Variability and uncertainty need to be properly understood. The industry and regulators should not get distracted on simplistic scenarios. They need to have a broader perspective of CCS.

Educating regulators to ensure that they fully aware of the current status of CCS is essential. This already happens in Norway and the US.

Minor issues, for example, raising ground levels by mms is of concern to land owners and developers so their needs have to be taken into consideration.

There needs to be a long-term repository for monitoring and data acquired from CCS sites to ensure continuity and good knowledge transfer. Learning from more demonstration sites, and the interpretation of data from different investigative techniques and processes, especially seismic, geomechanics and plume movement will build greater confidence in long term storage development.

How Modelling Fits in Risk Management, Rajesh Pawar, LANL

Modelling can provide information at various stages for different stakeholders, such as site feasibility calculations (e.g. capacity, injectivity), permit applications (to determine AOR) and site design parameters (injection rate, no of wells). Modelling can also be used to develop monitoring strategies (identifying which techniques that can be deployed and timing of their application). Mitigation strategies (development of leak/ impact mitigation approach), as well as post injection site closure (how long should it be monitored), can be developed from modelling. This will help to build confidence in long term strategies. However, it is necessary to understand how a quantitative risk assessment can be applied to ensure a high degree of confidence in modelling approaches and the magnitude of associated uncertainties.

A common uncertainty in model performance is plume development, which is generally under-predicted. The challenge of model application is the level of confidence that can be placed on predicted CO_2 behaviour and the timing of different processes. The extent to which different parameters affect uncertainty adds further complexity and ideally needs to be understood.

Iterative interplay between numerical simulations and risk assessment, Phil Jagucki, Schlumberger

At various points during a project there will be opportunities for input from new information. Results of calculations can be updated and model parameters adjusted. Any re-evaluation should always require expert judgement. A group of experts were asked to evaluate porosity and permeability from well

offset data. The results they produced were all very different.

If a plot of the relative frequency of an occurrence against a specific parameter (e.g. plume diameter) is generated, a narrow band of the most likely outcomes will not encompass the majority of outcomes; whereas a broadband of options is more likely to contain a more realistic solution.

Making decisions when monitoring data confronts the model, Charles Jenkins, CSIRO

Monitoring data is likely at some point to give false positives. Expert judgement is therefore necessary to decide when an action needs to be made. Decisions need to be based on which of the risks are more probable in light of the available data. Specific predictions are required to determine what will happen if the risks eventuate.

It is necessary to be aware of sensitivity and false alarm rates. The probability of the various risks is relevant and should be include. More reliable data are needed to give credence to an a priori unlikely event. Statistical information (distribution of errors) is extremely relevant and should have as much empirical backing as possible. Understanding background variation is important especially if there is an anomaly. Pre-characterisation is therefore essential. There is also a requirement for a long-term repository of monitoring data from CCS sites.

More integration from different investigative techniques, including seismic and geomechanics, will help build collective understanding of phenomena such as plume development.

Session 13: Panel Discussion: When does Uncertainty Matter?

Update from NRAP Stakeholder meeting, Grant Bromhal

NRAP activities are aimed at reducing uncertainties and include several aspects including: the estimation of potential release volumes by evaluating a range of scenarios; the determination of potential groundwater impacts by assessing a range of scenarios and aquifer types; the localised impacts on the atmosphere deduced from the evaluation of coupled processes; and the clarification of potential release volumes.

The introduction of Class VI regulations for wells has caused an increase in monitoring costs, mostly due to the requirement for a 50 year post-injection

monitoring period. This will need to be taken into account as part of risk assessments.

Stakeholder feedback included: a learning curve for agencies and reviewers; uncertainty in calculating Agent object Relationship (AoR) modeling; field consolidation; PISC length, the length of insurance and risk as a function of injection quantity. The feedback also considered what could authorization to inject look like and what does authorization for closure look like. It was concluded that there is always going to be uncertainty.

Panel Discussion - When does Uncertainty Matter?: Phil Jagucki, Schlumberger; Grant Bromhal, NETL, Charlie Gorecki, EERC; Andy Cavanagh, Statoil; Rob Trautz, EPRI; Jørg Aarnes, DNV

There are a number of uncertainties now impinging on CCS. For a utility perspective uncertainty has slowed progress. Only one new coal fired power plant was commissioned in 2012. There is no federal carbon trading system or climate change legislation or regulatory framework for CCS. Costs have also continued to increase. The estimated cost for a 1,600 MW coal fired power station has risen from $US4.4B to $US11B if CCS is included. Utility companies could consider the use and sale of CO_2 for EOR, fertilizer production or other applications. But selling into three different markets, all with different technical and commercial criteria, creates complications for any investment strategy. Investing in CO_2 storage also causes difficulties for a utility because there is a strong possibility of uncertainties created by natural heterogeneity within the site. Consequently it may not be possible to guarantee storage capacity or limit it to more conservative thresholds. There is a broad range of well costs of between 40 – 70% further adding to future uncertainty in cost.

Projecting the costs and performance of new sites will be speculative unless there is sufficient data and site characterisation. However, the understanding of the technical challenges should improve through time. Uncertainty will be greatest at the start of the project but diminish as injection and monitoring progress. There are examples where risk has been judged to be too high and caused potential projects to be abandoned. For example, Fort Nelson, where CO_2 was to be injected into the water leg of a depleted gas field. The movement of the CO_2 into the gas field was considered to be too risky and the project has not proceeded.

From a project manager's perspective, modelling objectives are different for different projects and for different stakeholders. For one project disposal of CO_2 from a gas processing operation into a gas field in close proximity was under consideration. There was a high degree of certainty that the aquifer was far enough away from the gas field, due to a large enough pressure sink, but to give a 100% certainty of no interference the storage site was shifted further away. For another project, there is uncertainty with compartmentalisation. In this case could injected CO_2 affect a nearby oilfield. Uncertainty is not necessarily bad, but there is concern where it could prevent good decisions or where there is a perceived consequence.

Uncertainty in plume shape and direction can affect the monitoring design. There needs to be intelligent interplay between modelling and risk assessment and modelling needs to encompass these uncertainties. If there is leakage the ability to detect it will depend on where it occurs and the rate of leakage. If there is uncertainty in storage capacity assessment needs to be based on how factors affect the capacity limit.

A reward system needs to be in place to encourage investment in new projects, but this incentive is only in place in Norway. If there is potential for a large upside, then operators will need to be prepared to incorporate uncertainties and manage risks, but the business philosophy around CO_2 storage requirements is different from the oil and gas industry. The majority of uncertainty is not technical but political, economic and regulatory. There are tools and methods, which can be adapted and updated, so it is important to be able to communicate technical understanding to financial, political and regulatory stakeholders.

Leakage can be detected through a containment monitoring programme, but the sensitivity of the programme needs to be considered to ensure detection of low levels of leakage. The detection threshold will depend on the number of wells and the scale of the CCS site. It will be necessary to monitor the extent of plume development especially if there is a risk that it will extend beyond the permitted boundaries. Predicting movement needs to be part of any mitigation strategy. Modelling can be used to manage uncertainties for example plume development over time. However there will need to be a high degree of confidence that the CO_2 remains in place.

Future CCS programmes need to take account of the unavailability of insurance. Insurance is not offered because the uncertainties are too high. Under these circumstances liabilities associated with CCS become federal government liabilities. In the state of New Mexico there is a carbon tax to fund liabilities associated with CCS.

If there is a lack of reward then projects are unlikely to proceed. BP have now moved away from a number of projects. The company was actively engaged in one offshore Australian project but this has not proceeded because of geological uncertainty. Norway is the only country where there is an active incentive to proceed with CCS. The Snøhvit CO_2 reinjection was driven by a business case i.e. avoiding a penalty for CO_2 emissions.

An example was given of a permit for the use of CO_2 for EOR. The oil company has no intention of using the depleted reservoir as a Carbon sequestration site. This would mean transferring the site from a Class II to a Class IV permit with aseries of additional requirements. (but if CO_2 is used for EOR would the technical issues be the same depending on the capacity of the EOR programme). This example also raises the question of whether CCS liability can be transferred across different jurisdictions for example between different states. It would be useful to raise these issues with financiers to get the perspective of potential investors.

The use of CO_2 in EOR also needs to take account of reservoir compartmentalization. Uncertainty needs to be evaluated but it should not lead to bad decisions or no decisions.

Risk evaluation depends on a number of components which need to be assessed as inter related issues i.e. a bow-tie approach.

Session 14: Risks due to Geomechanical Effects

The majority of induced seismicity observed from different sites has been mostly of a low magnitude, however, microseismic monitoring has been found to be particularly useful at a number of sites by enabling previously unmapped structures to be identified. It has also aided the assessment of caprock integrity. There are lessons from other industries where induced seismicity has occurred including mining and geothermal. Induced seismicity potential should be part of the risk assessment. It can be managed by

effective reservoir and injection engineering and by careful and effective site characterisation and selection.

The NRAP programme has been looking at a common method that can be used. A phased approach has been suggested.

Integrated microseismic monitoring and injection history analysis at In Salah CO_2 storage site, Algeria, Bahman Bohloli, NGI & Volker Oye, Norsar

There was a sharp uplift at the start of the injection period and indications of slight subsidence a few months after injection stopped. Microseismic events were recorded, but they were very small, the largest being M1. The occurrence of seismic activity before injection is not known.

Geophones were lowered into a shallow well but only one detector at 100 m worked. This makes identification of the location of seismicity very difficult. 200 events per day were recorded at the height of the injection programme and over 5,000 microseismic events were detected during the microseismic monitoring period. There was a high correlation between the occurrence of microseismic events and the injection rate. Only 1 – 2 events were recorded post storage. RSQSim code was used for modelling natural seismic events. The technique proved to be effective and provided valuable information particularly the detection of a fracture that extended into the caprock.

Probabilistic Seismic Risk Assessment for CCS, Josh White, LLNL

Work from NRAPs induced seismicity working group was presented. A typical scenario considered is a relatively small CO_2 plume surrounded by larger plume of pressurised brine. An existing well-oriented fault that caused concern is reactivated. It is too small to have been characterised but large enough to produce felt earthquakes. There will always be irreducible uncertainties associated with the seismic behaviour of a field, although it is possible to choose sites that are less susceptible to this phenomenon. Four key risks considered are damage risk, nuisance risk, brine leakage risk and CO_2 leakage risk. Each of these risks has nuances that should be considered separately.

Seismicity deserves attention when the characterisation, monitoring and mitigation plans are developed. A phased approach, combined with good contingency plans, can reduce cost while still addressing risk. Probabilistic seismic risk assessment provides a rigorous, quantitative framework.

Significant progress has been made adapting it to induced seismicity, but some important gaps in the science still exist.

Induced seismicity, and its associated impacts, can be regarded as a nuisance factor. In areas which have a direct economic link to industries which cause seismicity, such as mining, there is a greater degree of tolerance. Communities which have not been exposed to seismicity are likely to be less tolerant for example in Basel. Compensation might be a solution but there would be a financial implication for CCS. The necessity for a baseline is also important.

Microseismicity at the Aneth Field, Grant Bromhal, NETL

Injection at the Aneth field started in 2007 and is ongoing. Geophones to monitor microseismicity (as well as VSP) were installed three months later. The events were small (~-1) and initially increased with amount of CO_2 injection, although there is a better match when compared with salt water disposal. Event rates have now stabilised over the last year to around 10 per day. Microseismicity was able to reveal structures not seen in the initial seismic surveys. These were NW-SE striking structures confined to the reservoir.

Evidence from this injection programme shows that microseismicity (natural and induced) occurs almost everywhere. Most seismic and microseismic events are associated with pre-existing faults and low permeability zones. The phenomenon can help to identify geological features, such as critically stressed faults. Induced seismicity can be controlled through effective reservoir and injection engineering; and careful and effective site characterisation and selection.

Discussion – Induced seismicity discussions after Zoback's paper

The discussion session was introduced by Tim Dixon, IEAGHG and Charles Jenkins, CSIRO.

A recent IEAGHG report on induced seismicity suggested that understanding of the phenomenon and its associated risks would be improved by:

1. Increasing the induced seismicity catalogues publically available for development and testing of physical and statistical models,
2. Undertaking more systematic studies of sites populated by well constrained subsurface information and seismicity catalogues that are completely recorded down to small magnitudes,

3. Improving the physical reality of physical models by modelling such factors as poroelastic effects, multiple species of fluid, and non-critically stressed systems,
4. Studying the scaling effects associated with a move from pilot projects to full commercial implementation of CO_2 storage,
5. Developing standard risk management procedures and guidelines for induced seismicity for CCS projects,
6. Filling induced seismicity knowledge gaps in the CCS community by collaborating with seismologists working in other industries.

The discussion firstly focussed on what was covered in the report as many of the examples given were in granitic rock which is not relevant to CO_2 storage. There is also a distinction between induced seismicity related to shale gas and that to CO_2 storage, although the most relevant to CO_2 storage is likely to be waste water injection. Zoback has not been critical about seismicity related to shale gas extraction. He has some interest in this industry.

It was agreed that the paper was useful in bringing the topic to public attention and throwing light on current research related to induced seismicity. The debate has kick started several discussions on the subject. There have been several recent reports on the subject, including the national academy of science report, which may have gained more attention (in the scientific community). Zoback has provoked the CCS community to take induced seismicity more seriously even though he might have given CCS a negative image that is unjustified. In the US microseismicity has attracted media attention which has been highlighted by Zoback's views.

It was suggested that induced seismicity is likely to be more of an issue for felt earthquakes, rather than causing leakage. There is a broader question. What are the properties of faults especially in shales and other caprock lithologies and how do they respond to pressure increases. This is an area for future research.

Session 15: Meeting Conclusions

Modelling

The focus has changed from models to modelling approaches and comparisons, including the need to understand what datasets are important

for different models. There has also been more work looking at sensitivity and bounding as opposed to processes. The outcomes of benchmarks and toolsets are also of interest. Key uncertainties on how modellers set up problems and approach them bring understanding to the modelling process.

Models will under predict plume expansion and may struggle to accurately predict actual migration patterns. Models have improved with greater data and can be useful in helping to predict long-term behaviour and retention of CO_2. Heterogeneity within reservoirs will cause variations in migration.

Risk Management

Mitigation and remediation should have a greater focus, possibly using experience from other industries, such as gas storage. There is much to be learned from recent projects such as the unexpected behaviour of CO_2 and how has this been managed. Crisis management at the Decatur project is a good example which could be applied to other projects. Previous meetings have had more discussion of competing risk assessment methodologies; however, different methodologies have been applied successfully. Different methodologies may be useful to show different aspects, for example Bowtie is easy to visualise whereas the Tesla method is good for managing uncertainties.

Work in communication has progressed. Communication needs to be instigated from the start and the current focus is on how to send out clear messages. There is a requirement to discuss the balance between risk verses benefits and not just risk in isolation.

There are many issues with policy, especially in the US, where Class VI regulations are halting research projects. There are a number of outstanding issues to be resolved. Can long term liability be quantified? If the liability of a storage site can be transferred what are the criteria for handover? Some of these issues are handled in the EU guidance documents, but the post closure period remains uncertain. There is a longer term question over the reliably of leakage detection over the next 4,000 years and how this should be specified in guidelines and regulations.

Overall

Managing public perception needs to take account of local issues and their relevance to CCS. Greater public awareness and education is necessary to put

CCS into context with other options and energy supply.

There is a significant benefit from real projects because new phenomena can be observed and a better understanding of changes induced by CO_2 injection can be determined (i.e. pressure changes, induced seismicity, fracture propagation). When the injection does not go as predicted, there is actually benefit from more learning.

The behaviour of faults exposed to CO_2 induced stress needs to be better understood especially as faults and fractures could act as conduits or seals.

There is a difference in the perception of risk between different authorities and organisations. For example investors may not view risks associated with CCS compared to utility companies.

The feedback from monitoring and mitigation is very important to risk assessment modelling.

Uncertainty matters when the consequences are perceived to matter to 'decision-influencers'. In dealing with uncertainty, many had concluded that a 'phased approach' enabled progress to be made in a structured and rationale manner to arrive at appropriate conclusions.

2013-15 MONITORING NETWORK AND ENVIRONMENTAL RESEARCH NETWORK - COMBINED MEETING

Introduction

IEAGHG supports and operates a number of international research networks. This report presents the results of a workshop held by two of these international research networks. The report was prepared by IEAGHG as a record of the events of that workshop.

The workshop on Monitoring and Environmental Research was organised by IEAGHG in co-operation with CO2CRC. The organisers acknowledge the financial support provided by CO2CRC, Global CCS Institute, anlecr&d, The CarbonNet Project, Chevron Australia, Geoscience Australia, and Shell for this meeting and the hospitality provided by the hosts at University House, Canberra.

Richard Aldous, CO2CRC and Tim Dixon, IEAGHG introduced the network meeting, which was the 8th meeting of the Monitoring Network and the 4th meeting of the Environmental Research Network. The theme of this meeting was to cover the realistic monitoring of CO_2 migration – from the reservoir to the surface. The meeting was attended by 80 delegates from 12 countries.

Session 2: Regulatory Environment

Summary

International work to standardise the framework for CCS is being developed, included the UNFCCC Clean Development Mechanism (CDM) and ISO TC 265. While regulations are important for commercial projects, the US EPS Class VI rule, could potentially have a negative effect on research projects and it may be necessary to adapt the rule in order to apply it to smaller research projects. Regulators should also understand what they will require, such as a comprehensive list of failures that could be caused by unexpected migration outside the confining zone or storage complex. Another important aspect in identifying leakage is the stage where the CO_2 is attributed to the storage project and it was suggested that this be included as an additional step in regulations and guidelines.

Terminology is important for comprehensive understand of regulations, e.g. when to use seepage or leakage. Scientific data sharing with industry

could enhance accuracy of prediction models. Compliance efforts facilitate understanding of proposed projects and are important for public outreach. However, excessive regulations may be barrier to project development.

Overview and Update on ISO and CDM work; Tim Dixon, IEAGHG

At UNFCCC COP-17, in 2011 CCS Modalities and Procedures were agreed and adopted, which included assurance of environmental integrity and safety of a storage site, confirming containment and that the CO_2 behaves as predicted, determining GHG reductions and assessing remedial measures. IEAGHG Networks played a role in providing technical information to negotiators at a workshop in Abu Dhabi, including the 2011 meeting of the Monitoring Network which considered the specific issues which had been raised by UNFCCC. CDM project closure is when monitoring stops, which will not be less than 20 years after the last CDM crediting period. There is also the assumption of zero leakage, unless monitoring data suggests otherwise. In 2013 there was a consultation process on some specifics of operationalising CCS in the CDM, and IEAGHG provided further clarification on technical issues.

The process of determining international standards for CCS (ISO TC 265) started in 2011 with the aim to prepare standards for the design, construction, operation, environmental planning and management, risk management, quantification, monitoring and verification, and related activities in the field of CO2 capture, transportation, and geological storage. ISO standards are not obligatory, but can be adopted within national regulation.

US Regulations, Class 6 Requirements; Lee Spangler, MSU

Class VI regulations were designed by US EPA to protect underground sources of drinking water (USDWs) and are to be applicable to commercial scale CCS projects. It is also to be applied to all new research CCS projects, which do not have an EOR component. Certain aspects were found to be potentially detrimental to research projects (as well as in some cases larger projects). This includes the post-injection site care (PISC), which is by default 50 years, this is flexible, but could be an issue for pilot projects; it also does not take injectivity tests into account. There is also likely to be less flexibility with plan changes under Class VI, which may be a problem with research projects, which are often opportunistic. The Kevin Dome site, which has safely stored

natural CO_2 for 50 million years, was taken as an example. The aims of this project was to test monitoring technologies, mitigation methods, stacked storage and detection limits. As the storage formation is under pressures, this leads to a large area of review under the guidelines, which leads to an impact of costs, not only due to increased area, but also due depth of surface casing required. It will also not be possible to carry out a mitigation test, due to PISC implied liability. Because research projects do not have an economic driver, Class VI financial assurance requirements may also be a challenge.

Monitoring Protocols; Tim Dixon, IEAGHG

Detecting leakage emissions is challenging and quantification is very challenging as we need high sensitivities and low uncertainty. Current guidelines suggest monitoring to detect leakage, then more intensive monitoring for quantification of the leakage. However, it is suggested to have an intermediate step whereby the CO_2 detected is attributed to the injected CO_2. Methods that are available to do this include isotopic analysis, tracer gas signature and the process-based soil gas method, all of which have been used successfully at different times and discussed at IEAGHG Network meetings, so there is growing confidence in such 'attribution' monitoring.

Mapping the plume – What do Regulators Need to Require?; Sue Hovorka, BEG

It is important for regulators to understand when failure may occur and what to look out for to know when more information is needed. It is suggested that regulators should require a comprehensive list ofpossible failures of storage and for each case, the regulator should ask the project developer how they will know that this failure is not occurring and will not occur. To answer these questions there can be models created to illustrate failure cases and characterisation/ monitoring designed to disprove failure scenarios.

Most models look at the median, but when considering failure, we need to look at the outliers. It is also important to understand limits of measurement. Monitoring plans will be based on risk assessment, not models, as modelling cannot predict responses to unexpected parameters.

It is suggested that an inventory of failure scenarios are created, models of failure are created, conditions that precede failure are defined, then those conditions are characterised and monitored.

Comments after the talk included that the scenarios need to be credible, or there will be too much to consider. It is also important to understand if an unexpected migration is important – or is it still contained? Scenarios will also be project specific.

IEAGHG Monitoring Tool Update; Sarah Hannis, BGS

The Monitoring Tool was created and maintained by BGS for IEAGHG and has been on the IEAGHG website since 2006, though there have been several updates. It contained >40 monitoring techniques, which are selected and rated based on a user defined scenario. It is a decision support tool, which aims to identify and prioritise monitoring techniques that could form part of a monitoring programme from site characterisation through to post-closure.

The tool is updated from information from experts, new articles, papers and reports. New planned and possible updates to the tool are: inclusion of unranked tools; a benchmarking study using an existing site; further cost information (though this will not be used in the ranking system). User data is logged and there were 400 visits to the tool over a 6 month period. Feedback from participants included a suggested colour scheme change as the current traffic light colours may be considered 'backwards'. It could be tested with first time users for ease of useability, it could be made clearer that it use the tool, it was suggested that the ratings system could be more transparent and it was also suggested that porosity and permeability could be included. It was also commented that the tool is useful as a starting point for discussions by regulators.

Session 3: Monitoring Migration from the Reservoir

Summary

This session covered deep subsurface monitoring techniques. An innovative experiment at Otway injected a small mass of CO_2 and then documented stabilization induced by water flooding, monitored by time lapse pulsed neutron logging and downhole pressure gauges at different depths.

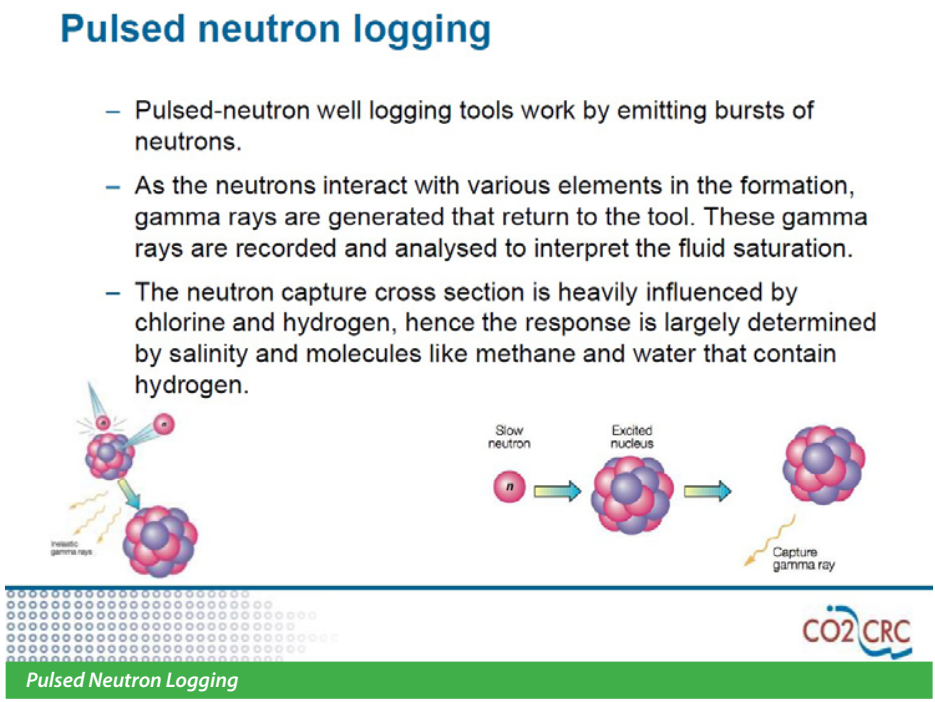
Methane leakage over geologic time from the Baracouta structure, Gibbsland basin was illustrated with geological data. At the SECARB "anthropogenic test" , under funding from CCP, LBNL designed a new multi-tool package, Modular Borehole Monitoring , allowing better deployment of complementary tools. The utility of the package was demonstrated during diagnosis of a well

completion problem. A permanent seismic receiver array at the Ketzin project was described. Some microseismic events were identified and the utility of the array for detection of changes in pressure at the reservoir level. Seismic detectability of CO_2 migration from the reservoir was evaluated in light of the need for climate change mitigation of a high storage retention standard and found that sensitivity to shallow accumulations in low noise settings is adequate to detect the relevant leakage.

An overview was given of a recent review paper prepared for IEAGHG on induced seismicity and its implications for geologic storage, using literature reports of induced events at 100 locations of large scale injection and withdrawal. A need for additional data for CCS was noted.

Otway Injection Experiment; Lincoln Paterson, CSIRO and CO2CRC

A small mass of CO_2 was injected, followed by water flooding. This was monitored using a wide variety of techniques, though this presentation focused on downhole pressure and pulsed neutron logging.



For downhole pressure measurements, there were two gauges above the perforation and two below. Water gave a greater pressure difference than CO_2, which is useful to tell which fluid is present. Downhole pressure was found to be very accurate, fast, continuous and inexpensive, but cannot give directional information. A fault which was around one kilometre away was able to be identified using Horner plots, but it is not possible to tell which direction it was using this method alone.

Pulsed neutron logging can be used to determine thickness and variability of saturation from an injected CO_2 plume with limited surface disturbance, however there is a very limited depth of penetration into the formation and it needs calibration. At Otway this was conducted at full water saturation, after CO_2 injection and after water injection to drive CO_2 to residual saturation. The saturation profiles show that the CO_2 has tended to migrate to the top of the injection interval under buoyancy, and that the average residual saturation is around 20% with some uncertainty arising from the calibration.

Evidence for Slow Migration of Fluids over Geologic Time Through the Cover Sequence in the Gippsland Basin; Nick Hoffman, CarbonNet

This area is very data rich, with wall to wall seismic and many wells. There are several oil and gas accumulations, which are all thought to be fill to spill, and so there may be seepage concerns where there are lower accumulations in a large closure. There is also a more recent low salinity wedge, which has caused biodegradation and water-washing of the hydrocarbons. The Lakes Entrance Formation acts as a regional seal and weak points related to Miocene channels have been identified. Some wells show a small amount of hydrocarbon above the seal, and seismic anomalies can be mapped as clusters – these show that fluids have moved 30km laterally through the overburden. It is suggested that there is 2 way pressure communication and that the fresh water can migrate and the path can be seen through dolomitisation.

The duration of fluid movements in the cover may extend to tens or hundreds of Ka – perhaps beyond human timeframes of MMV. The direction of movement of buoyant fluids can be predicted from the dip of the overlying strata. The area required for MMV can be mapped-out using predicted fluid paths in the cover sequence. Structures with dip closure in the cover sequence have a natural ability to constrain buoyant fluids, and smaller required areas for MMV, which may limit the opportunity for geochemical reactivity. Conversely,

structures with gentle but open dips allow long-distance migration of fluids and ample opportunity for geochemical reactivity, but are more challenging for MMV.

Modular Borehole Monitoring (MBM) at Citronelle and Project Update: SECARB's Integrated Anthropogenic CCS Pilot; Tom Daley, LBNL

CO_2 captured from a 25MW coal fired boiler at Southern Company's Plant Barry, is shipped by pipeline to the injection site in the saline Paluxy reservoir at Citronelle oilfield. Under funding from CCP, LBNL designed a new multi-tool package, Modular Borehole Monitoring, in order to allow better deployment of complementary tools and to maximize the efficient use of available wellbores for semi-permanent monitoring. The tool includes P/T gauges, U-tube fluid sampling, hydraulic clamping geophones, fiber optic temperature and heat pulse.

Initial testing of the MBM system was successful and useful in understanding well completion. MBM Fiber-optic seismic acquisition was tested and is very promising. Monitoring using the MBM system is continuing.

Four Years' Experience with Testing Continuous Seismic Monitoring at Ketzin; Rob Arts, TNO

The permanent seismic array is in boreholes 50 m deep and has been operational for almost 4 years continuously. Though a 3D layout is preferred, this was not feasible at Ketzin. Seismic data was recorded in 89 channels and sampled at 2 ms interval (16GB/day), which was increased to 0,5 ms when appropriate (68GB/day). There has been a huge amount of data including lots of noise and a lot of work has gone into determining data from the subsurface and filtering out surface noise; in this respect it was found to be useful to focus on events out of working hours. The signal to noise ratio was improved when burying the receivers at depths of >20-30m. There is still limited understanding of variable data quality (spectrogram plots), the existing algorithm is able to detect upgoing events automatically, improvements for localization and magnitude estimation of events is ongoing.

A low frequency vibrator was installed relatively close to the permanent array, where there was almost daily monitoring over a 1 month period. A combination of permanent source and permanent receivers has the potential for increased repeatability and signal to noise ratio. There was

good repeatability of shots, though some issues remain (being resolved now), changes are observed, but due to the HAN no clear conclusions can be drawn yet. Injection stops on 29th August 2013: Experiment is currently being repeated, unfortunately not with the permanent source, but with accelerated weight drop.

Induced Seismicity in Global Injection Projects and the Implications for CCS; Matt Gerstenberger, GNS

Induced seismicity has been observed in injection and extraction sites related to hydrocarbon production, geothermal activity and waste water disposal. Information has been taken from these sites to attempt to consider the potential risk at CO_2 storage sites. Some key questions considered are what magnitudes, rates, timing and locations of induced earthquakes can be expected; what don't we know about induced seismicity and how can these knowledge gaps be closed; what are the risks and can these be quantified; and how do we best reduce and mitigate the risks.

Complete monitoring down to small events is key to better understand the behaviour of induced earthquakes and to understand the behaviour of a particular reservoir. Few earthquakes have occurred at CCS sites, but there are generally small volumes of injected CO_2 and only a few sites. Observed empirical data show some relationships, most notably between maximum magnitude and total volume injected/injection rate. Physical and statistical models are in relatively early stages of development, though statistical models are better established. Risks can be reduced and mitigated using a systematic and structured risk management programme.

Spatial Monitoring in the Overburden: Detection Limits in 3-Dimensional Volumes; Andy Chadwick, BGS

Seismic detectability of CO_2 was evaluated in light of the climate change mitigation needs of a high storage retention standard. It may be difficult to detect a leakage in 1D and 2D, depending on the sample spacing, and though 3D seismic may have full coverage, there will still be detection limits. The Sleipner dataset was used as an example and a difference map of the first repeat survey shows some quiet areas and some not so quiet areas. Noisier data will have lower detection ability and it is one of the quiet areas above the storage formation that would be most suitable to monitor for leakage. The detection limits at the top of the Utsira were determined by spatial wavelet

decomposition. The method accurately extracts known CO_2 accumulations on synthetic data, though detection will depend on the thickness and the area (if the plume is too thin it will not be detected). It is therefore possible to say whether or not a site is leaking with respect to acceptable levels.

In conclusion, it can be said that detection limits are statistically manageable and allow comparison with performance acceptance criteria. The 'No detected leakage' requirement might be considered fulfilled if the monitoring system has detection capability sufficient to assure effective greenhouse mitigation performance. In discussion on what a leak would look like, it was thought that somewhere in the overburden there would be pooling of CO_2 sufficient to be detected.

Session 4: Migration of Fluids through the Overburden

Summary

Understanding the overburden is crucial to understanding leakage. We need to know how much CO_2 will be emitted at the surface if there is leakage from the reservoir, how long does it take to get there, where will it occur and how reservoir changes affect flow in the overburden, as well as the best way to monitor this.

There is evidence of major relatively recent dynamic flows in the overburden. It can also be seen how CO_2 – brine – rock interactions work on geological time-scales, migration up faults and within aquifers are key insights into this potential journey of CO_2 from reservoir to surface. Pressure propagates much quicker than fluid particles - influences monitoring preferences for rapid response. Reservoir pressure changes induce tiny geomechanical volume changes in the overburden pore-space can 'switch on' and 'switch off' the backgroundflux.

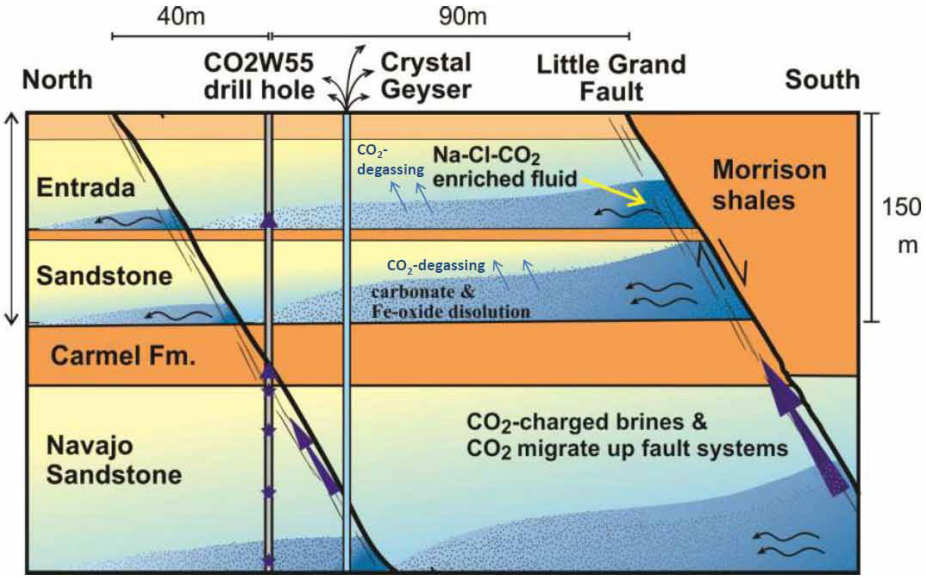
Fluid Migration in CO_2 Reservoirs and Faults: Constraints from the Green River Storage Site Analogue; Niko Kampman, University of Cambridge

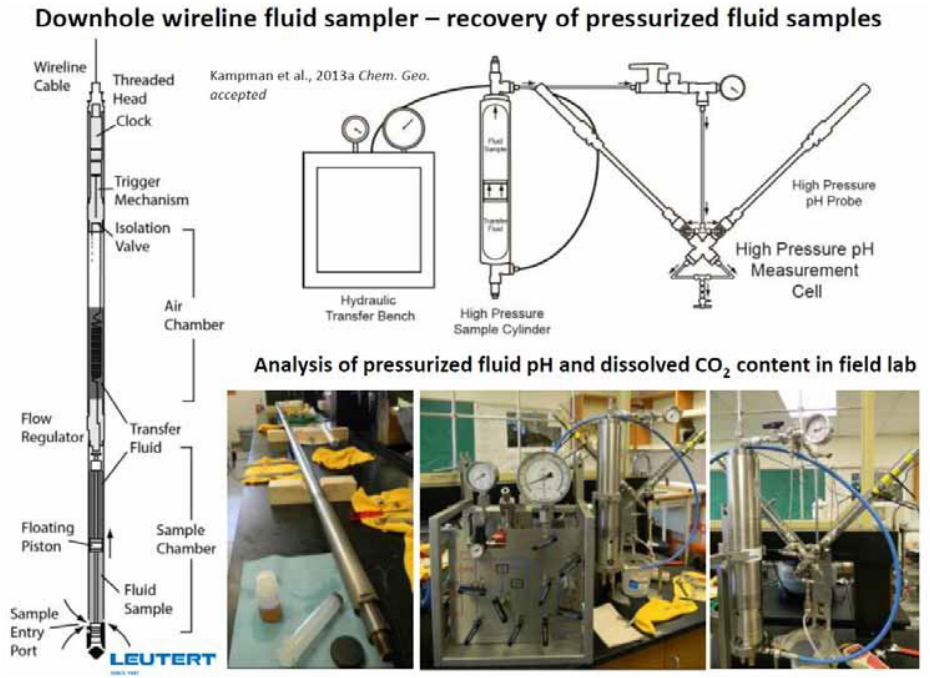
At this site CO_2 has migrated through 100m of overburden. CO_2/ CO_2-charged brines mainly migrate up fault zones and rock core across the fault was sampled. Downhole wireline fluid sampling was used to recover pressurised fluid samples. At depth, the brines are CO_2 saturated and at shallower depths become undersaturated; it appears that CO_2 is degassing at a depth of 50m,

though it is difficult to know the total amount of degassing as it may not be preserved in the rock record.

Some conclusions from this study are that thin siltstones form surprisingly impermeable caprocks; fluid-rock reactions strongly retard CO_2-transport & buffer fluid reactivity; the mineral dissolution front is only ~10cm thick after 100,000's of years of exposure; and carbonate dissolution/reprecipitation occurs with net dissolution in caprocks adjacent to the reservoir and net precipitation within the reservoir.

Natural systems have been shown to be useful for: testing theory, models and assumptions about coupling of fluid flow and brine-rock interactions along flow-paths where reaction fronts are preserved in the rock (also trace metal mobilization and biogeochemistry); two-phase CO_2-gas and brine migration in faults; and as test sites for subsurface monitoring and sampling equipment. They have not yet been found useful for understanding dynamic two- phase flow in storage reservoirs.



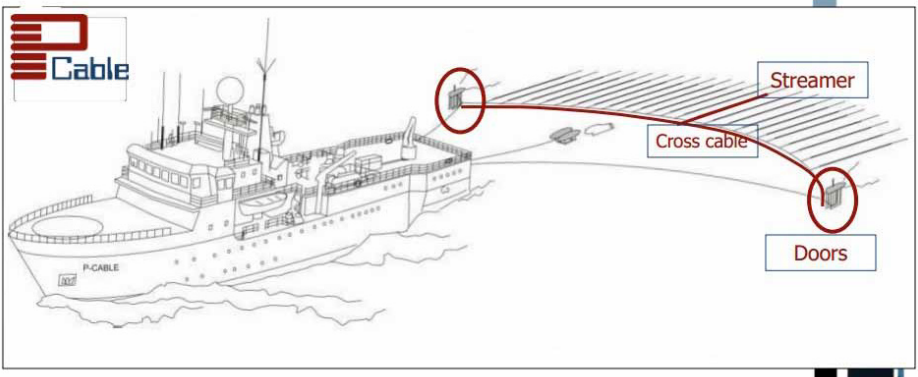


Green River Natural CO_2 Seeps

Fluid Migration Systems and Leakage Assessment in the Shallow Subsurface; Stefan Buenz, UIT

This assessment is part of work package 2 of the ECO_2 project and involves looking at flow features between the potential caprock and the seafloor in the North Sea. Different types of fluid flow are observed through pipes/ chimneys and along strata and are often seen in conjunction with gas hydrates. In the Barents sea gas chimneys are seen as bright spots on seismic. Faults can be identified, and there are indications of gas along faults. The origins of the observed features are thought to be from uplift and erosion from glaciation. A basin scale approach is needed to understand governing controls which impact leakage scenarios and risk assessment. It is also necessary to appreciate the varied dimension of fluid flow features and that their detectability hinges on suitable high-resolution approaches, particularly in detecting CO_2 leakage along these features.

P-Cable 3D seismic system



- A seismic cable towed perpendicular to the vessel's steaming direction
- Many single-channel seismic streamers attached to a wire held in place by two doors

Volcanic Basin Petroleum Research

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

IFM-GEOMAR

ECO2 Project's Offshore Monitoring of Shallow Subsurface

Insights into CO_2 Migration from Non-CCS Perspectives; Katherine Romanak, BEG

One of the challenges to understanding migration through the overburden is that it may occur over long timescales that are difficult to directly observe. Industrial analogues give us time scales of observation on the order of about 40 years (such as at the SACROC oilfield, Texas, USA where CO_2 injection for EOR has occurred since 1972) and natural systems which are 100,000s of years old. Reactions and migration processes that may occur over the time period of interest for a CO_2 storage project (1000 years) are therefore difficult to discern. When using natural systems as analogues for engineered storage sites, it is important to consider what aspects of the natural system are important and relevant to CO_2 storage sites, and how these systems can be used to predict the range of possible surface impacts that could result. Natural sites should be used cautiously with a detailed understanding of geological similarities and differences.

Whereas it is generally widely believed that macro-seepage along faults or wells would be the dominant mechanism for CO_2 migration in the overburden, there is some indication that micro-seepage may be important. In some cases microseepage appears to be rapid and therefore should be addressed by the CCS community. Cases considered included a Gulf Coast oilfield where after 30 years of decreasing pressure from oil production there was a disappearance of seepage signals at the surface. Lateral seepage is also possible, so it is very important to understand the geology to be able to predict CO_2 migrations rates, surface flux rates, surface location and impacts. Because CO_2 is reactive, a release from a storage formation may never reach the surface, so understanding CO_2-brine-rock interactions is important.

There was discussion about the mechanisms of surface micro-seepage and explanations as to how this can be switched on and off by pressure changes at reservoir level, pressure moving much faster than fluids, without an implication that this would mean that leakage of the CO_2 injected into the reservoir would occur.

Monitoring in the Overburden: Is Pressure or Geochemistry a Better Indicator of Leakage?; Sean Porse, BEG

The Hastings oil field was used as a case study to consider pressure and geochemical monitoring in determining leakage. There are hydrocarbon

accumulations around edge of the field and logs show a lack of continuity especially at a shallow level. It is thought that pressure monitoring may be more suitable due to the faster response to changes in subsurface conditions, though both methods could be used in concert to comprehensively to monitor for brine (and CO_2) migration into shallower aquifers over longer time frames.

Pressure monitoring at the Hastings field can work in all Miocene formations and geochemical monitoring works best in deep Miocene formations at monitoring points closest to the fault. Geochemistry can provide secondary information over longer monitoring periods. Understanding the hydraulic parameters of both formations and migration pathways are critical towards assessing the potential risk of fluid migration at a project. The probability that a monitoring technique will detect adverse leakage should be the driving factor in developing a subsurface monitoring network.

Geochemical monitoring is necessary to analyse effects on drinking water, but pressure can be considered as a pre indicator and if only geochemistry is used, it may be too late to protect drinking water as it may mean leakage has already occurred.

Session 5: Detection of Leakage into Shallow Groundwater

Summary

Groundwater monitoring can be conducted for different purposes (e.g., characterisation, regulatory compliance, research), and it is important to establish the goals of each of those purposes before a network is constructed and monitoring is initiated. Having more wells or sampling more frequently (i.e., increasing data density) can help address uncertainties in data interpretation, but is more costly. Regulators may not be completely familiar with monitoring needs and can benefit from project specific input and guidance. It is also important to understand the time scales, spatial scales and mechanisms of metal mobilisation in groundwater. Work is being carried out assessing the use of remote sensing for groundwater quality monitoring. As CCS projects move from the research and demonstration -scale with relatively small injected masses of CO_2 and high-intensity monitoring strategies, commercial-scale projects will seek cost-effective, lower intensity monitoring programs to meet regulatory monitoring requirements.

Experiences from the Illinois Basin – Decatur Project Groundwater Monitoring Program; Randy Locke, ISGS

For shallow (<100 m) groundwater assurance monitoring, primary goals for the Illinois Basin – Decatur Project (IBDP) include demonstrating that project activities are protective of human health and the environment. In particular, monitoring is documenting that there have not been project impacts to potable water supplies. Four regulatory compliance wells have been sampled quarterly for 11 indicator parameters to meet current injection permit conditions. To ensure spatial and temporal variability of groundwater quality is fully understood, the project operates 13 additional wells and samples more frequently than required by permit. There are more than 2 years of monthly baseline data for all 17 monitoring wells. The IBDP site has a relatively high intensity monitoring program in comparison with what may be implemented for larger, commercial-scale projects. The monitoring network for the adjacent Illinois Industrial CCS project (which will inject at up to 2,500 tpd or 2.5 times the IBDP rate) is more focused on optimizing monitoring intensity and regulatory requirements.

In a non-regulatory well about 560m from the injection well, increases in calcium, magnesium, and potassium concentrations were observed. This case illustrated how different durations of pre-injection data could lead to different conclusions about the causes of cation variability. The cation increases were attributed to multiple factors including 1) natural variability as was observed in the baseline record and 2) oxygenated water interacting with naturally occurring pyrite in the carbonate-rich, unconsolidated aquifer. This new information was useful in revising the hydrogeological conceptual model, showing more interaction between aquifers. The baseline data were also important, because they included the 3rd most severe local drought on record and showed shallow groundwater responses to a wide range of moisture conditions. Statistical assessments of IBDP groundwater data are based on the 2009 USEPA Unified Guidance, "Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities" as developed under the U.S. Resource Conservation and Recovery Act.

CO_2 Field Lab and CIPRES Experiments; Frédéric Gal, BRGM

The main objectives of the 2 projects differ slightly. For CO2FieldLab the objectives were to obtain knowledge about monitoring of CO_2 migration

and enable early detection of possible CO_2 leakage, as well as to provide guidelines to regulators, operators and technology providers. 1.7tonnes of gaseous CO_2 was injected into fluvio-glacial deposits at 20m depth through a deviated injection borehole.

The objectives of CIPRES are the quantification of the biogeochemical reactivity of CO_2 to estimate impacts on water quality and potential associated risks and to establish methodological guidelines and recommendations for monitoring programs (Drinking Water Standards). It involved an Injection of 10m3 of water saturated in CO_2 in shallow aquifer in between 12 and 20m depth in chalk aquifer.

There were strong effects on soil gas even if the CO_2 is injected in water. Channelling in heterogeneous formations can lead to adverse effects even in near surface formations. Extensive site characterisation is required. Basic characterisation of the water (e.g. pH, electrical conductivity…) is sufficient to account for leakage, but there is a need of using more complex systematics

(isotopes) to account for more complex phenomena (mixing). Water/rock interaction processes may have rapid kinetics that strongly affects water chemistry (or quality considering trace metal elements); good from a monitoring point of view, but critical from a water management point of view.

Cranfield Airborne Geophysical Survey

Value of Airborne Conductivity and Magnetics for CCS: Test Xase at Cranfield; Sue Hovorka, BEG

It may be necessary to be able to detect and characterise over a large area. Using ground methods it is not possible to monitor everywhere, so it is helpful to be able to determine the best places to monitor. Future leakage may follow the path of other previous gases, e.g. methane, therefore understanding past gas migration is useful in deciding the monitoring plan. To characterise previous pathways, methane may be detected, or methane impacts through iron mobilisation and mineralisation, which could produce a detectable magnetic signal.

At the Cranfield site, the survey was flown in April 2013 and initial EM and magnetic processing is completed. Known wells have associated magnetic anomalies that were detected by the survey. Additional magnetic anomalies may represent additional wells and possible preferred pathways. Shallow and moderate depth conductivity images indicate possible pre-existing salinisation of soil and groundwater. Processing, analysis and interpretation have just begun.

Session 6: Terrestrial Detection Monitoring and Environmental Impacts

Summary

The discussion focused on finding leaks, attributing Leaks to sources, quantifying Leaks and assessing Impacts of leaks. The technologies for these tasks vary. Hyperspectral analysis shows some promise for wide area detection, but is an indirect method. Improvements in processing and analysis are reducing the number of false positives and negatives. Wide area detection still remains a target for improved technologies. Process based methods and isotopic analysis show promise as methods to attribute the source of CO_2. Atmospheric methods have potential for leakage quantification but are not as well suited for locating leaks. Surface flux is patchy and flux areas do not necessarily match vadose zone elevated CO_2 in the soil gas. Natural leaks and controlled release sites both indicate that surface impacts are likely confined to relatively small areas. Plant response can potentially be used as a semi-quantitative measure of CO_2 soil gas concentration.

Remote Leakage Detection Methods; Anna Korre, Imperial College

Indirect detection methods have been used at the Latera and Laacher See natural release sites. The Latera site has used hyperspectral and multispectral remote sensing analysis and validation of leakage locations with gas flux measurements. In Laacher See, hyperspectral remote sensing analysis has been compared with open path mobile laser measurements.

Direct and indirect measurements need to be combined and it is necessary to be able to distinguish a leakage target from the background as false alarms are possible.

Detection of leakage by monitoring inevitably involves statistical analysis – detecting the leakage signal above noise and dealing with missing signals in monitoring data. Different monitoring datasets may refer to

different spatial and temporal domains and may refer to open systems, affected by varying factors outside monitoring control, which may also be unknown or not recorded. Joining up different monitored data analysis in a statistical framework allows improvement of leakage detection and reduces vulnerability to false alarms and handles data uncertainty.

Detection of leakage pathways is feasible and benefits from the use of independent datasets to corroborate detection. Common to all broad categories of detection is the need for detailed information in the statistical structure of the data and the uncertainties in that knowledge. Accumulation of enough background data may be impractical. However, many statistical techniques are available when dealing with uncertainties.

Further work is planned on also considering false negatives using the same method.

Synthesis of RISCS Results: (Near Surface) Terrestrial Impacts; Dave Jones, BGS

The RISCS project has been running for 4 years and is due to end this year; its aim was to research onshore and marine impacts of leakage from CCS. This involved scenario and reference environment development, studies at experimental sites, lab experiments, field observations, comparisons with previous studies, results from other projects and modelling.

Experiments on the effect of CO_2 on plants showed that below 10% CO_2 concentration at 20cm injection depth is the threshold for observing changes in plant coverage. Between 10 and 50% monocotyledenous (grasses) plants dominate and above 50%, there is a rapid decrease in plant coverage. Raised CO_2 may be a benefit to cereal crops. Bioindicator species were also identified. Microbial activity was studied and found to have a very complex relationship to soil CO_2 concentrations. CO_2 concentrations above 15-20% seem to be threshold for microbiological changes. At natural sites the microbial community has adapted to increased CO_2 concentrations, there has been a shift to anaerobic and acidotolerant/philic species (Archaea or SRB) and anaerobic methane generation observed.

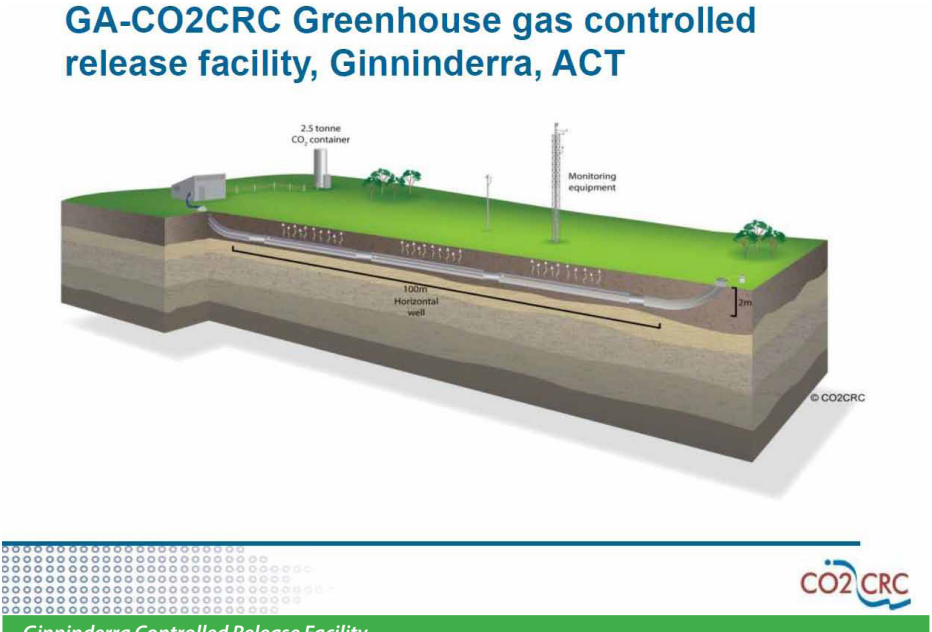
Overall conclusions of the project are that impacts are spatially limited – there is a small effect on overall yield with implications for monitoring; some fertilisation effects counteracting negative impacts; limited to soil gas effects

(rapid dispersal of CO_2 in the atmosphere); only occur above ~ 10% CO_2 at 20cm, effects are rapid (1 - 4 weeks), recovery and impact on long-term fertility is less clear, with different species sensitivity (better bioindicators or indicator species), plant development stage and timing of exposure are important; effects are blurred by seasonal/annual factors; effects can be used for monitoring (with some limitations – they are seasonal and not necessarily CO_2-specific); impacts appear to be manageable – they are small compared with the effects of other climatic/meteorological factors or pests.

CO_2 Leak Detection at the Ginninderra Controlled Release Facility; Andrew Feitz, Geoscience Australia

The Ginninderra site is situated in 800 hectares of cropping/ grazing land, 10km from the centre of Canberra. It is a similar setup to the ZERT site, though there are different soil types. Several techniques have been tested.

The CO_2 was released along a pipe, but mostly came out at a particular point, due to strong lateral migration, thought to be due to clay layers. Atmospheric monitoring methods used were Eddy covariance and atmospheric tomography. Detection with eddy covariance was seen to work, but it was



difficult to know where the leak was. Detection is only up to 200m and quantification is problematic. Leaks are patchy, not diffuse. There are issues with eddy covariance due to the horizontal component of flow. Atmospheric tomography (bayesian inversion) looks at the CO_2 gradient difference and worked well. The CO_2 emission rate was determined to within 3%, however, tubes were needed all over the site. Sensor arrays were tried instead and while there were accuracy issues, this may be a more practical method.

Much of the challenge is locating a leak, for which atmospheric techniques may not be good, but once the leak location is known, it can be quantified.

In summary CO_2 surface expression is less than sub-surface footprint (no "V"); quantification techniques still require work; finding small surface leaks over large areas remains the greatest challenge; and cross calibration of techniques is important.

Detection of Signal Over Hydrocarbon-Induced Noise at Cranfield; Katherine Romanak, BEG

A method for near-surface leakage assessment and its use at the Cranfield site was presented. The leakage assessment method consists of locating an anomaly and then attributing its source as either in-situ or exogenous. If exogenous, the gas is then assessed as either originating from an intermediate gas-producing zone or from within the reservoir. If a soil gas signal is from the reservoir, leakage may be indicated and migration mechanism and leakage flux should be determined.

A near-surface anomaly discovered at the Cranfield site was determined to be exogenous using the process-based soil gas method and was then determined by an isotopic analysis to be from the Tuscaloosa formation (the storage reservoir) and not the intermediate Wilcox Formation. This anomaly represented an active migration pathway from the reservoir to the surface. At the time of its discovery, the anomaly contained only gases from the reservoir without injected CO_2. The anomaly was located 10s of feet from a plugged and abandoned well that was re-entered in 2010 to become a producer. Shortly after injected CO_2 flooded the area, both a process-based analysis and isotopes confirmed that injectate CO_2 had reached the surface within the anomaly. The leakage signal was transient over time. The migration mechanism is currently being investigated.

Session 7: Marine Detection Monitoring and Environmental Impacts

Summary

Potential leakage sites are large and leakage could be point source or dispersed. Leakage plumes will be dynamic and complex. There are various detection methods, geophysics, acoustics, chemical, and which a mix will likely be required. Sensors exist and accuracy is adequate, deployment can be via fixed platform and roving AUVs. Various modelling techniques can improve monitoring strategies but these will be site specific. Much improved baseline data is needed to evaluate and tune these models. The baseline needs both spatial (topography) and temporal (seasonal – inter-annual) content. The sea floor gives the best opportunity for quantification and will need spatial and temporal resolution. Quantification will still be difficult, given the observed lateral spread within sediments. Shallow movement of gas plumes is greatly influenced by stratigraphy and sediment type. Chemical transformations are complex and will be sediment specific. Biological monitoring addresses scale and impact, but may not be useful for detection.

The Future of Water-Column and Shallow Sub-Seafloor Monitoring of Offshore CCS sites; Ian Wright, NOC

Tools are able to detect both gas and dissolved phase. Physical detection of bubbles can be done through hydrophones and quantification can be with passive and active systems. Active sonar can sit on the seafloor and be used to image bubble plumes and passive sonar can be mounted on gliders or AUVs. Forward reactive chemistry modelling can be used to test what can be detected. There area range of pH monitoring tools available and methane sensors can possibly be extended for use with other gases.

CCS sites with large spatial seafloor extent and overlying ocean volumes (with potentially dispersed and localised emission sources) provide a monitoring challenge. Essential rationale for monitoring will be baseline studies, leakage detection, and flux emission quantification. Potential CO_2 leakage may have precursor fluid release of reducing sediment pore fluids ± aquifer brines (each of which has a unique chemical signature). Shallow sub-seafloor geophysics can detect gas leakage as low as 85 kgs day-1. New marine sensor and underwater platform technology is developing to deploy long-term point observing and remotely surveyed monitoring of the critical fluid parameters at the necessary sensitivity and spatial scales for CCS sites (and at relative low

cost). Seafloor / ocean monitoring can detect both dissolved phase (using chemical detection) and gas phase (using passive and active sonar), but is not yet commercially deployable. Chemical and sonar monitoring systems may provide a tractable and robust method for quantifying leakage loss beyond just detection.

Fate of Emitted CO_2; Guttorm Alendal, UIB

Once CO_2 leaks to the seabed, the current governs its movement and waves cause turbulence, which results in mixing of the CO_2. Spatial resolution is very dependent on topography. Predicting dynamic systems is very difficult, particularly when looking at longer than a few days. There are some systems where flows come together and some where they diverge, if it can be understood what flow is most likely, then it can be understood where is the best place for the monitoring equipment. If there is a leak, we can look at expected concentration and can calculate the probability of detecting this from a certain place and from this where to monitor.

Modelling Approaches to Assess CO_2 Leakage; Keisuke Uchimoto, RITE

If CO_2 leaks to the seabed, the distribution is influenced by ocean dynamics and the leaked CO2 is likely to be mainly bubbles. Modelling efforts have couple the MEC model – ocean physical model and a CO_2 2 phase flow model, to calculate bubble dissolution. Leaked CO_2 simulations were conducted in Ise Bay in Japan using this model. It shows strong stratification near the surface and weak in the deeper layers.

Distributions of simulated ΔpCO_2 provide information on the monitoring area to be investigated, and potential impacts on organisms based on a biological impacts database. In the simulations, a leakage rate of 3,800 t/y (based on data from an EOR site) makes just a small increase of TCO_2 and pCO_2. A leakage rate of 38,000 t/y (the same order as a natural analogue site) may impact organisms, but the area is limited to above the leakage area.

Effects of CO_2 Leakage on Benthic Biogeochemistry: Findings from the QICS in Situ Release Experiment; Henrik Stahl, SAMS

The geochemical objectives of this project are to: determine geochemical properties of water column and sediments before, during and after the release; monitor the fate of carbonate system parameters (DIC, TA, δ13CDIC, pH) in sediment and water column – spatial and temporal dynamics;

detect and quantify mineral transformation and possible release of toxic components (metals); and to quantify fluxes of DIC, O_2 and metals across the sediment-water interface.

CO_2 bubbles were seen in the water column within hours of injection. Gas chimneys and pock marks could be observed in sub-surface/surface sediments by seismic profiling and multibeam. Up to 35 distinct bubble streams were observed, with flow rates affected by tidal phase and >10% of injected gas escaping as bubbles at low tide. Elevated pCO_2 values where observed in bottom water at release site, which varied with tidal phase and injection rate. Significant changes in carbonate parameters were observed in sediments and water column at the release site. $CaCO_3$ dissolution had a buffering effect on the dissolved CO_2. There was no evidence of elevated 'dissolved' flux of DIC. Impacts were spatially restricted and recovery to background values occurred within a month after terminating the gas release.

Biological Impacts of CCS Leakage, Monitoring Opportunities; Steve Widdicombe, PML

The effect of CO_2 is very dependent on the nature of the habitat, for example, what is the chemical buffering potential of the sediment. At the QICS site on injection of CO_2 there was seen to be a decrease in species, though there was an increase at the control site due to natural seasonal changes. After injection there was a decrease at both sites, due to a storm and after 12 months there was a return to the initial state. This all shows the importance of understanding the natural cycles within the system and other environmental drivers that might affect the fauna.

Marine organisms are used to natural changes in CO_2 and pH so many have developed physiological mechanisms to cope with short term fluctuations. These mechanisms will require energy which may be provided by increased feeding and/ or reduced growth and reproduction. In the short term this may be a suitable solution but in the long term this may not be sustainable so with leakage it is important to consider not only the magnitude of the leak but also how long it persists. There may also be a behavioural response, such as coming to the surface. Another indicator could be microbial mats, where cyanobacteria bloom in the presence of CO_2, though they will only exist in shallow areas with lots of light. Biological monitoring can integrate

the impacts of periodic or stochastic events; quantify the severity and spatial extent of damage caused by CO_2 leakage on organisms, communities, processes and ecosystem services; track recovery of the marine system following a leakage; some behavioural or microbial responses may illustrate visually areas where CO_2 (or other pollutants) may be leaking to the sediment surface or altering pore water chemistry; provide assurance that marine ecosystems are not being impacted by CCS activities; and describe natural cycles to differentiate between natural and CO_2 induced changes.

One area of impact that has received little study so far is the potential impact of displaced formation water on marine organisms.

Accounting for Environmental Variability in Monitoring Design and Leak Detection in Bass Strait; Nick Hardman-Mountford, CSIRO

A leak plume was simulated, forced by measured current velocities. The source of the plume was varied randomly (1000 iterations) and the results were analysed to assess monitoring strategies for such a dynamic marine system. The oscillating flow caused an intermittent plume, which may be more difficult to detect. Using the model to evaluate optimal placement of sensors suggested that the first sensor should be placed where the CO_2 is most likely to flow according to the modelling results, the second sensor where the first sensor is least able to detect and so on, to increase total coverage. Increasing the number of sampling locations would decrease the rate of leakage by increasing detectability, but with diminishing returns as more sampling locations are added. Consideration of natural environmental variability from background marine CO_2 monitoring showed this to be 6-20x the state of the art detection limit, thus limiting the detectability of the plume more than sensor/method sensitivity constraints.

Preliminary conclusions from this study are that the plume is potentially mappable; the baseline environmental variability overwhelms measurement sensitivity; a few fixed monitoring sites are unlikely to distinguish the plume from background environmental variability, except for large leaks; and large area monitoring is needed to identify the plume above background variability, i.e. reduce the detection threshold towards sampling / sensor limits.

Session 8: Complexity of the Natural System and Implications for Quantification

Summary

For terrestrial baselines, atmospheric monitoring is more sensitive close to the ground, wide-area coverage is needed and leaks may be small; it is important to understand baselines and 'baseline functions' and what the influencing parameters are. Marine systems are complex, though detection will be better closer to the seabed. There is much model based work and real data is needed. Understanding the system will better enable understanding of false alarms. It is important to understand the reality and site specificity, and what questions to ask. This understanding can be increased through the use of controlled release projects.

Natural Variability in Onshore Baselines; Dave Jones, BGS

Case studies of Weyburn, CO_2FieldLab and ASGARD are used to demonstrate the usefulness of different soil gas, flux and atmospheric monitoring approaches. There are clear seasonal and year on year effects at Weyburn with variation related to rainfall and temperature. Season effects are also seen in continuous monitoring at Weyburn; soil gas measurements broadly follow temperature with a slight lag. Short term increases of CO_2 found with eddy covariance, during the working day, were found to be from human activity at a nearby well. At both ASGARD and CO_2FieldLab eddy covariance and soil gas and flux methods were used. Atmospheric methods like Eddy covariance are affected greatly by the wind speed and direction. At this site there was a low background CO_2 flux and seepage was therefore easily distinguishable.

Monitoring needs to take account of background variation; some experiments have given a clear cut difference above the baseline, but at another site, this could theoretically fall into the background. Baselines are site specific depending on location, soil and vegetation characteristics, climate and weather (T, P, rain, wind). Gas concentrations and fluxes vary diurnally, over days to weeks, seasonally and from year to year. Monitoring needs to take account of these changes (done for continuous monitoring). Soil gas is generally best measured in the autumn/winter, when there is low biological activity. Leakage signals can give clear cut anomalies, but at very low levels could disappear into the background noise. Atmospheric monitoring is more

sensitive close to the ground with higher leakage detection capability at low wind speeds.

Permanent Soil Gas Monitoring; Franz May, BGR

Due to temporal variability of soil CO_2, caused by numerous controls, including amongst others land use, weather, soil type, temperature, water flux and microbial activity; site specific understanding is necessary. The concept of 'baseline functions' was introduced, describing the complexity of interactions behind baselines.

Examples from the Altmark natural gas field were presented for locations and periods where temperature and soil gas CO_2 concentrations follow each other, but in the summer the CO_2 decreases, due to the land becoming very dry. Other examples illustrate a trend with barometric pressure, but with a 20 hour time shift.

Challenges to soil gas monitoring include spacing and frequency of sampling points and formulation of baseline functions from sparse data, as well as issues of quantifying diffuse flux. Wet lowland sites, cause particular issues with ponding water, whereby the CO_2 level drops close to zero at a critical water level. Condensation and freezing can cause technical issues with the equipment, and while there are technical solutions, these can be very expensive.

It is recommended that site characterisation is always done prior to installation; where possible avoid wet, disturbed or soils rich in organic matter; to abandon and replace unsuitable sites early; recording of technical and environmental parameters is essential for process understanding and data interpretation; monitoring concentration (gradients) below top soil (more sensitive than surface fluxes); process simulations can supplement baseline measurements and can be used to establish calibrated baseline functions.

Natural Variability in Marine Baselines; Jerry Blackford, PML

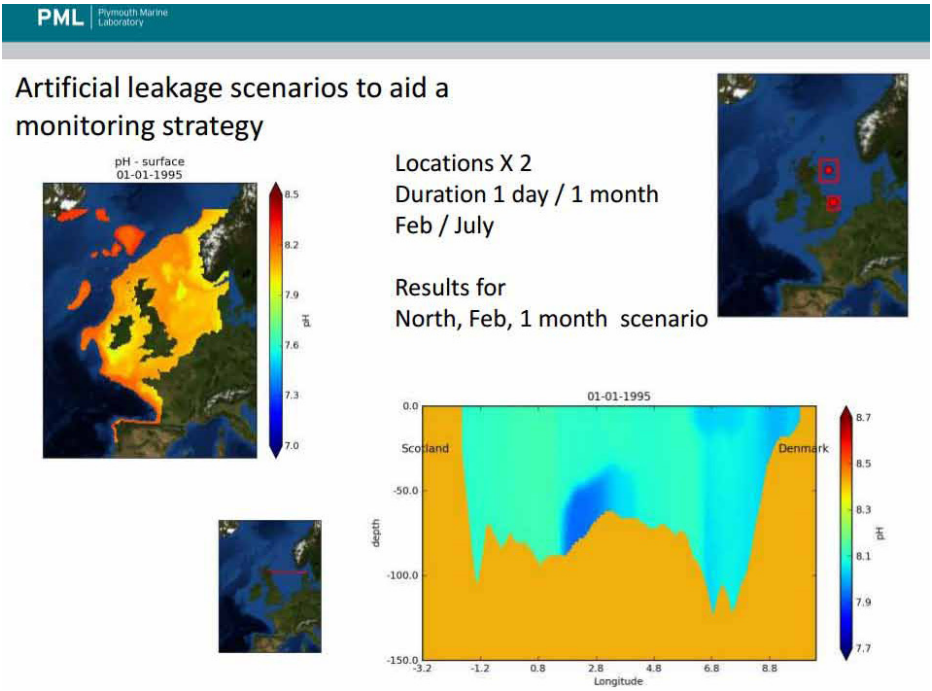
This study was carried out using model based data, which a range of influences, including the buffering effect of the carbonate system, release chemical species, temperature, pH, effect on nutrients and bacterial effects. The carbonate system is very complex, DIC (dissolved inorganic carbon) is a

good indicator, but is difficult to measure. pCO_2 and pH are easier to measure, but more understanding of the system is needed.

There is much variability in temperature, which will affect pCO_2, the biological variation changes pH – the variation is around 4 pH points. Real data shows great variability.

The nature of the leakage plume is that there will be a small region where there is a large difference and around that there will be smaller differences, which will be harder to determine and further away than that we will not able to detect, but the effects will be small/ none. However, it is not so simple as there will be an initial buoyant plume, but as dissolution of CO_2 takes place, there will be lateral migration and there is also the tidal effect.

Covariance of ph with oxygen/ temperature can be used to aid a monitoring system, but to take out the biological effects, very site specific data is needed. In summary the marine system is highly dynamic in space and time, at



Modelled pH Baselines to Assess Leakage Monitoring

multiple scales, especially in regions favoured for European CS; pH etc similarly vary with multiple drivers; a leakage plume is dynamic affected by tidal mixing and seasonal stratification; the most detectable signal will be close to the epicentre. The relatively larger area of slightly increased CO2 may be hard to distinguish from the background variability. Spatial resolution is critical; covariance with O_2 & T shows some promise, but natural signals are also variable; algorithms, if useful, will need to be site and season specific.

There is a need for extensive baseline data including carbonate chemistry, sediment carbonate concentration and biological proxies.

Variability of Monitoring Measurements – How do we Monitor "Nothing"?; Charles Jenkins, CSIRO/ CO2CRC

At the Otway site, soil gas was monitored through annual surveys, largely due to access issues, as much of the area is agricultural – there are 6 years of data. The CO_2 source is magmatic and so the C13 works as a good tracer. There is a large spread of data and the median CO_2 has decreased over time. This change is all due to weather changes, as this area has come out of a very long drought, then been subjected to flooding. Which emphasises the need to understand the background CO_2.

In the Bass Strait there is a reasonable idea of variability of DIC, but more information is necessary to model the plume as it is important to keep the false alarm rate low. Real data is needed to put into the statistical model and it is necessary to understand the physical processes and set an appropriate threshold. We need to have models of what happens when a leak occurs, in order to understand when we are measuring something and not nothing.

If the only model of the data is that there is nothing there, then the data will never match perfectly and in fact they often will not match very well. So we need to understand what does match better, or, are the models you are worried about plainly a worse match. We are in the business of making decisions with data and to do this we have to choose between nothing and something.

Study of Site Specific Tool Sensitivity; Sue Hovorka, BEG

When selecting a tool, it is important to consider, not just what is being detected, but whether that tool is fit for purpose for that particular site. Several parameters have been reviewed including groundwater geochemistry,

pressure, thermal and seismic sensitivity. Freshwater geochemical sensitivity will depend on groundwater composition and what would change were there to be leakage and what can be measured. When measuring AZMI (above zone monitoring interval) pressure, the pressure increase will depend on the boundary conditions and well spacing. For seismic sensitivity, a stronger 4D signal will results from higher rock compressibility and higher fluid compressibility contrast. Other sensitivities are the thickness of the layer and depth. When several experts used data from Cranfield, they put the plume in different places, which can make it difficult for regulators to assess the situation, but what the regulators need to know is when to ask questions about the data, and understanding different sensitivities and basic principles can help.

The next steps of the project are to add pulsed neutron sensitivity and try to frame more near-surface tools.

DOE Carbon Storage Goals and Supporting Research; George Guthrie, NETL; and Discussion Session

The main aim of the US DOEs carbon storage programme is to develop effective and economically viable enabling technologies — then validate them in small- and large-scale (extensive monitoring) field projects to ensure safe and permanent storage of CO_2 from power and industrial sources.

The 99% storage research goal was originally derived from the IPCC Special Report's policy summary, though this has evolved through time to now being to develop technologies to measure and account for 99% of injected CO_2. Other goals are to predict storage capacity to within +- 30%, to improve storage reservoir efficiency, and to develop best practice manuals.

Topics were given for the meeting to discuss:

- How do the CCS goals compare internationally?

In the EU, a project will only be permitted if no leakage is expected; there is then a zero leakage assumption, though leakage must be monitored for. It is only if the CO_2 reaches the surface that emissions need to be paid for. The US is partly similar, with the clean air act, whereby emissions need to be accounted for, though there is not an emissions trading system that there is in the EU.

No other country has specified numbers in measuring CO_2 retained in the ground. Only to quantify CO_2 leaked into the atmosphere or water column.

In the EU mitigation and testing corrective measures are high on the agenda.

In Australia the goals and regulations are not based so much on the IPCC Special Report, but on potential significant impacts on the environment and petroleum resources. It also needs to be shown that the reservoir is acting as predicted.

- Are the drivers for goals similar or different?

In the US, current regulatory drivers are protection of USDWs.

- Have the drivers changed over time?

The drivers are moving from just storage performance to include accounting.

- Is there agreement on the technical justification for goals, how far can we advance these technologies?

The most sensitive meters in pipelines have a 1% uncertainty, therefore it is extremely unlikely that techniques measuring in the deep subsurface, will ever be able to obtain the same accuracy. It is useful to know how much CO_2 can be quantified, but 99% is too high for in-situ storage.

Goal should be for 100% retention, but this may never be able to be quantified exactly.

The goals could also be related to the power plant capture rate. Is it acceptable for this to change, but not acceptable to the storage retention to go below 100%. The full chain must be considered.

- Can goals be modified based on knowledge gained to date for future revisions?

A reasonable goal might be to look at what is expected to be monitored for other fluid injection (e.g. waste water/ gas storage).

The goal was set before there was a regulatory environment, so an idea could be to step back and completely update the goals with this is mind and try not to set numbers, which may not be a good idea with respect to public perception. A suggestion is to identify leak sources and if a leak were to reach a sensitive zone, be able to carry out conformance and containment monitoring. This is not to say that a site should be permitted if leakage is

expected, but that this needs to be part of the risk assessment. There should be objective based regulations, so if looking at safety, to have risk as low as is reasonably practicable. It can be shown quantitatively what the lower detection limit is.

A research goal could be to show if that the site is acting as expected and if not, whether there is any significant environmental impact.

Goals could also be to incentivise research in area where it is needed, such as:

- Controlled release experiments
- Understanding the intermediate zone between the reservoir and the surface (overburden)
- Fault transmissivity and fault detection

There could be rankings on key uncertainties for which there is not sufficient investment.

It was suggested that goals be differentiated more clearly into objective for research, objectives for regulators and objectives for accounting conventions. All three are different, so it might help to separate them.

Session 9: Discussion Session – Realistic Monitoring of CO_2 Migration from the reservoir to the Surface

Discussion points:

- What is "realistic" to monitor? (e.g. very small diffuse leakage)
- How to monitor wide areas esp. USDW
- Missing methods of monitoring?
- Mechanisms of migration in overburden – what does it look like?
- Are we thinking enough about consequences ("so what")
- Do we adequately convey the limitations on what we can do to the relevant stakeholders?

The theme of the meeting was to consider realistic monitoring, which includes understanding what is being monitoredand what is significant.

It is necessary to see the CO_2 during injection as if the first time it is seen is

when leakage is occurring, it may already be too late. Monitoring needs to be done early and cost effectively. Some key questions are; where will the CO_2 go? How quickly will it get there? Will it cause a significant problem, ie 'so what?'.

In general, it seems that offshore monitoring is much easier than onshore, for example because of poorer repeatability of seismic onshore, land-owner access issues, and background variability and complexity. It is useful to think in terms of detection limits, especially in a complex system. It may also be useful to think about how simple the system can be made.

Considering the Lindeberg leakage rates (from Andy Chadwick's presentation), it might help to think statistically about how many bad sites can be afforded.

Diffuse and focussed flow was discussed, what is more likely? What can be detected? From results of projects, diffuse leakage is looking less likely, especially offshore because it does not have a vadose zone for atmospheric mixing, and any leakage offshore is likely to be in the form of bubbles, which can be detected. This may be a useful focus. However, diffuse leakage could occur if there is lateral spread before the CO_2 reaches the surface (which has been seen in experiments) and would be harder to detect, but its extent and importance (in terms of the total leakage) has not been evaluated so it isn't known if it is significant or not. It might be useful to look for diffuse halos around anomalies, in order to discover the best detection method, though this may be buried in noise.

As the seafloor is heterogeneous, it is thought likely to be a more focussed flow. From modelling it can be seen that there is strong fingering if there is heterogeneity.

The type of flow will depend on processes, it can be driven by preferential pathways, or buoyancy/relative permeability effect. Onshore, it can get more complicated, due to soil etc. and can potentially be diffuse. It can be focussed at depth, spread laterally and become more diffuse, then appear at the surface as smaller point sources.

As everything on seafloor is saturated, flow will be through capillary pressures - focused flow. At terrestrial sites, diffuse flow may be more possible if the soil is well mixed with atmosphere. It wouldn't be focused where there is not a

capillary barrier.

Monitoring for leakage was discussed.

Most monitoring is at wells and there are other wide area methods at the reservoir (seismic). At the surface there are other wide area methods, such as using AUVs. However there is a shortage of techniques for the overburden.

Some sites will use tracers, while others may not. Tracers may be useful, but consideration has to be given to how they are deployed. The right partitioning coefficient is needed as partitioning onto mineral phases needs to be understood. It is be exercised in the use of tracers as any near surface spillage will limit their usefulness.

Pressure may be the most useful method for understanding what is occurring in the overburden, though there needs to be more work separating out the geomechanics. The expectation will be for projects to monitor the overburden and Gorgon and Quest will have downhole pressure gauges to do this. However, this may not be necessary in confined aquifers, e.g. the ROAD project.

There is also the potential to utilise passive seismic methods more as ambient noise can be used as the source, which will propagate through the subsurface and reflect back. Different noise levels will give more information.

Session 10: Conclusions

To draw the meeting to a close, the overall gaps, conclusions and recommendations were agreed.

Gaps in knowledge exist for the overburden, in terms of understanding mechanisms of transmission of CO_2 and monitoring. There is a need for techniques for wide area monitoring in the overburden and at the surface which are also able to find small leaks. There was a call for work on a common terminology or glossary, and it was noted that the ISO work includes this. First projects set important precedents, and there is a lack of examples of completed regulatory compliance to set such precedents. There is also a need for definition of consequences that matter, and their context (research, regulatory, accounting).

Learning from medium sized public-funded projects that will run under

regulatory regimes would be good for researchers to be linked in to see where there are issues, and feedback to regulators, and IEAGHG could have a role in that feedback. This forum is good for researchers to share and consolidate ideas and experiences.

The overall conclusions were that offshore monitoring is looking promising, that near-surface monitoring has advanced significantly, recognition of the value of controlled release projects, that there is better understanding of environmental impacts and their use for monitoring, acknowledgement of the complexity of natural variability and the implications for monitoring, and that regulatory support is very important in fostering early learning with research pilot and demonstration projects. In the U.S., some demonstration scale projects are being permitted as if they were full-scale industrial injections and an additional, more-flexible, way of permitting the demonstration scale projects would be beneficial (as is done in the EU). This is important because the learning from the demonstration projects can significantly inform larger scale and longer term permitting needs.

In terms of recommendations for work and actions, the following summary list was agreed:

- More work on overburden topics, such as migration mechanisms, faults, natural analogues
- Need for meaningful engagement with regulatory community
- Value of conceptualisation and testing of failure scenarios
- Monitoring for geomechanics, including entire system geomechanics
- More controlled releases
- Need for more data for baselines and 'baseline functions', especially marine
- More consideration of diffuse leakage and mechanisms
- Understanding detection limits.

It was also recognised throughout the meeting that an important next stage is the progression from research projects with more intensive monitoring, to industrial-scale projects with less intensive but appropriate monitoring, and so work in this context will be required.

Site Visits

Geoscience Australia organised very interesting sites visits to the Ginninderra controlled release site, to Geoscience Australia where the group saw the cores from the CO2CRC Otway project, and to local geological features in the Canberra region including outcrops of limestone, sandstone beds, examples of faults at different scales, an unconformity, and a new dam being filled.

Steering Committee

A steering committee was formed to develop the technical programme of this meeting, formed from members of the steering committees for the two respective networks. The steering committee members were:

- Tim Dixon, IEAGHG (Chair)
- Charles Jenkins, CSIRO/CO2CRC (Co-Chair, Host)
- Andy Chadwick, BGS
- Sue Hovorka, The University of Texas
- Lee Spangler, Montana State University
- Jerry Blackford, PML
- Julie West / Dave Jones, BGS
- Hubert Fabriol, BRGM
- Katherine Romanak, The University of Texas
- Don White, NRCan
- Steve Whittaker, Global CCS Institute
- Jun Kita, RITE
- Ziqiu Xue, RITE
- Millie Basava-Reddi, IEAGHG

2013-17 IEAGHG/OPEC: REPORT OF WORKSHOP ON CCS AND CDM

Introduction

This report outlines the discussions and outcomes from a workshop jointly held by the IEA Greenhouse Gas R&D implementing agreement (IEAGHG) and the Organisation of Petroleum Exporting Countries (OPEC) on the topic of "Carbon Dioxide Capture and Storage in the UN Clean Development Mechanism". The workshop was the latest in a series of activities by IEAGHG in supporting CCS in the CDM. The objective of the workshop was to share knowledge amongst IEAGHG technical experts and OPEC secretariat and member country delegates, and enhance the understanding amongst all participants of the issues, challenges and approaches to developing CCS projects under the UNs clean development mechanism (CDM) with a focus on OPEC member countries.

It was held on 29th - 30th October 2013 at OPEC's headquarters in Vienna, Austria.

Workshop Structure and Participation

The main topics covered in the workshop were as follows:

1. CCS technical, economic and regulatory matters;
2. Case studies of CCS projects under development around the world; and,
3. CDM regulatory and methodological requirements for CCS.

The final session of the workshop involved a group task, where participants worked together to develop solutions for CCS CDM related issues and challenges.

Participants were made up of technical experts on various aspects of CCS and CDM, IEAGHG and OPEC secretariat staff, and OPEC member country delegates whose work involves consideration of CCS and climate change policy. Participants in the workshop were from the OPEC member countries of Algeria, Iran, Libya, Qatar, Saudi Arabia, United Arab Emirates, and Venezuela. A full list of participants is set out in Annex A.

Framing Issues

The CDM allows emission reduction projects in developing countries to generate tradable carbon credits – know as certified emission reductions or "CERs" – that can be sold to developed country Parties to the Kyoto Protocol to help them meet their emission reduction targets. According to statistics published by the UNFCCC, the CDM currently has stimulated over 7000 low-carbon projects in developing countries, representing over 2,000 Mt of CO_2 emission reductions.

The CDM is governed by rules set out in its modalities and procedures,[1] which covers methodological, procedural and governance aspects for registering emission reduction projects as CDM project activities. Several unique issues posed by CCS projects compared to other emission reduction project types meant that several Parties held concerns regarding the inclusion of CCS in the CDM under the existing modalities and procedures. For this reason, new modalities and procedures specific to CCS projects were agreed at the Durban UN Climate Conference in 2011 (the CCS M&Ps). 2 The CCS M&Ps address several concerns of Parties through inclusion of the following elements:

1. Technical standards and guidance – in order to mitigate the risk of carbon dioxide (CO_2) leaking from geological reservoirs into the atmosphere (known as "seepage"), it is essential that only properly selected and managed geological reservoirs are used. To address this, the CCS M&Ps contain technical standards and procedures for geological storage site selection, risk assessment, monitoring and management;
2. Environmental integrity – in the event of seepage, the environmental integrity of CERs generated by a CCS project activity would be compromised. This risk is managed through provisions in the CCS M&Ps relating to a "net reversal of storage", which allocates responsibilities and procedures for replacing emission reduction units equal to the amount determined to have seeped;
3. Damages, remediation and liability – in case of seepage and local impacts, especially over the long-term, the CCS M&Ps set out provisions for the allocation of "liability" for the geologically stored CO2 and obligations for remediation and compensation;
4. Participation requirements – because many of the issues described above

are best governed under local laws and regulations, new participation requirements are included for countries wishing to host CCS CDM project activities.

OPEC member countries are interested to develop CCS projects to mitigate CO_2 emissions in their countries, and a key means for financing such activities is through development of projects under the CDM.

Technical, Legal, Economic and Regulatory Aspects

The workshop was opened and welcomed by Dr Abdul-Hamid, Director of Research at OPEC. Following welcoming messages, the first day concentrated on a range of technical, regulatory and economic factors affecting CCS development and deployment, based around the issues set out in the section above. CCS technology, capture applications, geological storage and costs.

Participants were provided with an overview of CCS, ongoing activities around the world, and typical technical applications covering both capture and geological storage of CO_2.

Following the presentations, participants discussed how CCS can be best presented as an effective option for climate change mitigation within various fora, and in particular the UNFCCC. It was commented that in general, there is a low level of understanding about CCS technologies within this forum, and many concerns about safety and costs persist amongst UNFCCC negotiators, especially from developing countries. It was broadly agreed that greater efforts need to be made to increase awareness of the benefits and role that CCS can play in reducing greenhouse gas emissions to atmosphere, perhaps through inclusion of a common umbrella for CCS-related interests as can be seen for avoiding emissions from deforestation under the auspices of the UNFCCC (known as "REDD"). The challenge of making a case for CCS investment with low CER prices and the emergence of shale oil and gas at the current time was also discussed. In these contexts, it was noted that greater effort should be made to:

- Present CCS costs relative to renewable energy sources and with different fuel costs; and,
- Highlight the wider benefits available through utilisation of captured CO_2 such as with enhanced oil recovery (EOR) or use in algae growing,

which can help offset the costs of capture and provide important sources of revenue to project developers.

A range of technical options for utilising CO_2 in EOR to support more rapid CCS deployment were also discussed, including the use of CO_2 flooding earlier in the life of an oilfield.

Site selection, characterisation, risk management and monitoring

A review of different techniques applied to select geological storage sites and to assess risk and safety of particular storage reservoirs was provided to participants. The experience presented was drawn for real world project examples being developed by Shell. Following this, an overview of techniques to detect CO_2, and in particular leaking CO_2, was provided, drawing on examples in the USA and Canada.

The ensuing discussions focussed on the need to increase awareness amongst the public and policy-makers about the range of measures and techniques that can be used to reduce risks and ensure the safety of CCS projects. Some concerns were raised regarding the rigour of requirements under the CCS M&Ps, although it was noted that these are similar to requirements in developed country jurisdictions, and are technically achievable.

Regulation, liability and costs

The range of legal instruments applicable to regulate CCS were introduced to participants, and specific attention was given to matters relating to liability. The presentations showed that a framework for regulating CCS is emerging in many parts of the world under international law (e.g. London Convention; 2006 IPCC Guidelines for National Greenhouse Gas Inventories; the CCS M&Ps) and also regional and local laws (e.g. in Europe and the US). It was also noted that the CCS M&Ps draw heavily on the precedents set down in international and national laws and regulations governing CCS. An overview of liabilities associated with CO_2 storage sites was presented, and the principles and models for allocating liability outlined from a project developer perspective. The example of the EU approach was used to illustrate approaches and issues.

Most of the discussions about the session focussed on liability matters, and in particular the challenges of getting private investment, the appropriate balancing of risk and rewards, and the potential role of the insurance industry

in supporting such a risk/reward balance.

Case studies

Presentations were provided for various ongoing CCS project developments around the world, including the Quest Project (Alberta, Canada), Weyburn-Midale and Aquistore (Saskatchewan, Canada) and Peterhead-Goldeneye (Scotland, UK).

CCS in the CDM

The second day of the workshop was dedicated to issues relating to CDM and implementation of CCS projects thereunder.

Legal, technical, procedural and methodological aspects

The first session gave participants an overview of the CDM, covering its origins, its rules and governance arrangements, its basic principles and procedures for CDM applications. This was followed by specific presentations regarding the CCS rules as set out under the CCS M&Ps, and the existing standards and documentation for CCS CDM applications, namely: the guidelines and templates for:

1. completing an proposed new methodology for CCS (CCS PNM), and;
2. completing a project design document (PDD) for a CCS project activity under the CDM.

This included brand new up-to-date provisions specific for CCS within the PNM and PDD templates. Thoughts were also provided about the future of the UN process, the CDM and other new forms of climate finance that emerge under the UNFCCC (e.g. the Green Climate Fund, the New Market Mechanism).

Participants then discussed a variety of aspects of CCS inclusion under the CDM, including how future mechanisms could draw from the CCS CDM experience to-date, and the general challenges for launching a CDM process for CCS today given the uncertainty around the future of the international carbon market. It was generally agreed that even though CDM may not be a clear incentive to develop CCS in developing countries today, much of the experience and knowledge designed into the CCS M&Ps and related implementation aspects (e.g. the PNM and PDD guidance) could be readily

transferrable to new forms of climate finance that may emerge over coming years.

Group Work

The final sessions of the workshop focussed on a group work exercise based on a hypothetical case study involving the capture and storage of CO_2 from natural gas processing plant that currently vents to atmosphere, and its dehydration, compression and storage in saline formation. In the group work, participants were asked to solve questions around project boundaries, project emissions, baselines, additionality, regulatory issues, and monitoring.

The group work provided participants with an opportunity to learn about the approaches and issues for CDM project development in a more nuanced way, based the particular issues presented by the case study example. The participants from OPEC member countries brought an interesting range of views to the discussion based on their own expertise and perspectives, covering technical research managers in petroleum engineering to senior climate change negotiators in the UNFCCC. Based on the information provided in the workshop, and their own perspectives, the participants identified the key issues, and answers and approaches to these. Rapporteurs from each group presented their answers in plenary, and results were compared to a set of model answers prepared by the technical experts. On the whole, the group session demonstrated that participants had grasped many of the technical, legal and methodological issues associated with developing a CCS CDM application. It was again noted that many of the items under consideration were likely to be transferable to wider discussions regarding CCS and climate finance under the UNFCCC.

Conclusions

The workshop provided an opportunity for OPEC member country participants to learn more about the various aspects of CCS project development, how these would apply in developing a CCS project under the CDM, and how the issues may be transferrable to other types of climate finance in the future. It also allowed technical experts to discuss various issues of interest in the context of OPEC member country specific circumstances, responsibilities and respective capabilities. The spirit of open dialogue and information exchange meant that all participants were able to gain new knowledge and ideas through from the workshop. More broadly, participants appreciated

and enjoyed the workshop as a learning exercise.

Many thanks go to Paul Zakkour of Carbon Counts, the hosts OPEC, and to the technical experts from CCSA, The University of Texas, Shell, PTRC, and from IEAGHG.

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

Pure Office, Cheltenham Office Park, Hatherley Lane
Cheltenham, Glos. GL51 6SH, UK

Tel: +44 1242 802911

mail@ieaghg.org
www.ieaghg.org