40th ExCo MEETING, 31st OCTOBER - 2nd NOVEMBER 2011, LONDON, UNITED KINGDOM
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IEA GREENHOUSE GAS R&D PROGRAMME
40th EXECUTIVE COMMITTEE MEETING

MOTION ON PROCEDURE AT THE MEETING

The following motion is proposed:

Anyone who is present at this meeting shall have the right to speak, when recognised by the Chairman.

To gain the Chairman’s attention, members should turn their nameplate onto its end. This will help the Chairman ensure that everyone who wishes to speak has a chance to do so.
IEA GREENHOUSE GAS R&D PROGRAMME
40th EXECUTIVE COMMITTEE MEETING

ELECTION OF CHAIRMAN

By the rules of the Implementing Agreement the Officers of the Executive Committee are subject to election on a 2-year cycle. The Chair and Vice-chair must represent Contracting Parties. Sponsors are not eligible for Office, but by previous practice of the ExCo, are entitled to vote in the election.

The position of Chairman is due for election at this meeting. (The position of Vice-chairman will fall due for election at the 42nd ExCo in autumn 2012.)

Prof Kelly Thambimuthu has agreed to stand for re-election.

The Operating Agent has contacted members to ask if any other members wish to nominate themselves to stand as Chair. If any other nominees come forward the members will be advised at the ExCo meeting prior to the election taking place.

**Actions**

In the event that Prof Thambimuthu is the only nominee

A Proposer and a Seconder for Prof Thambimuthu’s nomination will be required.

Then members will then be requested to unanimously approve the election of Dr Kelly Thambimuthu as Chairman of the IEA Greenhouse Gas R&D Programme Executive Committee for a further 2 years.
### IEA GREENHOUSE GAS R&D PROGRAMME
#### 40th EXECUTIVE COMMITTEE MEETING
**London, United Kingdom, 31st October - 2nd November 2011**

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IEA GREENHOUSE GAS R&D PROGRAMME
39th EXECUTIVE COMMITTEE MEETING

LIST OF ATTENDEES

Members

Dr John Carras CSIRO Australia
Prof Kelly Thambimuthu (Chair) University of Queensland Australia
Dr Eddy Chui NRCan Canada
Dr Malcolm Wilson University of Regina Canada
Mr Eemeli Tsupari VTT Finland
Mr Jürgen-Fr. Hake Forschungszentrum Jülich Germany
Dr Ryo Kubo RITE Japan
Mr Daan Jansen ECN The Netherlands
Mr Peter Versteegh Agentschap NL The Netherlands
Dr Klaus Schöffel Gassnova Norway
Dr Taher Najah OPEC South Africa
Dr Anthony Surridge SANERI South Africa
Dr Jang Kyung-Ryong KEPRI South Korea
Miss Mónica Lupión CIUDEN Spain
Mr Sven-Olov Ericson (Vice Chair) Ministry of Sustainable Development Sweden
Ms Camilla Axelsson Swedish Energy Agency Sweden
Dr Gunter Siddiqi Swiss Federal Office of Energy Switzerland
Dr Jay Braitsch US DOE USA
Mr Markus Wolf ALSTOM
Mrs Gina Downes CIAB
Dr Sven Unterberger EnBW Kraftweke AG
Dr Tim Hill E.ON
Mr Richard Rhudy EPRI
Dr Klaas van Alphen GCCSI
Mr Shimada Hidemitsu JGC
Dr Johannes Heithoff RWE Power AG
Dr Gabriel Marquette Schlumberger
Dr Tony Booer Schlumberger
Mrs Annet Stones Shell
Dr Helle Brit Mostad Statoil
Mr Dominique Copin Total

IEA GHG

Dr John Topper IEA EPL
Mr John Gale IEA EPL - IEAGHG Team
Mr Neil Wildgust IEA EPL - IEAGHG Team
Mr Tim Dixon IEA EPL - IEAGHG Team
Observers

Prof Krzysztof Warmuzinski  Polish Academy of Sciences  Poland
Mr Mark Boneham  Alstom  South Africa
Ms Kate McIntyre  Anglo American Thermal Coal  South Africa
Ms Nandi Malumbazo  CSIR  South Africa
Dr Jovita Juodityte  Eskom  South Africa
Mr Ras Myburgh  Eskom  South Africa
Neo Coangae  Exxaro Resources Ltd  South Africa
Mr Paul White  Fossil Fuel Foundation  South Africa
Assoc Prof Nicola Wagner  University of Witwatersand  South Africa
Prof Rosemary Falcon  University of Witwatersand  South Africa
Mr Brendan Beck  IEA  France
Ms Justine Garrett  IEA  France

Apologies

Mr Theodor Zilner  Ministry of Transport Innovation and Technology  Austria
Mr Trygve Riis  The Research Council of Norway  Norway
Mrs Brony Daw  DECC  UK
Mr Jeremy Martin  DECC  UK
Mr Kevin McCauley  Babcock & Wilcox  UK
Dr Ilkka Savolainen  VTT  Finland
Mr Keith Burnard  IEA  France
Mr David Jones  BG Group  France
Mr David Campbell  ScottishPower  UK
Mr Arthur Lee  Chevron  France
Dr Nathalie Thybaud  ADEME  France
Mrs Sarah Edman  ConocoPhillips  UK
Dr Ziqui Xue  RITE  Japan
1. WELCOME AND INTRODUCTIONS
On behalf of the Executive Committee (ExCo), Kelly Thambimuthu (Chair) opened the meeting and welcomed all new members, new member representatives and observers attending the ExCo for the first time. Kelly specifically thanked Tony Surridge for facilitating the first meeting in South Africa. Dr Surridge welcomed the Executive Committee members to South Africa.

2. ADOPTION OF AGENDA
The agenda and motion for procedure at the meeting (documents GHG/11/01 and GHG/11/02) were adopted.

3. MINUTES OF THE PREVIOUS (38th) MEETING
Documents GHG/11/03 and GHG/11/04 refer. John Gale presented these papers, and described that an only couple of members made minor contextual and grammatical amendments, which have been made. Members formally approved the minutes of the 38th meeting.

4. MATTERS ARISING FROM THE 38th MEETING
Document GHG/11/05 refers. John Gale presented this paper and explained that the majority of actions were complete, several will be addressed during the course of the meeting, or immediately afterwards. In relation to Indian participation in the activities of the ExCo, this is still outstanding and our desk officer at the IEA is involved with this action.

Peter Versteegh (Netherlands) commented on the action on Geo-engineering and understood that the action was to review following GHGT-10. John Gale explained that we brought forward the action on unconventional storage first. Staff time will be balanced to address this first, and then follow on to the geo-engineering topic.

Action 1: General Manager

5. RENEWAL OF IEA MANDATE
Document GHG/11/06 refers. John Gale reminded members that the IEAGHG has to renew our IEA mandate which members approved at the last meeting. The required documents have been circulated and members need to approve these to enable John Gale to send them to the IEA in time for the next WPFF meeting scheduled for June 2011. Members unanimously approved the documents and requested John Gale to submit these to the IEA on their behalf.

Action 2: General Manager

John Gale informed members that it had been brought to his attention by the IEA’s Office of Legal Council (OLC) recommends that our Implementing Agreement legal text needs amending in particular Article 12 (a).

The IEA Legal Office recommends that the GHG IA ExCo vote unanimously to amend Article 12(a) of the IA legal text, for two reasons. First, although the ExCo has voted to invite Masdar, an entity from an OECD non-Member country, to participate in the IA as a Sponsor, the GHG text does not permit Sponsors from OECD non-Member countries. Second, the current Article 12(a) allows the ExCo to invite Sponsors only “in exceptional cases.” This does not accord with the fact that the GHG IA has 23 (and soon 24) Sponsors. Third, and most important, is that this provision is inconsistent with Article 3.3 of the IEA Framework, which is incorporated into the GHG IA legal text as Exhibit A:

"3.3 Sponsors may be
(a) Entities of OECD member countries or OECD non-member countries who are not designated by the governments of their respective countries to participate in a particular Implementing Agreement; and
(b) Non-intergovernmental international entities in which one or more entities of OECD member countries or OECD non-member countries participate."
Current Article 12(a)

"The Executive Committee may in exceptional cases and with the approval of the Committee on Energy Research and Technology (CERT) of the Agency invite any entity of an OECD Member country that is not designated by that country to participate in the Agreement or any non-inter-governmental international entity in which one or more entities of OECD Member countries participate, to participate in the Programme as "Sponsors" in accordance with this article."

For the reasons above, the IEA Legal Office suggests that the ExCo vote unanimously to replace the above provision with the following text:

Proposed Article 12(a)

"The Executive Committee may, with the approval of the Committee on Energy Research and Technology (CERT) of the Agency invite any entity from an OECD Member country or an OECD non-Member country that is not designated by the government of its country to participate in the Agreement, or any non-inter governmental international entity in which one or more entities of OECD Member countries or OECD non-Member countries participate, to participate in the Programme as "Sponsors" in accordance with this article."

As long as the ExCo is voting on amending the GHG IA text, it may as well vote also to make two small changes in Article 3(e)(2):

(2) In cases in which this Agreement requires the Executive Committee to act by unanimity or where no express provision is made in this Agreement, this shall require unanimous agreement of each member or alternate member present and voting, and in respect of decisions and recommendations for which a majority voting provision is made in this Agreement, the Executive Committee shall act by a majority vote of the members or alternate members present and voting.

In the original text the "or" was missing and "provision" was spelled "prevision." These two small typographical errors have persisted in the GHG IA legal text for many years.

The Chair confirmed that he read the proposal by the Legal Office thoroughly, and the changes are necessary and do not change anything in existing agreements. John Topper has also looked through the changes and confirmed that they are not going to alter the IA in any detrimental way.

After discussion and review of the proposed text by members, Members voted unanimously to make the changes to the IA Legal Text as recommended by the IEA Legal Office. John Gale will inform the Legal Office of this decision by members and request the Legal Office make the necessary changes to the IA legal text.

Action 3: General Manager

6. PROGRESS REPORT – MEMBERS PROGRAMME
Document GHG/11/07 refers. John Gale presented this paper; he explained that Mike Haines has now formally retired, but will now work for IEAGHG on a casual basis under contract. Mohammad Abu Zahra has also resigned as he is joining Masdar Institute of Science and Technology (MIST) as an Assistant Professor. He asked it to be noted that Mike has made a particular contribution to the programme. John Topper thanked Mike for 9 years of outstanding and dedicated service, and he will be missed as a full time member of staff. Mohammad will also be missed, but will retain an association with until the beginning of May as he is still involved with the PCCC1. The Chair also thanked Mike, for his contributions to the programme and is grateful that he will still be involved to some extent. Also to Mohammad, who came to us highly recommended and demonstrated his worth in the short time that he was with us.

John Gale explained that we have only produced 2 technical study reports since the last ExCo, but that we have a large number in the pre-reporting stage. There have been problems with certain contractors and several reports have been returned to the contractors at the draft stage as not suitable. This means that we will have a large number to report at the next ExCo, and to remedy this we would like to report
some of these before the ExCo. We could look at webinars for reporting these, which has received mixed reviews from members with some favouring it, and some a little sceptical. It would allow more discussion of individual reports as we would not be so time constrained.

John Carras (Australia) expressed the view that it should be tried, and if it is ineffective, we can revert to the current system. Jay Braitsch (USA) commented that the webinar option is becoming more popular, and suggested that they could be recorded and put on-line for comment, which could be helpful for our diverse time zones. Peter Versteegh (the Netherlands) spoke of his experience of such webinars, and they worked well in IEA situations, so we should trial this; perhaps on the easier, less complex studies first to allow us to evaluate the technology. Richard Rhudy explained that EPRI use this option often, his worry would be in the instance of a controversial report, where it could be tricky to provide full feedback. John Gale explained that this is a fair point, and we would carefully select the reports we used for this. Jürgen-Friedrich Hake (Germany) expressed concerns that the use of webinars could bypass the ExCo approval process for study reports.

The Chair concluded that we have the technical discussion that currently occurs at the ExCo is taken at the webinar, and then a short summary of the webinar is given at ExCo, shortening the discussion at ExCo, and the approval of the overview remains as it currently is. The programme team will initiate a trial of this for 1 or 2 studies and members will review the experience and suitability of the process at the next meeting.

Action 4: General Manager

John Gale described the programmes activities in facilitating implementation since the last ExCo, and the activities arising from these associations. Following on from the DNV JIP CO2QUALSTARE, we were asked to join the new JIP CO2RISKMAN, and as the cost was low, JG took the decision to join, and the guidance documents arising from this will be available on our website. Comments were invited from members, and other than clarification of the CCSA acronym, none were forthcoming.

Under facilitating international collaboration, the programme team have held 3 network meetings since the last ExCo, and the topic of CCS costs which was the subject of a meeting following the last ExCo. Regarding the cost meeting there will be a follow-up meeting as no decision was made as to the establishment of a network. The results of the second meeting will be communicated to members in due course.

Action 5: General Manager

John Gale explained that we will be withdrawing from involvement in practical R&D projects, such as the EC funded projects, and the Weyburn project, and we will switch to the higher level national projects as suggested by members. Following comments from Gabriel Marquette (Schlumberger), John Gale confirmed that we are still maintaining an advisory role on selected projects where we feel we can contribute. We are open to suggestions on participation in projects in the future. The Chair summed up our position as promoting awareness at the technical level, rather than the policy level, and what John Gale was proposing was to ensure we take part in those areas where we are able to make a valuable contribution. We still enable the practical projects to present at our research networks, and this is an area we are keen to retain.

Annet Stones (Shell) asked if we had any influence on the decision to only look at offshore projects in the Netherlands, and John Gale explained that we do not have input on such decisions, we provide technical advisory roles only, rather than policy advisory roles.

On dissemination information, we are moving into the 21st century with a twitter feed and facebook page. Information sharing is now more proactive, with monthly submissions from some members and access to newsletters for articles. We are holding all documents circulated in an information library which can be found on our website.

GHGT-10 was a huge success, with proceedings now available, and the summary report is available on our website. GHGT-11 is now ramping up, with bi-monthly Steering Committee meetings, and the Programme Committee is now forming. A Professional Conference Organiser (PCO) Japanese
Conference Services (who were involved in GHGT-6) has been engaged to take the local organising activities in hand. Budget discussions are in hand, and sponsorship is scaling up. At the most recent Steering Committee meeting, we reviewed the recent situation in Japan and the decision is to continue as planned, especially considering the great distance of Kyoto from the Fukushima region. However we are budgeting conservatively at this stage with a reduced expectancy on delegate numbers compared to GHGT-9 and 10 and due to the low chance of the Japanese government sponsoring the event following recent events. There is a surplus available from GHGT-10 and we propose to pass this to the Japanese organisers to reduce the financial risk to the conference. Issues with sponsorship levels are also expected due to the global financial situation, and this surplus will also be used to combat this. Gunter Sidiqi (Switzerland) asked whether there was sufficient surplus to ensure the budget was met, and John Gale explained that it was intended to only transfer the surplus from GHGT-10 in order to balance the budget. We have the GHGT-9 surplus available, but it is not intended to use this at this stage.

Members approved the suggested amendments and surplus usage.

Planning for PCCC-1 and OCC-2 are well underway, and running to schedule and budget. It is not anticipated that the OCC-2 will be affected by the earlier floods that affected the region.

Members of the IEAGHG team took part in a media training exercise, which is a valuable thing to have undertaken as CCS will continue to attract a focus in the news. This raised again the issue of the shortening of our name by some from IEA GHG to IEA, which was a pattern the media trainers fell immediately into. We are looking for ways to address this further, and there will be ongoing discussions with the trainers to determine the way forward.

Interactions with the IEA CCS Unit are developing, we continue to contribute to the IEA Regulators network, and John Davison helped with the Capture report. We have discussed the cost network, and there is a suggestion to take this on together with the IEA; where the technical/regulatory split sits here is an area where we can combine quite well. Also, when IEAGHG creates an overview, we strip out the policy messages and focus on the technical messages, whereas IEA tend to focus on the policy messages, so we will use the Bio-CCS report to determine how this growing relationship can be used to see what IEA can take in terms of policy messages from our technical reports.

7. FEEDBACK FROM AD HOC GROUP DISCUSSION

Document GHG/11/08 refers. John Gale presented the results from the Ad Hoc discussions, and started by reporting the decisions regarding selling IEA GHG reports or making them freely accessible. The decisions are that members have access to reports for 6-12 months, and after that point, access becomes free. ExCo members will have the option to waive this period at their discretion. The chair asked members for comments as to whether they should be freely available after 6 or 12 months.

- Tony Surridge (South Africa) commented that there was a general feeling from the previous meeting that if reports would be freely available there would be less impetus to become members.
- Kelly Thambimuthu (Chair) said that previously the decision was made to disseminate more widely, with the thought that it would not inhibit members joining, rather it may encourage membership.
- Tim Hill (EoN) explained that the 6-12 month period gave members a feeling of value of being able to access these reports 6-12 months ahead of the ‘competition’ and this should not be removed.
- John Carras (Australia) commented to put the discussion in context; IEAGHG have different types of members, and each member has its own circumstances, some may be consortium members, some are governments and some are industrial, so the wide spread makes it difficult to create a simple way to meet all views. The proposal from the ad hoc group is a good compromise, encompassing all views.

The Chair confirmed that the decision of immediate or delayed release will be taken when reports are discussed at ExCo. The only thing therefore to decide is the length of delay. The proposal is 6 months, and members were asked for comments. Jay Braitsch (USA) suggested we have guidelines for the decision on immediate release. The Chair replied that each case is different, but it is usually clear if a
The Chair asked for any objections to the 6 month proposal. Gina Downes suggested 12 months to facilitate dissemination within companies. Annett Stones (Shell) suggested the 12 month delay could be too long for some studies, and would reduce their value and impact. The Chair proposed that the 12 month timeframe would make the immediate release decisions somewhat fraught, and the consensus of the group is for 6 months, to which members agreed. This delay period on external reporting will now be instigated by the Programme Team.

**Action 6: General Manager**

The second item for the Ad Hoc group was regarding the cooperation of other groups activities within GHGT, for example the Society of Petroleum Engineers (SPE) wishing to hold sessions within GHGT for SPE papers. This is thought to be counter-productive and takes away from the GHGT reputation. The European Association of Geoscientists and Engineers (EAGE) group have approached us as well. Our current business model worked, that of a major sponsor from the host country, has worked well in the past. The EAGE model focuses on an exhibition to fund the conference rather than a key sponsor. The Ad Hoc group decided this wasn’t appropriate as we still have countries coming forward to host based on the current model. We have had a suggestion from the University of Austin Texas (with support from DOE) to hold GHGT-12 which continues the current rotation and Sintef/NTNU have expressed interest in hosting GHGT-13 in Norway, which brings the rotation back to Europe. It was felt that the future interest in hosting GHGT conferences demonstrates that the current business model works, and there is no need to change it at the moment. Members were invited to comment on whether IEA GHG can proceed to invite the University of Austin to proceed to develop a proposal for consideration by the ExCo. This was unanimously agreed.

**Action 7: General Manager**

The Ad Hoc group also expressed concerns in relation to the workload the IEAGHG staff were under. John Gale commented that he felt the team was at full capacity, and that we couldn’t take up another activity without dropping an existing activity. He added we have agreed a strategic plan which says everything can be done. But we haven’t addressing in the strategic discussion whether we should look more towards meetings / networks in the future, and reduce the number of technical studies for example. John Gale suggested that the Ad Hoc group discusses this and develops a position for our next 5 years of operation to be discussed by members at the next ExCo meeting.

The Chair summed up John Gale’s comments and asked members for comments. Jürgen-Friedrich Hake (Germany) asked for clarification as to the use of the terms GHG and CCS – is the GHGT conference only dealing with CCS? Kelly Thambimuthu confirmed that all GHG’s are encompassed by the scope of the programme, but the main work is carried out looking at CCS. John Carras (Australia) explained that the scope of GHGT did encompass presentations and sessions on non-CCS mitigation options. John Gale commented that the early GHGT’s had a broader scope, with sessions on non-GHG and other mitigation options, but these sessions were not usually filled. The conference retains a broad scope, but the topics presented have become narrower. GHGT-10 did focus on attracting papers in other, non-CCS areas, and this worked well. We will look again at the scope for GHGT-11, and the intention is to take the scope broader to encompass wider climate change issues; the plan is to try to return the conference to ‘Greenhouse Gas Mitigation Options’ which could take some time. Kelly Thambimuthu confirmed that this fits well with the need for a broad portfolio of options to combat climate change. The flexibility needs to be maintained. It was asked if there was an intention to move into countries that aren’t as active in CCS. The Chair commented that Japan is not overly pro-CCS, but we have to go where we receive offers of hosting. Members commented on the need for a wider inclusion of topics, highlighting the inclusion within GHGT-11 of talks of CCS-reuse as an aspect of this.

The question of whether a separate annex is required for the IEAGHG team to manage the conference workload; the general feeling is that this isn’t required with the current business model of using a local Organising Committee. John Topper strongly advised members that there isn’t a need for a separate annex and the additional administrational efforts required for this would be counter-productive. Peter Versteegh (Netherlands) suggested that this should be subject to greater scrutiny as it could be seen as more transparent; but the Chair countered that with the committee structure as it is, there is already a clear distinction and transparency. The business model works, so it should be left as it is for the
moment to avoid the problematic issues that would arise from administering a separate annex. The Chair suggested that the idea of a separate annex should be dropped, but that a strategic discussion was required to consider where to focus future efforts. He proposed that the existing ad hoc group take this action on. Any members wishing to leave or join the Ad Hoc group should contact John Gale after the meeting.

Action 8: General Manager/Ad Hoc Group  
Action 9: Members

8. MEMBERSHIP ISSUES / NEW MEMBERS
Documents GHG/11/09 refers. John Gale presented this paper. MASER membership is proving to be slow, the invitation has been sent, but letters have not yet been returned to the IEA. John Gale is monitoring this to try to ensure they can be approved by the next CERT meeting. IIE (Mexico) have expressed interest in joining. OLC has been approached, and they have confirmed that the Ministry of Energy in Mexico are happy for IIE to join as a sponsor. The formalities of IIE’s membership will be expedited as soon as is practical.

Action 10: General Manager

Membership by China, Brazil and Kuwait has not progressed since the last ExCo. The CCPC in Canada have expressed interest, possibly more a recognition that they have been involved in the past, and would like to be more involved in the future. Eddy Chui has informed John Gale that there are discussions ongoing relating to the joining of an industry consortium from Canada.

9. OPERATING AGENT’S REPORT
No paper. John Topper first explained the role of the operating agent for those new to the ExCo. He explained that the pension deficit issue previously reported of £440,000 has been negotiated down to around £400,000, and an agreement has been made as to how that deficit will be restored; half will be repaid in this financial year, with the balance to be repaid monthly over the next 5 years. Tony Surridge (South Africa) asked who the money will be paid to, and John explained that this will be paid to the accounts of the pension scheme trustees. Secondly, with regard to the VAT registration issue, IEAGHG have won the appeal, and the stopped VAT has been repaid. This equates to a repayment of around £124,000.

At the next ExCo, the post of Chair will be up for election. Any nominations should be sent to John and be received in good time. He was pleased to confirm that Kelly Thambimuthu intends to stand for re-election, so any other candidates should consult with him rather than the chair.

Action 11: Members

10. FINANCIAL REPORT / ANNUAL ACCOUNTS

2009/10 Members Accounts
Document GHG/11/10 refers. John Gale presented this topic. He explained that the annual audited accounts approved by the IEA EPL Board have now been completed and were distributed prior to the meeting. At the 38th ExCo meeting an expected loss of £60,000 was reported. The actual loss is the audited accounts were only £33,000 and this included a £24,000 bad debt write-off. If the VAT issue had been resolved in the financial year there would not have been a loss as we would have recovered some £42k of VAT in the year. In addition we have tightened our travel policy and savings have been identified in various areas, such as travel limitations and also in production and distribution of the newsletter.

Members unanimously approved the audited accounts.

2010/11 Projected Out Turn
Document GHG/11/11 refers. John Gale apologised for the finance papers not been in the members folder. He had held these back until he had a meeting with the new accountants, which has now been completed, so that he was at the best position to advise members on the likely outcome for the financial year. John added that the new accountants are now up and running with the accounts and we were beginning to build a good working relationship with them. Based on 10 sets of monthly management accounts, excluding the profit from GHGT-10 we estimate that we will be in surplus this year.
potentially as high as £100,000. Discussions with the accountants indicate that they feel this is a realistic end of year position.

2011/12 Proposed Budget
Document GHG/11/12 refers. John Gale explained the budget to members. The projected turnover at £2million is the highest yet. The reason for this was the projected income expenditure for the OCC and PCC conferences in addition to 8 network meetings, the summer school, and two ExCo’s scheduled for this year. The 40th ExCo will host the 20th Anniversary party and will therefore incur additional costs. The meetingconference income and expenditure broadly matches due to the surpluses expected from the two conferences. In all other cases the budget varies very little to that from the previous year, and doesn’t include the forthcoming membership subscriptions from Masdar and others. Members were asked to approve the budget.

The Members unanimously approved the proposed budget for 2011/12

11. ANNUAL REVIEW
Document GHG/11/13 refers. John Gale presented this to members. The draft was circulated before ExCo, and a copy was distributed at the meeting. Members are asked to make comments or return comments to Toby Aiken after the meeting.

12. COMPLETED / ONGOING ACTIVITIES

Groundwater Impacts
Document GHG/11/14 refers. Neil Wildgust presented this study report. Members advised caution over the use of words such as conflict in the presentation; it was suggested to say that there may be overlap, rather than conflict as conflict suggests more of an issue. Caution was also advised over the diagrams illustrating leakage pathways. Neil Wildgust confirmed we would take some care over the language and diagrams in the final report. Tim Hill (EoN) questioned what use the report will be put to; is there any way it will help people overcome the next stage – if there is an overlap of interests, will this help to identify the risk elements? Neil confirmed that there was extensive discussion with regard to the scale of potential impacts, but this was not highlighted in the slides. The Chair suggested this is the first in a series of studies on related subjects. Richard Rhudy (EPRI) asked about the variation in salt quantity; the report mentions brine and fresh water, but doesn’t account for the gradual change in salt content. Neil accepted that the systems would be more complex than the diagrams shown, and there was no specific value given to discern between brine and freshwater, and all assumptions will be made transparent in the report.

Biomass CCS
Document GHG/11/15 refers. Tim Dixon presented this completed study. Markus Wolf (Alstom) found this study of interest, and noted that it is also worth questioning the value of CO₂ mentioned, as currently the EU ETS doesn’t account for this, as it is unclear how to classify it. There is no conclusive report on these gaps, and John Gale suggested that this should now be passed to the IEA CCS Unit as they are better placed to carry this further. Sven-Olov Ericson (Sweden) agreed that the policy aspect here is very sensitive, but IEA GHG could comment on the EU ETS without prescribing policy. It is clear that the ETS discriminates between the available fuels, and that CCS is not recognised with biomass. This is an anomaly in the climate energy package, between the ETS directive, CCS directive, the renewable energy directive and the fuel quality directive. In all except one, CCS from bio-energy is fully recognised. This is not a policy objective; rather it is an oversight in the wording of the directives. This could be amended, so this would not necessarily be policy prescriptive. Tim Hill (EoN) questioned that the potential for IGCC is 20 times greater than PC – what is the reason for this? Jay Braitsch (USA) explained that there is literature to support this factor. Eemeli Tsupari (Finland) commented that there were some studies including bio-CCS in Finland, and it can be feasible in some cases in ETS. Kelly Thambimuthu summed up that this sits once again within a portfolio of options, and will be more suited to certain niche locations. John Carras (Australia) commented on the context and size of the savings highlighted in the report, and the context of any CO₂ savings must be clearly indicated. Jay Braitsch (USA) commented that the assumptions used in economic calculations make reports difficult to read, and affect their viability. There is an argument that this study effectively promotes other studies, specifically those dealing with costing’s, which allow direct comparisons of
technology options described and evaluated in other studies. Annett Stones (Shell) highlighted studies carried out within the Netherlands, by Shell, looking at different plant types and scales, and the affect of these variations on storage costs. Dominique Copin (Total) commented on the statement relating to the source of the CO₂, questioning the importance of the source; there are some examples in Germany where public acceptance issues have been identified as the source of the CO₂ was from another region. Brendan Beck (IEA) requested clarification of the terms used in relation to technical and economic potential, whether the Gt units referred to be CO₂ stored or CO₂ avoided? Also whether the Decatur bio-ethanol plant, which will be storing CO₂ within the next 6 months, was considered? He felt the bio-CCS discussion would benefit from analysis of this plant once it is operational. Tim Dixon replied to the comments, mentioning a discussion paper that would be available to anyone who wanted to look into this further, and this was the basis of a poster submitted to GHGT-10. The economic figures used were taken from previous work, and this is noted as an assumption within the report; it will be highlighted in the overview. In reply to the question on the CO₂ Gt figures used, the figures reflect net CO₂, so not CO₂ stored, but the CO₂ net reduction was for a ‘typical’ plant size. Kelly Thambimuthu concluded that the methodology must be transparent, and this will ensure the value of the report in further assessments.

**Caprock Systems**
Document GHG/11/16 refers. Neil Wildgust reported on this completed study. Markus Wolf (Alstom) highlighted a question in a recent meeting relating to seismicity, and the affect of this on the caprock. Neil explained that the report does look at this, though not in great detail. A proposed study does address induced seismicity in its own right. Tony Booer (Schlumberger) disagreed with the comment that much is known about caprocks in oil and gas regions, whereas almost nothing is known in reality. Hopefully the report highlights the need for thorough site selection. Neil Wildgust explained that the report did note the absence of a database of caprock information, and highlighted the difficulties in gaining access to this information. Neil mentioned that the report will be presented at the forthcoming Modelling Network meeting in Perth, Australia.

**Technical Review on CO₂ Storage in Basalts**
Document GHG/11/17 refers. Neil Wildgust presented this technical review. Jürgen- Friedrich Hake (Germany) asked if there is an energy balance for basalt injection, did it take 2 or 3 times more energy than injecting into a deep saline formation (DSF). Neil replied that we don’t have that depth of data yet as there had not yet been an injection project into basalts yet. Malcolm Wilson (Canada) commented that the reality of basalts is that the CO₂ will migrate long distances very quickly and hence contacting might be an issue or you might need to fracture the basalts to get good interactivity between layers. Richard Rhuddy (EPRI) felt that fracturing would be needed but that injectivity could be the critical issue. Richard also said he had heard that for every tonne of CO₂ injected they extracted 20tonnes of water. Neil said he was unaware of that statistic but would try and find out. Annett Stones said that Shell was actively involved in the Wallula basalt injection project and that the key challenge was how you fracture the basalts. Tony Surridge (South Africa) commented that one of the reasons for requesting a literature review on low permeable reservoirs was in relation to the Karoo basin in South Africa, which had dolomite inclusions. They don’t want to abandon the Karoo because it underlies where most of the major CO₂ emission sources are. But they need to come up with an R & D proposal. Richard Rhuddy (EPRI) suggested that the study gets Shell’s input to this. The IEAGHG review and any implications that can be drawn for the Karoo basin will be sent to Tony as soon as it is available.

**Action 13: General Manager**

**Solid Looping**
Document GHG/11/18 refers. Tim Dixon informed members that there would be no presentation on this topic. A summary of the last network meeting was included in the ExCo paper folder for members to read at their leisure.

**Key Outcomes from Social Research Network**
Document GHG/11/19 refers. Tim Dixon presented this paper covering the 2nd meeting of the Social Research Network, the industry day, and the CSIRO project case studies. Jürgen- Friedrich Hake (Germany) asked what type of report would be generated from the network meeting, would it be a research focused report? He also commented that he thought the reports from meetings took too long to produce. Tim commented that the report will be research orientated and focus on learnings and
knowledge gaps aimed at the social science research community involved in CCS. Jürgen felt that if you focused only on knowledge gaps that were too general and he questioned how you focus on issues directly related to CCS. Tim answered that these are all in the context of CCS. Based on the feedback Jürgen received from a member of his staff that attended was that the network lacked focus. Brendan Beck (IEA) commented that one way to bring some focus was to include industry which Tony Boer (Schlumberger) echoed and warned that the results would not be as valuable if it were solely academically driven. Tim explained that the network members were resistant to bringing in industry but that we encouraged GCCSI and CSIRO to run industry days alongside the network meetings that facilitated the very important transfer of knowledge from these researchers to industry, and had been really valuable again this time in Tokyo. Also members of the network were not just academically focussed but some are directly involved in communication for real projects, also several had produced the guidelines now being used by projects. Peter Versteegh (the Netherlands) asked whether there was potential to share learning and experiences on public perception with other Low Carbon options - are the experiences different or common and able to identify what we can learn. Tim replied that this network meeting did include presentations from renewable energy, electricity grid, and nuclear industries for that purpose. Jürgen- Friedrich Hake (Germany) commented that careful phrasing of results was very important and asked if professional communication people were involved. Tim said they were. Dominique Copin said that Total were happy to get involved and share their experiences from the Lacq project.

**Key Outcomes from Environmental Impacts Workshop**

Document GHG/11/20 refers. Tim Dixon reported on this activity. John Gale commented that this area was core to our technical area, and compared to several years ago, there is much more information available, and this is a potentially valuable area where we can work in. However, without some review of our current workshop / network workload we are unable to operate an additional research area. It is therefore suggested that we defer a decision on further work until the 40th ExCo when the Ad Hoc group has reviewed our work programme. Members concurred with John’s comments. Tim Hill (EoN) commented that Tim gave a good summary of the workshop and he supported this activity because it is an important area, and he would support IEAGHG forming this into a network at a later point. One thing he felt he had picked up was that there was an apparent absence of flux rate data which needed to be looked into.

**Summer School Programme 2011 to 2015**

Document GHG/11/21 refers. Tim Dixon presented this paper. Monica Lupion (Spain) formally expressed the interest of CIUDEN to host the 2013 Summer School. Tony Surridge (South Africa) thanked IEAGHG for the opportunity to send students to the summer school, and commented that students always come back full of praise for the programme. The Chair thanked Monica Lupion for CIUDEN’s contributions in the past and for their future interest in hosting the 2013 Summer School.

**Workshop on Nitrosamine Formation**

No paper. Tim Dixon presented this topic on behalf of Mohammad Abu Zahra. Tim Hill (EoN) expressed his thanks to IEAGHG for helping co-ordinate this meeting. He commented that there will be an EU workshop in May and he has recommended IEAGHG are invited to follow up this issue. Markus Wolf (Alstom) felt the workshop had been helpful in framing the issues. Helle Brit Mostad (Statoil) commented that the meeting seemed to have focused on the nitrosamines but the nitramines might be more stable species of concern.

**13. STUDY PRIORITISATION**

Document GHG/11/22 refers. Tim Dixon described the study prioritisation voting results.

**Re-Evaluation and Update of Costs Estimates for Pre-Post- and Oxy- Combustion Plants**

Document GHG/11/23 refers. Tim Dixon presented this study proposal. The Chair commented on the historical issues associated with cost estimates of power plants, and the difficulties with this. Should IEAGHG be attempting this aiming to come to grips with the cost of first of a kind plant that are always more expensive than those reported for nth of a kind plants in most studies. Richard Rhudy (EPRI) questioned the process to be used for PC capture, as the different processes will have different associated costs. Also, following installation, there are additional infrastructure costs associated, and
we need to be transparent as to what is included in this cost estimate. Tim confirmed that this would be part of the study - either selecting a representative technology option or covering a range of options and this would be clearly identified. Tim Hill (EoN) questioned the title of the report as the specification will focus on post-combustion rather than pre and oxy fuel. Tim Dixon confirmed that the title can be adjusted, but the study will assess the differences in the process costs. Tim Hill (EoN) commented that the GCCSI cost work has recently been published, and asked what the additional benefit of this study would be? John Gale commented that the GCCSI methodology was fairly superficial, and this would be more detailed, and would incorporate regional sensitivities based on EU ZEP work. John confirmed we would make best use of existing available information. Jay Braitsch (USDOE) explained that the USDOE has completed several investigations in this area, and created baseline data on which to model new plants against. From their experience, it is worth looking at the contractors who have worked on this before, as we could piggy-back on completed work. John Carras (Australia) also questioned the value as there are many other cost estimates being carried out, and therefore moving this to a different level would be the added-value option; maybe this could review and critique the work completed before, to gain more of a valuable report. The Chair agreed, and we should ensure that any activity would add value; this should be allowed for in creating a technical specification. Members were cautious over the added benefit over the EU ZEP work, and John Gale explained that we will provide a report that allows for more regional sensitivity, and will hopefully give us a base for comparison with other low-carbon options, such as bio-CCS. John Topper suggested an initial review before the next ExCo to determine the value we could add, and John Gale agreed we would attempt this, but with the recent staff leavers we are short-staffed on capture topics, so this could be hard to complete before the next ExCo. Richard Rhudy (EPRI) asked if we would consider cost variations on regional sensitivities, as this would be seen as an added benefit to the work already completed, he also suggested we approach Howard Herzog’s MIT group for input to the process. Klaus Schoffel (Gassnova) highlighted the costs of a Norwegian PC project, costing a total $1billion, of which only 1/3 of this relates to the capture; hence the associated costs form the greater part of such a project.

The Chair summarised that we need a review initially and it should assess all 3 capture options and reported back when possible.

**Action 13: Members**

**Potential Implications of Gas Production from Shales and Coal for CO₂ Geological Storage**

Document GHG/11/24 refers. Neil Wildgust presented this study proposal. Annett Stones (Shell) commented that the public opposition to these tight gas production options are similar to that of CO₂ storage, so looking at these together is worthwhile. Neil indicated that this was not part of the existing study but could be a follow on once we have more definitive knowledge of the impacts of shale gas production. Gabriel Marquette (Schlumberger) asked about the possible connection with a GASH consortium, looking at mapping the processes involved with shale gas production. John Gale asked for a link to this group to be provided and we would follow this up. Tony Booer (Schlumberger) felt the study had two main focuses; the technical impact on production and its influence on cap rock integrity. Richard Rhuddy (EPRI) questioned why coal was included. John Carras and Kelly both supported keeping coal in the study although the issues might be different. Peter Versteegh said that there were potential economic and public engagement issues with gas shales in the Netherlands and he asked if the study would look at this. The Chair noted that these issues should perhaps be followed at a later time.

The Chair concluded that members approved this study proposal.

**Induced Seismicity**

Document GHG/11/25 refers. Neil Wildgust presented this study proposal. Tony Booer (Schlumberger) commented that the study was a critical topic for CO₂ storage, and echoed Neil’s comments that the report must be very careful over language use. Gunter Sidiqi commented that Swiss public perception associated CO₂ injection with induced seismicity in a negative manner, and maybe this study could remedy this and generate good support from operators of projects. The Chair concluded that the specification should look at analogues for learning on this topic. Tim Hill (EoN) advised caution again over the language used as the report will be of interest to early project operators.
Jay Braitsch commented that the USDOE will be starting a similar study, and will make the information available to the team where possible.

The Chair concluded that members approved proceeding with this study.

**Subsurface Resource Interaction with CO₂ Geological Storage**

Document GHG/11/26 refers. Neil Wildgust presented this study proposal. Tony Booer (Schlumberger) commented on the overlap with the shale study, and wondered whether these shouldn’t be combined. Neil explained that this would be more of an overview study, rather than going into such a detailed level. We would of course encourage contact between the contractors to ensure compatibility. Tony Booer also commented about the use of the sub-surface criteria, but asked if this should look at surface interactions as well? Sub-surface interactions could affect the ability to monitor and inject. Neil suggested that this would take the scope and size of the study too far, and would result in a too-broad study, without sufficient detail. Tony Surridge (South Africa) supported the study, and encouraged a subsequent study to look at surface interactions. South Africa has some existing legislation to address resource interactions with mineral deposits. He also suggested that any case studies should cover different regions of the world. Sven-Olov Ericson commented that the Sweden would be particularly interested in the outcomes of this study.

The Chair concluded that members approved the study, with possible future work on surface interactions.

**Key Messages for Communication Needs for Stakeholders**

Document GHG/11/27 refers. Tim Dixon presented this study proposal. Kelly Thambimuthu commented that the factsheets that the programme produced some 5-6 years ago were very useful, and this is an idea ready for revision. Jay Braitsch (USDOE) commented that with regard to dealing with background opinions, there is more to this than just producing factsheets. There is a need to also provide a little guidance as to where factsheets are used. Tony Booer (Schlumberger) highlighted the need for carefully selected terminology to make this accessible to lay-persons. Tony Surridge (South Africa) suggested we need to tailor the messages depending on whether we are talking to stakeholders, the general public, NGO’s, or local residents to projects.

The Chair concluded that members approved this study.

**Monitoring Tool on Website**

Document GHG/11/28 refers. No presentation was given for this, as the voting supported the ongoing maintenance of the Monitoring Selection Tool, so no presentation was necessary. Members endorsed the Programme team’s continuation of this existing activity.

**14. STUDIES TO BE RECONSIDERED FOR FUTURE VOTING ROUNDS / MEMBERS IDEAS FOR FUTURE STUDIES**

No paper. Kelly Thambimuthu asked members if they were happy for unsuccessful studies to be resubmitted for the next voting round and the members agreed. Tim Dixon highlighted that the basalt study would be dropped pending the outcomes of the technical review now underway. Sven-Olov Ericson commented on the geo-engineering proposal, suggesting there is still value on keeping it in the voting options. He also asked what context the biogas proposal was initiated, and whether it could be adjusted before being resubmitted. Tim Dixon explained that the scope as it stood was a direct follow-on from previous Shell/Dutch work, and therefore would be best in its current form. Jay Braitsch described the USDOE work alongside the renewable energy programmes, and wanted to address the issues of cooperation with bio-ethanol groups, and whether we could create a scope comparing biofuels with CCS versus chemical processes with CCS. John Gale suggested that we would expand this into a proposal for the next voting round.

**Action 14: General Manager**
15. **UPDATE ON GCCSI PROGRAMME**
Document GHG/11/29 refers. Tim presented an overview of the IEAGHG / GCCSI activities since the last ExCo.

**Impurities Study**
Document GHG/11/30 refers. Neil Wildgust presented this paper. Kelly Thambimuthu asked if for the decrease in capacity observed as density decreases, whether the fluid was still single-phase. Neil confirmed that it is still supercritical. Richard Rhudy (EPRI) asked if the study looked at higher than 15% impurity levels. Neil suggested that the modelling used 15% as a worst case scenario, although different levels were used. The report details the impact of differing levels of impurity on storage capacity. Members made several comments relating to groups working on similar areas that could contribute to the overview, and Neil will follow this up after the meeting.

**Action 15: General Manager**

**Storage Resource Gap Analysis for Policymakers**
Document GHG/11/31 refers. Neil Wildgust presented this paper. Neil explained that this study is not ready for publication yet, and further input is expected. Tony Booer and Kelly Thambimuthu suggested that capture has as far to go as storage, and we need to have the capability of both in order to fulfil CCS. There needs to be a drive towards identifying the sites where CCS can occur at scale. Brendan Beck (IEA) expressed interest in this activity. The IEA CCS Roadmap operated at a very high level, and this activity works from a lower level, which complements the IEA Roadmap activity very nicely. There is an anomaly where we will not reach the IEA 2050 target of 100 projects, so these activities need to identify what needs to be changed in order to reach this target.

**Student Mentoring Programme**
Document GHG/11/32 refers. Tim Dixon presented on this activity no comments were received.

16. **FEEDBACK ON IEA ACTIVITIES**
No Paper. A report on the IEA activities provided by the desk officer, Keith Burnard had been circulated to members. Brendan Beck commented that he thought that there was a good synergistic relationship building between the IEA CCS Unit and IEAGHG and the CCS unit recognised the value of the work done by the programme.

17. **FEEDBACK ON MEMBERS ACTIVITIES**
No Papers. Presentations were given by Gabriel Marquette on the Eurogia Project, Eemeli Tsupari on the Finnish CCS activities, and Malcolm Wilson on Canadian CCS activities.

18. **DATE OF NEXT MEETING**
Document GHG/11/33 refers. John Gale outlined the next planned ExCo meetings and invited members to volunteer to host further meetings. Members are asked to approve the 42nd ExCo to be held in conjunction with the GHGT-11 conference. The Chair asked for member’s approval of this, and no objections were noted.

**Presentation on 40th ExCo Meeting – London UK**
No paper. John Gale presented this topic to members. It is proposed that we will hold the ExCo over 2.5 days starting midday on the Monday due to the amount of studies that are due to be presented amongst other topics. This was unanimously approved by members. John went on to outline the plans for the 20th Anniversary celebrations that will follow on from the 40th ExCo. Kelly Thambimuthu suggested that we should invite those individuals involved with the programme historically, and John Gale confirmed that this was the intention. Tony Surridge (South Africa) asked if we would be able to produce a booklet describing the achievements of the programme, and John Gale confirmed that we were planning something along these lines.

19. **ANY OTHER BUSINESS**
No Paper. Members were asked if they had any other business, and none was declared.
20. **CLOSE OF MEETING**

The Chair thanked the members for their input, and declared the meeting closed, offering thanks once again to the hosts, South Africa, and Tony Surridge in particular.
There were only minor editorial changes, which were made as requested.

Members are asked to formally approve the minutes.
### IEA GREENHOUSE GAS R&D PROGRAMME
### 40th EXECUTIVE COMMITTEE MEETING

#### LIST OF ACTIONS

<table>
<thead>
<tr>
<th>Action No.</th>
<th>On</th>
<th>Action</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>General Manager</td>
<td>Follow up on review of gen-engineering</td>
<td>See GHG/11/51</td>
</tr>
<tr>
<td>2</td>
<td>General Manager</td>
<td>Expedite renewal of IEA mandate</td>
<td>Complete</td>
</tr>
<tr>
<td>3</td>
<td>General Manager</td>
<td>Expedite changes to IA legal text</td>
<td>Underway</td>
</tr>
<tr>
<td>4</td>
<td>General Manager</td>
<td>Trial webinar for overview dissemination</td>
<td>Complete</td>
</tr>
<tr>
<td>5</td>
<td>General Manager</td>
<td>Communicate conclusions of second ‘costs’ meeting to members</td>
<td>Complete</td>
</tr>
<tr>
<td>6</td>
<td>General Manager</td>
<td>Instigate 6 month delay on open availability of reports</td>
<td>Complete</td>
</tr>
<tr>
<td>7</td>
<td>General Manager</td>
<td>Invite University of Austin to submit proposal for GHGT-12</td>
<td>Complete</td>
</tr>
<tr>
<td>8</td>
<td>General Manager / Ad Hoc Group</td>
<td>Discuss future focus of efforts in relation to management of GHGT conferences</td>
<td>Complete</td>
</tr>
<tr>
<td>9</td>
<td>Members</td>
<td>Express wish to leave of join Ad Hoc Group</td>
<td>Complete</td>
</tr>
<tr>
<td>10</td>
<td>General Manager</td>
<td>Complete negotiations with IIE</td>
<td>In hand</td>
</tr>
<tr>
<td>11</td>
<td>Members</td>
<td>Nominations for ExCo chair to be presented to John Topper</td>
<td>Complete</td>
</tr>
<tr>
<td>12</td>
<td>Members</td>
<td>Submit comments / corrections on Annual Review to Toby Aiken</td>
<td>Complete</td>
</tr>
<tr>
<td>13</td>
<td>General Manager</td>
<td>Send Basalts storage TR to Tony Surridge when available</td>
<td>Complete</td>
</tr>
<tr>
<td>14</td>
<td>General Manager</td>
<td>Develop scope of study for comparison of biofuels with CCS against chemical processes with CCS</td>
<td>In hand</td>
</tr>
<tr>
<td>15</td>
<td>General Manager</td>
<td>Contact 3rd party groups to contribute to overview of impurities study</td>
<td>Complete</td>
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Introduction
This report provides a summary of activities completed since the last ExCo meeting (39th) held in Johannesburg, South Africa in April 2011. The report covers a 6 month period which included the summer holiday period.

Staff Changes
Two new staff members have been hired to work in the Capture and Integrated Systems team, which was short staffed due to Mohammad Abu Zahra’s departure and Mike Haines retirement. The new staff members are Dr Prachi Singh and Dr Jasmin Kemper. Steve Goldthorpe (New Zealand) has been with the team for a six month period in the UK to help out during the period of Mohammad’s departure and the new staff arriving. They are both expected to start in early December 2011.

Regretfully Neil Wildgust has resigned to take up a position with PTRC in Canada beginning in October 2011. However IEAGHG has signed an MOU with PTRC that will give us continued access to Neil’s services, up to 10-15% of his time per year. Neil will act as in a capacity to help IEAGHG remain up to date activities relating to the Weyburn-Midale, AQUISTORE and Boundary Dam projects in Saskatchewan.

Office/Operational Changes
There have been no further operational/organisational changes in the period. Demolition of the old office buildings on the Stoke Orchard site is expected to begin in the autumn of 2011. We hope that this will not cause any operational problems.

Progress on Delivery of the Technical Programme
a) Technical Studies
A summary of the status of studies is presented at the time of drafting this paper is provided, an updated summary will be presented at the ExCo meeting.

Studies in progress
Studies that are expected to be published between the 39th and 40th meetings, studies that will be underway at the time of the 38th meeting and studies that are outstanding are summarised in the tables below.

Table 1  Technical Studies published since the 39th ExCo meeting

<table>
<thead>
<tr>
<th>Title</th>
<th>Contractor</th>
<th>Report number</th>
<th>Publication date</th>
</tr>
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<tbody>
<tr>
<td>Retrofitting CO2 Capture to Existing Power Plants</td>
<td>IC Consultants Ltd.</td>
<td>2011-02</td>
<td>May 2011</td>
</tr>
<tr>
<td>Effects of Impurities on Geological Storage of CO2</td>
<td>Canmet ENERGY,</td>
<td>2011-04</td>
<td>June 2011</td>
</tr>
<tr>
<td>Potential for Biomass and Carbon Dioxide Capture and Storage</td>
<td>Ecofys</td>
<td>2011-06</td>
<td>July 2011</td>
</tr>
<tr>
<td>Rotating Equipment</td>
<td>Foster Wheeler</td>
<td>2011-07</td>
<td>September 2011</td>
</tr>
<tr>
<td>Storage Cost Calculator</td>
<td>Joint Report with ZEP</td>
<td></td>
<td>August 2011</td>
</tr>
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</table>
Global Storage Resource Gap Analysis for Policymakers (GCCSI) | GeoGreen | 2011-08 | October 2011
Ground Water Impacts | CO2GeoNet | 2011-10 | October 2011
CCS Capacity Constraints | EcoFys | 2011-11 | November 2011
Impacts of high concentrations of SO₂ and SO₃ and CO₂ capture systems | Doosan Babcock | 2011-09 | December 2011

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Studies being reported</th>
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</thead>
<tbody>
<tr>
<td>Title</td>
<td>Contractor</td>
</tr>
<tr>
<td>Incorporating future technological change in existing capture plants</td>
<td>IC Consulting</td>
</tr>
<tr>
<td>Emissions of substances other than CO₂ from power plants with CCS</td>
<td>TNO</td>
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<tr>
<td>Quantification techniques for CO₂ leakage</td>
<td>CO₂GeoNet</td>
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<tr>
<td>Feasibility of Monitoring Techniques for Substances Mobilised by CO₂ Storage in Geological Formations</td>
<td>CO₂CRC</td>
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<tr>
<td>Evaluation of CO₂ Post-Combustion Capture Chemical Emissions and Technologies for Chemicals Deep Removal</td>
<td>CSIRO</td>
</tr>
<tr>
<td>Ethical Attitudes to CCS</td>
<td>UMIST</td>
</tr>
<tr>
<td>Iron and Steel study</td>
<td>MEFOS</td>
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<tr>
<td>Removal of impurities from CO₂</td>
<td>Advantica</td>
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</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Studies underway</th>
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</thead>
<tbody>
<tr>
<td>Title</td>
<td>Contractor</td>
</tr>
<tr>
<td>Abstraction of brine from geological storage formations</td>
<td>CO₂CRC</td>
</tr>
<tr>
<td>Financial Mechanisms for Long Term Liability</td>
<td>ICF International</td>
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<tr>
<td>Operating Flexibility of CCS in Future Energy Systems</td>
<td>IC Consulting</td>
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<tr>
<td>Capture in Gas Fired Power Plant</td>
<td>Parsons Brinkerhoff</td>
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<td>Co₂RiskMan</td>
<td>DNV</td>
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<tr>
<td>Monitoring Selection Tool</td>
<td>BGS</td>
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<tr>
<td>Induced Seismicity</td>
<td>CO₂CRC</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Studies out to tender</th>
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<tbody>
<tr>
<td>Title</td>
<td>Proposal number</td>
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<tr>
<td>Post Combustion Capture Process Scale-up Challenges and Strategy</td>
<td>37-1</td>
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<tr>
<td>Key messages for stakeholders</td>
<td>39-10</td>
</tr>
<tr>
<td>Subsurface resource interactions</td>
<td>39-05</td>
</tr>
<tr>
<td>Implications of gas production on shale’s and coals</td>
<td>39-03</td>
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</table>

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Studies outstanding awaiting start</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title</td>
<td>Proposal number</td>
</tr>
<tr>
<td>Potential for Reducing the Life Cycle GHG Emissions of CCS Plants</td>
<td>38-09</td>
</tr>
<tr>
<td>Use of Renewable Energy in CO₂ Capture Processes</td>
<td>38-03</td>
</tr>
<tr>
<td>Ship Transport of CO₂</td>
<td>38-04</td>
</tr>
</tbody>
</table>
b) Facilitating implementation

The IEAGHG helps to facilitate the implementation of CCS by: participating in key meetings to support CCS policy/implementation strategies and by undertaking workshops or studies to provide information that is needed to assist implementation. Meetings that IEAGHG has participated since the last ExCo include:

- **UNFCCC.** The workshop to address the issues in the Cancun Decision was held in Abu Dhabi 7-8 September. IEAGHG assisted with speakers, and drew on consideration of the Cancun decision issues in the three storage Network meetings this year (Modelling, Monitoring, and Risk). IEAGHG attended (Tim Dixon) presenting on Transboundary Issues, and network members presented on Storage, Monitoring, Risk Assessment, and Groundwater and other Environmental Impacts. The workshop was considered overall a success in addressing the long-outstanding technical issues. A brief note was sent out to members on the 14 September, and paper GHG/11/46 refers. Tim Dixon is working with GCCSI for COP-17 in Durban in December.

- **CSLF Technical Group/PIRT.** IEAGHG attended (Ameena Camps) the CSLF Technical Group meetings in Edmonton, Canada in May, giving an updates on IEAGHG activities to PIRT and the TG, and chaired the Academic Task Force meeting and participated in the Risk Task Force. IEAGHG (Tim Dixon) attended the CSLF Ministerial in Beijing from 19-23 September, providing updates on IEAGHG activities and co-chairing the Academic Task Force.

- **EU ZEP.** IEAGHG has continued to contribute to the Policy and Regulation Task Force (Tim Dixon) and the Technology Task Force (Neil Wildgust). The Technology Task Force issued its new report in July on The Costs of CO₂ Capture, Transport and Storage. IEAGHG contributed to the storage parts.

- **Joint Task Force on Bio-CCS** is a task Force set up by ZEP and the EU Biomass Technology Platform to address development and deployment issues for biomass use with CCS, including co-firing. IEAGHG (Tim Dixon) was invited onto the task force and attended the first meeting on 9 February, and has contributed to subsequent meetings. The JTF is organising an international workshop on Bio-CCS on 25-26 October in Cardiff UK, IEAGHG are involved and co-sponsoring.

- **IEA Network of CCS Regulators.** IEAGHG assists IEA with this Network. The third annual meeting was held on the 1-2 March at IEA. IEAGHG contributed to the second edition of the IEA Legal and Regulatory Review. All this material and information from the IEA Regulators Network is available at: http://www.iea.org/subjectqueries/ccs/ccs_legal.asp.

- **London Convention.** IEAGHG attends or follows the meetings of this marine convention, specifically to support Members. A science event on monitoring of CO₂ in oceans (including from CO₂ storage leaks) was held on 15 April in Estonia, in conjunction with the Scientific Group meeting in Estonia (11-15th) which considered revision of the CO₂ Specific Guidance in relation to the trans-boundary amendment. This work is ongoing and will conclude in May 2012. IEAGHG (Ameena Camps) participated and presented on IEAGHG work in the science event. IEAGHG receives requests from other organizations for information on the CCS work in the London Convention, since the last ExCo from IEA, CCSA, and UNFCCC. The annual meeting of the London Convention will be 17-21 October in London, it expected that transboundary CCS will be on the agenda and IEAGHG may then participate.

- **CCSA.** IEAGHG (Tim Dixon) participates in the Post-2012 Working Group. IEAGHG (Tim Dixon) is also an observer in the CCSA Working Group on Regulation. IEAGHG anticipate participating in the meetings of both during October.

- **EU CCS Demonstration Network.** IEAGHG participates in the EU CCS Project Network Advisory Forum. IEAGHG (John Gale) participated in the European CCS Demonstration Project Network Meeting on 10 May in Rotterdam.

- **CCUS Action Group.** IEAGHG was invited to take over the lead of the storage working group of the CCUS AG. IEAGHG (Tim Dixon) took this on, and participated
in the 13 February meeting with Neil Wildgust who presented on the Global Storage Gap Analysis. IEAGHG then contributed to the work that resulted in the CCUS agreement at the Clean Energy Ministerial in Abu Dhabi in April where Ministers endorsed the eight recommendations on financial gap, funding in developing economies, legal and regulatory frameworks, marine treaty amendments, sharing knowledge, investigating CO₂ storage, supporting CCS in industry, and reporting on progress to the Clean Energy Ministerial in 2012. More information can be found at http://www.cleanenergyministerial.org/CCUS/index.html.

The 2011 Summer School was hosted by Illinois State Geological Survey (USA) at Champaign from 18th to 22nd July. 53 students attended from 25 countries. The technical programme included new topics on China CCUS developments, an NGO perspective and two dedicated panel discussions on project integration and industry perspective on the potential sector growth with reference to careers and future needs. As well as the technical programme and group work, the students visited the Illinois Basin - Decatur Project (IBDP), where they were taken to various different stations showing the surface monitoring facilities, the local geology and the Mt Simon sandstone reservoir rock, the compression facility and the injection well which will soon be injected CO₂. This year’s group winner was Group Six, presenting on the topic: Should CCS be mandatory in the developed world? Group four were also highly commended for presentation of the topic: How can CCS be made part of a commercially viable integrated, sustainable and secure energy system? This year’s two outstanding students were Viktor Andersson from Chalmers University of Technology, Sweden and Carrie Petrik-Huff from The University of Massachusetts, USA, who will be joining the 2012 IEAGHG International CCS Summer School as student mentors.

Next year’s 2012 IEAGHG International CCS Summer School will be held in Beijing, China hosted by Tsinghua University, and work is underway liaising with Tsinghua University.

The CO2QUALSTORE project has completed and reported. DNV has now established a User Forum for this Guideline. IEAGHG is a member.

Following the success of the CO2QUALSTORE project IEAGHG was invited to join a new Joint Industry Project (JIP) called CO2RISKMAN. IEAGHG has now joined. The aim of CO2RISKMAN JIP is to develop guidance for the emerging CCS industry on effective risk management of HSE major accident hazards from the CO2 stream within a CCS operation. The project kick-off meeting was held on 7 September meeting in London and attended by Sam Neades, who is now on the on the CO2RISKMAN steering committee. Partners in the project include: Shell, Vattenfall, Gassco, National Grid, HSE, PSA, UK’s Environmental Agency, EON, DECC, Gassnova, Norton Rose, IEAGHG, Air Liquide and the GCCSI. DNV’s intention is to initiate the CO2RISKMAN JIP as quickly as possible, with guidance release in mid-2012.

In October, 2010, IEAGHG attended the workshop: Carbon Capture and Storage (CCS): can anything be learned from 35 years’ experience in geological disposal of radioactive wastes; organised and hosted by the ITC School of Underground Waste Storage and Disposal, The British Geological Survey and the Universitat Politecnica de Catalunya. Given the lack of discourse between energy technologies, increasing competition and the need to resolve possible conflicts, it is timely to discuss this further, and IEAGHG will produce a discussion paper in preparation for the 41st Executive Committee.
IEAGHG’s activities under the GCCSI contract also fall under this theme but progress on this activity will be reported separately to members see paper GHG/11/71.

c) Facilitating international collaboration

International Research Networks

Two international research network meeting and one international research workshop will have been held since the 39th ExCo meeting. The meetings held are listed in the table below:

<table>
<thead>
<tr>
<th>Network</th>
<th>Date</th>
<th>Venue</th>
<th>Hosts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined meeting of Well Bore and Modelling Networks</td>
<td>27th – 29th April 2011</td>
<td>Perth, Australia</td>
<td>Curtin University and UWA</td>
</tr>
<tr>
<td>7th Monitoring Network</td>
<td>7th – 9th June 2011</td>
<td>Potsdam, Germany</td>
<td>GFZ</td>
</tr>
<tr>
<td>6th Risk Assessment Meeting</td>
<td>21st – 23rd June 2011</td>
<td>Pau, France</td>
<td>BRGM</td>
</tr>
<tr>
<td>3rd High Temperature Solid Looping Network</td>
<td>30th August – 1st September</td>
<td>Vienna, Austria</td>
<td>TU Wien</td>
</tr>
</tbody>
</table>

Reports on all the network meetings are currently being prepared. An update on the outcomes of these meetings will be given at the ExCo meeting (see paper GHG/11/61)

The presentations given at all these workshops and the reports have to date been hosted on the website: [http://www.ieaghg.org](http://www.ieaghg.org).

Network meetings planned for the coming year are still in the planning stage.

Practical R&D Activities.

IEAGHG is no longer directly participating any EU supported practical R&D projects. IEAGHG does provide in direct support in an advisory capacity to the Mustang and RISCS projects.

IEAGHG is participating in the IEAGHG Weyburn-Midale CO₂ Monitoring project. This project will complete the research programme in 2011 and incorporate the results into a best practice guide (draft due in 2011). Tim Dixon represents IEAGHG on the management committee and Neil Wildgust on the Technical Committee. This project has been in the news in January due to the alleged leak, much media coverage occurred in North America, some very negative. Consequently IEAGHG have been involved with PTRC on the technical response, and Tim Dixon presented for PTRC on the alleged leak at the IEA Regulators Network in March 2011. Drawing upon the monitoring research project results, including the baseline measurements, there is no evidence to substantiate the leakage allegation. Investigations into the allegations are underway by BGS, IPAC and other research organisations. IEAGHG (Tim Dixon) currently sits on IPAC’s International Advisory Committee.
Dissemination activities

Website. Following the report from the 39th ExCo on the successful launch of the new www.ieaghg.org website, we now have 1216 members across 12 networks.

During the period 22/02/12/2011 – 21/09/2011 we have had 37,044 visits with 139,432 pages viewed from 19,266 different visitors. 36% is direct traffic, 39% from search engines and 24% from referring sites. The average visitor spends 3.24 minutes on the site. The table below shows the breakdown of the location of our visitors.

<table>
<thead>
<tr>
<th>Location</th>
<th>Visits</th>
<th>Pages/Visit</th>
<th>Avg. time on site</th>
<th>% new visits</th>
</tr>
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<tbody>
<tr>
<td>United Kingdom</td>
<td>6,750</td>
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<td>49.85%</td>
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<tr>
<td>United States</td>
<td>4,690</td>
<td>3.73</td>
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<td>55.18%</td>
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<td>Germany</td>
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<tr>
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<td>00:04:52</td>
<td>51.19%</td>
</tr>
</tbody>
</table>

Greenhouse Issues
Nothing new to report

Conference series.

GHGT-11. Planning for the GHGT-11 conference to be held in Kyoto, Japan 18th -22nd November 2012 is well underway. The main developments are:

- The conference Programme Committee has been formed.
- The call for papers goes out in September 2011
- The following organizations have agreed to sponsor/support GHGT-11: Gassnova, GCCSI, Schlumberger, and Elsevier. Other parties who have expressed interest in sponsoring GHGT-11 to date include: EU ZEP and ExxonMobil

GHGT 12.
Discussions are underway with University of Austin Texas with regard to the hosting and organisation of GHGT-12 in 2014 Provisional dates 5th-9th October.

PCCC-1. The 1st Post Combustion Capture Conference (PCCC1) was held on 17th-19th May, Abu Dhabi, UAE. A summary of the outcomes from the conference will be presented at the ExCo meeting (see Paper GHG/11/62).
The 2nd Oxy-fuel Combustion Conference was held on, 12th-16th September, in Yeppoon, Queensland, Australia. An update on the conference will be presented at the ExCo meeting (see Paper GHG/11/63).

International Journal on Greenhouse Gas Control (IJGGC). The Journal is now in its fifth year, the impact Factor for 2010 increased to 4.074 from 3.644 in 2009. The 5 year Impact Factor was also up to 4.781 from 3.654. The flow of papers to the journal for publication remains good with increasing submissions from Asia. We are continuing to publish 6 standard issues per year. This year we have also published a supplementary issue based on the OCC conference series, Stanley Santos is the Managing Guest Editor for this issue. We expect other supplementary issues to follow.

New planned developments

- **Social Networking.** We are continuing to develop our presence on social media, with a steady growth in people following our Twitter feed, and regularly viewing our Facebook page. We are also monitoring LinkedIn, and are looking at possibilities to use the numerous CCS themed groups to further publicise our reports and activities. We may also look to post job vacancies on these pages as it provides easy and free access to a large resource of people already working in or interested in CCS and related activities.

- **Animations & Videos.** The Communications team are looking at the possibilities of developing short animations describing the various components of a CCS system, and although there are other animations available, notably from the EU ZEP group, we feel that it would be a worthwhile tool to have our own custom animations as this will increase our presence on the internet, and allow us to highlight specific areas where we have contributed to global understanding or areas that we feel require attention. We may also look to develop short video interviews or talks from key people around the world to add to a YouTube channel, but this is very much in the early stages of planning and investigation.

- **IEAGHG Blog.** Following discussions with Kristina Stefanova from the GCCSI, we are also planning to develop a blog to add to our website, featuring articles from IEAGHG staff, ExCo members, and other professionals about current or trending aspects and subjects relating to CCS.

- **Information Sharing Facility** - The methodology whereby members are given the opportunity on a monthly basis to complete a simple form and return electronically to provide information on any new activities or initiatives within their organisation or sphere of operation is established and is growing in effectiveness, although it is noted that contributions tend to come from a handful of members, and it would be great to see an increase in participation in this.

- **Press Releases.** We are considering the benefit of press releases to increase awareness of our study reports as and when they are either published, or become available for open access (depending on the decision to waive the 6 month members-only access clause). A recent study was included in a press release form the contractors in strict cooperation with IEAGHG and we saw a massive increase in requests for this report from people eligible to access the report - in the first month, we received 79 requests - the most popular report to date received 28 requests over a 2 year period, so this is definitely an effective manner of communicating results.
Publications/presentations
The table overleaf provides a list of papers presented and presentations made at external conferences and workshops since the last meeting. Note: these are in addition to presentations given at our own workshops. Copies of these presentations are now placed on the member’s pages on the Programme web site for future reference.
### IEAGHG Presentations

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<td>Carbon Dioxide Capture and Storage. Transboundary Issues</td>
<td>UNFCCC Technical Workshop on Modalities and Procedures for CCS in the CDM, Abu Dhabi</td>
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<td>Overview of IEAGHG Activities</td>
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<td>Issues</td>
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<td>Potential Impacts of CO₂ Storage on Groundwater Resources</td>
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<td>IEAGHG Study Programme Update</td>
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<td>Preliminary results for the Global Storage Gap Analysis for Policymakers Study</td>
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<td>A Global Perspective on CO₂-EOR as part of CCS</td>
<td>London, UK</td>
<td>Neil Wildgust</td>
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MEMBERSHIP ISSUES/NEW MEMBERS

Members Status
Masdar’s membership as a sponsor was confirmed at the CERT meeting in March 2010. The formality of the signing of the IA is still outstanding. The membership therefore stands at 47 members – 21 contracting parties and 26 sponsors. The status of invited parties is as follows:

- At the 33rd ExCo members invited CEPAC to join on behalf of Brazil. CEPAC’s membership is currently on hold, see below.

New Members
The Electric Research Institute (IIE) of Mexico has expressed interest in joining IEAGHG as a sponsor member. IIE’s membership is supported by Mexico’s Ministry of Energy (SENER). The IEA OLC has confirmed that there is no impediment to sponsor membership by IIE.

IIE’s interest and details of their activities have been circulated to members, in keeping with the new membership guidelines. No objections have been raised by any members.

Contracting Parties will be asked to vote and invite IIE to become a member and ask the General Manager to complete negotiations on the member’s behalf.

Interested Parties
The following progress with interested parties can be reported:

- At the IEA Working Party on Fossil Fuels (WPFF) meeting held in Brazil contact with Petrobras and the Brazilian Ministry of Mines and Energy (MME) was made. During the meeting IEAGHG was invited to send a proposal for Petrobras to consider joining as a sponsor member, with the support of the MME. Petrobras have been invited to the ExCo as an Observer.
- At the CSLF Ministerial in Beijing, Tim Dixon met with representatives of MOST and ACCA21 regarding Chinese membership of IEAGHG. MOST were invited to attend the ExCo as an observer.
- At the GCCUS conference in Beijing, the Chair met with senior representatives of the China Huaneng Clean Energy Group and the Chinese National Oil Company. These initial contacts have been followed up with invitations to both groups to consider joining IEAGHG as sponsors.
- Two parties that may be interested in joining as sponsors are Saskatchewan Power and Drax, UK. After initial informal contacts no further responses have been received from either party.
Members Accounts for 2010/11

The annual audit of the IEA EPL finances was completed in September 2010 and a draft set of the IEAGHG Members’ Accounts drawn up by the accountants. The IEA EPL Board has reviewed and approved the draft audited accounts. A copy of the final audited accounts has now been circulated to the IEA EPL Board for final approval and signature. A copy of the signed final Members accounts will be sent to member’s as soon as they are available or distributed at the ExCo meeting.

End of Year Adjustment for 2009/10

The key feature of the IEAGHG members’ and statutory accounts was the prior year adjustment and restatement of the result for the previous year where the previous auditor and accountant (RSM Tenon) had failed to take account of income receipts from the GCCSI project. As a consequence, the reported deficit of £32,383 had been restated as a surplus of £138,000 at 31 March 2010. IEA EPL (IEAGHG Team) had concerns regarding last year’s deficit result produced by RSM Tenon in the previous year but was ill-equipped to challenge it. IEA EPL (IEAGHG team) are pleased with the performance of the new auditors (ChantreyVellacott) in so much that they had uncovered and successfully resolved the accounting error from the previous year.

End of Year 2010/11 Financial Summary

At the 39th ExCo members were presented with an out turn project for 200910/ which indicated an under spend of £100k on the year on income versus expenditure (see paper GHG/11/09) on the members accountants. Incorporating the GCCSI projects activities into the member’s accounts for the year the result for the year at March 2011 indicated a surplus of income over expenditure, of £228,000.

Overall Financial situation

The overall situation as of end of March 2011 was a healthy one with no prospect of cash flow problems and ample reserves on deposit. As of March 31st 2010, IEAGHG had £2,330,000 on deposits in various accounts and bonds plus £1,440,000 cash in hand at the bank. In addition IEAGHG had £95,000 held over from GHGT-9 and £140,000 held against the GCCSI contract.
IEA GREENHOUSE GAS R&D PROGRAMME
40th EXECUTIVE COMMITTEE MEETING

2011/12 FINANCIAL UPDATE

In order to give members the most up to date financial information, at the half year stage, this paper will be distributed at the ExCo meeting.
IEA GREENHOUSE GAS R&D PROGRAMME
40th EXECUTIVE COMMITTEE MEETING

ISSUES ARISING FROM IEA WPFF MEETING

The General Manager attended the 60th IEA WPFF meeting in Rio De Janerio, Brazil on to present IEAGHG’s request to the WPFF for a renewed 5 year mandate for the IA.

The presentation on our activities/achievements over the last 5 years was well received and impressed many of the delegates. There were two questions posed regarding overlap with other IA’s.

1. The Chair asked a question on how we managed overlap with other IA’s. I explained our relationship with bioenergy and use of members in our interactions with other agreements like ENARD etc., I also made great emphasis about our interactions with IEA CCS unit which Keith Burnard (IEA) spoke up for us on. All was again well received.
2. One question raised specifically addressed our relationship with the IEACCC, the main tenet of the question was that IEAGHG overlapped with IEACCC to closely. It was stated that IEACCC covered CO2 capture and that IEAGHG did not, our new PCC conference series was therefore deliberate overlap on our part.

I responded on behalf of IEAGHG with 5 points:

1. Since its inception in 1991, the GHG IA had always covered the full chain of CCS including capture.
2. The PPC conference was a development of the PPC network that had ran for 12 years prior to the conference so it was not new.
3. IEA CCC had done its first report focusing fully on CO2 capture (jointly with IEAGHG) about 3-4 years ago. I re-emphasised the difference in modus operandi, IEAGHG doing original research, whilst IEACCC reviews published research.
4. I emphasised our up and coming work on gas, biomass CCS, integration of renewables also separated IEA GHG from IEACCC, which can only work on coal

It was then agreed after discussion that:

1. The IEA WPFF fully endorsed our renewal.
2. The IEA WPFF chair will write to the GHG IA chair to congratulate him on the GHG IA’s work. This letter is appended and has already been distributed to members.
3. The WPFF chair will write to John Topper (Operating agent) to seek clarification of the differences between the 2 IA’s.

It is noted that a similar comment on overlap was raised at an earlier IEACCC ExCo. In response to the question raised the Head of Service of IEACCC and the General Manager produced a summary slide showing the differences between the two IA’s which is attached.

The IEACCC is going through its renewal process with the IEA as IEAGHG has just done and have a strategic planning activity underway. A verbal report on this activity and any implications this might have on this operational summary will be presented at the ExCo meeting by John Topper (IEA EPL/IEA CCC).

\footnote{Note that CCS has been an element of other IEA CCC reports from an earlier date}
Dear Dr. Thambimuthu,

On behalf of the IEA’s Working Party on Fossil Fuels, I would like to congratulate you on the outstanding work of the Greenhouse Gas R&D Programme Implementing Agreement (GHG IA). Many Working Party delegates are familiar with the work of the GHG IA and, following discussion at the WPFF meeting in Rio de Janeiro (8-9 July 2011), they all felt that a commendation from them would be in order.

After around 20 years in existence as an Implementing Agreement, the GHG IA team has grown and team members have come and gone. However over that same period, the strategic content of the IA has continued to evolve to meet its members’ needs and to address the important climate change issues of our time. Your large and growing membership is testament to this.

We remain impressed with the depth and the breadth of the activities undertaken by the team in Cheltenham. We also remain impressed with the quality of output. The technical evaluations are highly regarded; the research networks very popular; and the programme of conferences for which you are responsible world class. We know that individuals within the team are highly sought after as authorities in their particular areas of expertise.

The IEA recognises the value the GHG IA brings to its Energy Technology Network. Many IEA publications have benefitted from its input, expert review or both. In conclusion, the WPFF is proud of its association with you.

In light of the merits mentioned above, I wish to formally convey WPFF’s endorsement to the request for extension of the mandate of the GHG IA. Relevant parties within IEA will be informed accordingly. Our very best wishes for the future.

Best regards

Mr. Jostein Dahl KARLSEN
Chair, IEA WPFF
cc  Ms. Barbara MCKEE, Vice-Chair, IEA WPFF
    Mr. John GALE, General Manager, GHG IA
    Mr. Keith BURNARD, IEA Secretariat

Mr. Hubert HÖWENER, Vice-Chair, IEA WPFF
Mr. John TOPPER, MD, Environmental Projects Ltd
IEA CCC & IEA GHG Areas of Work

**Clean Coal**
- Low emission coal
  - FGD
  - DeNOx
  - Particulates
- Efficient use of coal in Power & Industry
- Use of low quality/rank coal
- Advances in CCTs
  - IGCC
  - CFBC
  - Supercritical pf
- Coal markets
- Country studies
- Mercury & coal science workshops
- CCT conference series
- Databases
  - Coal Abstracts
  - CoalPower
  - Emissions
  - Coal Meetings
  - Clean Coal Technologies

**Carbon Capture**
- Only from coal for CCC
- From coal, oil & gas for GHG
- CCC
  - Reviews on coal related capture technologies using GHG sources and jointly published
  - Related aspects to operation of coal-fired plant
- GHG
  - In depth studies on a new and emerging capture technologies for coal, oil, gas in industrial and power generation applications and integration into future energy systems
  - Reviews of experience gained from pilot/demo. capture plants
  - Conference and workshops on oxyfuel & post combustion capture

**CO₂ Transport & Storage**
- In depth studies on:
  - Transmission by pipeline & ship
  - CO₂ quality issues for transport and storage
  - Storage in a variety of geological formations
  - Storage integrity & capacity assessments
  - Societal issues associated with transport and storage
- Workshop series on technical aspects of storage
- Best practice guidelines and regulatory development
- Health/Safety and Environmental Issues
- GHGT conference series
- CCS projects database
- Databases
  - Coal Abstracts
  - CoalPower
  - Emissions
  - Coal Meetings
  - Clean Coal Technologies
IEA GREENHOUSE GAS R&D PROGRAMME
40th EXECUTIVE COMMITTEE MEETING

IEA CCC STRATEGIC PLANNING EXERCISE

The IEA CCC is going through its renewal process with the IEA as IEAGHG did this year. As part of that review, IEACCC is undertaking a strategic planning exercise. In the light of comments made at the WPFF meeting regarding overlap between the two IA’s a verbal report will be given by John Topper on this IEA CCC exercise and its impact if any on the issue of overlap between the two IA’s.
An Ad Hoc Group on Strategy was set up after the 38th ExCo meeting with a remit to consider two strategic issues raised at that meeting which were: the dissemination of IEAGHG reports and the involvement of other organisations in the GHGT conference series. The Ad Hoc group met by email between the ExCo meetings and gave feedback to the full membership at the 39th ExCo. Following that feedback members agreed to a new policy on the release of reports by the IEAGHG team and to retain the existing business model for GHGT conferences and not include any groups that had contacted us to date (see Paper GHG/11/37).

At the 39th ExCo meeting the Chair invited the Ad Hoc Group to consider a further issue and report back to the 40th ExCo meeting. A new Ad Hoc group was constituted, due to some member representative changes. The reconstituted group included:

John Carras - Chair (Australia)
Jay Braitsch (USA)
Peter Versteegh (Netherlands)
Taher Najah (OPEC)
Eddy Chui (Canada)
Gunter Siddiqi (Switzerland)
Richard Rhuddy (EPRI)
Klaas van Alphen (GCCSI)
Tim Hill (EoN)
Arthur Lee (Chevron)
Secretariat: John Gale – IEA EPL, IEAGHG team

The remit from the 39th ExCo was for the group to review and comment on the distribution of effort of the IEA EPL -IEAGHG Team activities for the forthcoming 5 year phase, 2011-2017.

As a starting point for the discussions, the Chair (John Carras) asked the group to review the Strategic plan that was agreed previously, this was already some 18 months old and is designed to be evolutionary. It was noted that there were comments at the recent WPFF meeting that the plan per se did not fully reflect some of the thinking in the presentation given by John Gale, i.e. more emphasis on gas CCS etc. Following the WPFF meeting the strategy document had been updated to reflect the latest thinking following the 39th ExCo. See attached. This updated document (see overleaf) was circulated to the group members for comment.

There have been a number of suggestions from the Ad Hoc group for updates to the Strategy Paper will be reported and discussed with members at the 40th ExCo.

The second discussion area was in relation to the distribution of the IEAGHG team’s effort in the forthcoming phase. The Group had formed an opinion that a SWOT analysis would be extremely helpful in helping to assess the future scope/activities for IEAGHG. As discussions are on-going the outcome of the decision and scope of this SWOT analysis will be fed back directly to members for discussion at the 40th ExCo.
IEA GREENHOUSE GAS R&D PROGRAMME
STRATEGY POSITION PAPER (2011-2017)

The IEA Greenhouse Gas R&D Programme

The IEA Greenhouse Gas R&D Programme (IEAGHG) is an Implementing Agreement (IA) established under the guidelines set out by the International Energy Agency (IEA) based in Paris, France. The IA was established in 1991 with a membership of 11 Contracting Parties and an annual turnover of £600,000. Since that time the membership has grown substantially as has the turnover. At the start 2010, the IEAGHG has 42 members equally divided between Contracting Parties (Country members) and sponsors (industry members). In 2009/2010 the turnover of the IEAGHG was some £1.8million. The IEA GHG is a cost shared IA where all members contribute an annual fee to a common research fund, and the IEAGHG manages this fund on behalf of its members. The fees payable by contracting parties are based on the individual countries annual CO2 emissions, while sponsors all pay a set annual fee. Membership is open to all OECD/IEA members and non OECD countries as well providing they fit with the agreed membership criteria. Membership as a sponsor is open to all industrial companies providing they conform to the agreed membership criteria. The IEAGHG aims to keep a balance of contracting party and sponsor members.

Each member nominates a member and alternate to sit on the Executive Committee (ExCo) which meets every 6 months to assess the work programme of IEAGHG. At the ExCo meetings, the IEAGHG team report on the completed activities, and propose the work programme for the coming 6 months. The ExCo are then responsible for approving the activities, and also have the opportunity to suggest activities for the future.

The IEAGHG provides technical information to its membership based on the research it undertakes on behalf of the membership. This research is used by country members in the development of their national/regional policy initiatives and is also used to identify research needs for more extensive support in their national and/or regional greenhouse gas mitigation programmes. The sponsors also utilise the research provided by the IEAGHG in the development of their corporate greenhouse gas mitigation strategies and in the planning of their corporate research activities.

The interaction between government and industry around the ExCo table in discussing research needs and priorities for greenhouse gas mitigation is seen as a major strength of the IEAGHG operation.

International Context

On the international stage there are a number of bodies that are active in the field of greenhouse gas mitigation. The most influential body is the United Nations Framework Convention on Climate Change (UNFCCC), which produces regular assessments of the increases in global greenhouse gas emissions and their impacts on the global climate. These reports also identify research needs to mitigate greenhouse gas emissions globally and assess technology options for global greenhouse gas mitigation for all greenhouse gases across all sectors including the power sector, industry, agriculture, buildings, transport etc., IEAGHG however focuses its activities on the reduction of greenhouse gas emissions from fossil fuel use in the power and industry sectors. The greenhouse gas of primary interest to IEAGHG is therefore CO2 and

Guidelines for new members were approved by members at the 36th Executive Committee meeting held in Zurich, Switzerland in October 2009.

Document amended 20/08/2011 – J.Gale
much of the focus of IEAGHGs research in the last operating phase was on CO₂ Capture and storage (CCS) as a mitigation option in the power and industry sectors. This emphasis on CCS will continue for the foreseeable future. CCS was also the focus of a Special Report by the UNFCCC in 2005 to which IEAGHG was a significant contributor.

In the area of CCS, there are a number of international bodies active which IEAGHG co-operates or interacts with. These bodies include the IEA, the IEA Clean Coal Centre, the Carbon Sequestration Leadership Forum and the Global Carbon Capture and Storage Institute. With the exception of the IEA Clean Coal Centre these other bodies have a more policy related remit, whereas IEAGHG is a technical research group. However the technical results that IEAGHG generates can be utilised by these bodies in their policy messages to Government Ministers and as such the work of the IEAGHG and these bodies is complementary. Details of IEAGHG’s current interactions with these other bodies are given in Annex 1.

**Remit and Operating Tenure of IEAGHG**

The remit of the IEAGHG as defined in the IA which all members sign is:

- To evaluate options and assess the progress of technologies that can reduce greenhouse gas emissions derived from the use of fossil fuels.

The objective of the programme as defined in the IA is:

- To provide our members with definitive information on the role that technology can play in reducing greenhouse gas emissions.

The main activities of the IEAGHG as defined in the IA to achieve the above objective are:

1. To evaluate technology options for greenhouse gas mitigation from fossil fuels,
2. To help facilitate implementation of potential mitigation options,
3. To help facilitate international collaborative activities,
4. To disseminate the results of our work as widely as possible.

The IEA mandates its IA’s in 5 year blocks or phases. The IEA GHG’s current mandate (Phase 5) ends in November 2011. The IEAGHG will seek a mandate from the IEA for a further 5 years running starting in November 2011 (Phase 6).

**Focus of IEAGHG activities**

The remit of the IA covers all greenhouse gases (CO₂, CH₄, and N₂O); however IEAGHG’s research activities have focused in previous phases on CO₂. This focus will continue into the new phase. Carbon dioxide is the most significant greenhouse gas emitted in volume terms from fossil fuel utilisation. In earlier phases IEAGHG researched the main sources of the other greenhouse gases, for N₂O the primary source was agriculture, and IEAGHG considered it could contribute little in this field to the mitigation of N₂O. For methane, earlier research work indicated the main emission sources are: coal production, the oil and gas sector, disposal of solid waste in landfill and agriculture (ruminant production and rice cultivation). A global initiative to target mitigation actions for methane called the USEPA Methane to Markets programme was launched in 2005. This covered all sectors of methane emissions. In October 2010 thirty-eight governments, the European Commission, the Asian Development Bank, and the Inter-American Development Bank launched the Global Methane Initiative (GMI) to build
on the existing structure and success of the Methane to Markets Partnership to reduce emissions of methane, while enhancing and expanding these efforts and encouraging new resource commitments from country partners. The IEAGHG therefore feels that this major global initiative on methane mitigation covers this greenhouse gas more than adequately and that IEAGHG cannot contribute significantly in this field of research with the funds it has available and that it would not be a wise use of member’s funds to attempt to duplicate work in this area.

The remit of IEAGHG covers all fossil fuels which includes; coal, natural gas (conventional and unconventional), oil, orimulsion/tar sands as well as co-firing of fossil fuels with biomass and wastes. Coal will remain the major fossil fuel deployed in the power and large manufacturing industry sectors for the foreseeable future. However, there is an increasing potential for natural gas due to recent large field discoveries/developments in South America the Middle East and South East Asia and the discoveries of substantial quantities of shale gas globally. There is therefore increasing interest in the use of natural gas for power generation, which must include CCS if global emission reduction targets are to be met.

The main technical focus of the work in the current and planned next phase will be on CO2 Capture and Storage (CCS) in both the power and industry sectors it is noted that IEAGHG’s work will not be exclusive to CCS and other mitigation options will also be considered as appropriate. Other key mitigation options for fossil fuels include energy efficiency and fuel switching. Energy Efficiency in the power sector, with respect to coal is covered by IEACCC, and developments in technology such as gas turbines are largely manufacturer lead. In industry IEAGHG did work on energy efficiency improvements in sectors like cement, steel oil and gas refining and aluminium industries. These developments are largely lead by industry in a drive to reduce fuel costs. The next stage in the industry sectors to significantly reduce emissions is to deploy CCS either to decarbonise the electricity sector or in industry itself.

The scope for IEAGHG’s work in its Implementing Agreement also allows for it to undertake comparative assessments of other mitigation technologies to see how the relative merits of each technology compare. One such technology is biomass-CCS; this technology has the potential for negative emissions and could be a technology driver for gaining public acceptance for fossil fuelled CCS. Other technologies that could be considered to assess their relative merits compared to CCS include direct air capture, biochar, and CO2 utilisation.

The focus of the work will be revisited and reviewed at the mid-term of the new phase (2014/2015).

**Strategic Plan for 2012-2017**

The strategic plan for 2012-2017 has been framed against the back drop that this will be a critical period for the implementation of CCS. The proposed plan lies within the timeframe of the G8 objective for 20 CCS demonstration plants to be operational by 2020. It also lies within the timeframe set by the IEA in their road map for CCS and thus results from our work will feed into the development of the CCS road map. The strategic plan is consistent with the milestones set by these initiatives and aims to be supportive of the technology developments required to implement both these initiatives. The strategic plan is also mindful that a longer time frame must be considered i.e. from 2020 onwards when there will still be a need to develop and implement new (often called second or third generation technologies) which have significant potential to reduce the cost and energy efficiency penalties associated with earlier generation capture technology.

Document amended 20/08/2011 – J. Gale
The key focus areas in the strategic plan for the period up to 2020 included in the IEAGHG’s strategic plan are:

- The evaluation of the current technical state of knowledge on CCS and the identification of gaps and R&D needs
- The evaluation of the most important technical issues/barriers for CCS implementation and addressing how to remove any identified technical barriers
- The evaluation of which second or third generation technology options have the highest probability of success as they move from laboratory to pilot scale and assess their potential to reduce the cost and energy penalty for CCS
- The evaluation the long term breakthrough technologies and how their technical development from concept to laboratory to pilot scale might be assisted based on experience gained from other technologies
- The evaluation of the transition phase to the low carbon economy and the technology needs and issues that may arise, such as integration in both energy systems and of renewable technologies into fossil fuel plant and the relative merits of other mitigation options during that transition period.

Key technical actions by activity area are:

1. To evaluate technology options for greenhouse gas mitigation from fossil fuels.

During Phase 6 the IEAGHG would continue to undertake a series of technical evaluations as it has in earlier phases. These studies will aim to be topical and address key areas of research for CCS with emphasis on both near market needs and longer term research needs. Such evaluations would be undertaken using the IEAGHG’s standard procedures for contract management to ensure a consistency of approach, that the results remain objective and would use, and develop as appropriate, our standard evaluation methodology so that the studies can be compared with previous and other new assessments. These technical evaluations could consider, but would not be limited to, nearer term issues such as:

- the status of 1st generation capture technologies\(^1\) and related issues such as scale up issues, cost savings, energy penalty savings, environmental impacts and safety issues etc., arising in their implementation stage in both the power and industrial sectors for both coal and natural gas fired plants,
- the transport system options available their status, costs and environmental impacts, impacts of impurities, corrosion and safety issues and technical issues arising from the establishment of large scale pipeline networks etc.,
- the geological storage options available, in particular issues such as status of monitoring, modelling and risk assessment tools, environmental impact/safety issues, capacity assessments, site characterisation, site closure and remediation etc.,
- whole CCS system issues such as operational flexibility, component and system integration/adaptation, integration of renewable at plant and system levels, LCA etc.,
- The technical potential for biomass CCS and an assessment of the relative costs, energy penalties and efficiencies compared to fossil based CCS plants.
- Carbon capture from industrial sources may need more attention in the next phase as each of the major industries has its unique capture related issues that is not encountered in the power sector

Longer term issues such as will also be considered:

\(^1\) 1st generation capture technology is considered to be both post, pre and oxyfuel capture processes that are currently available for market application.

Document amended 20/08/2011 – J.Gale
the status and potential of 2nd/3rd generation capture technology, to reduce costs, energy penalty, environmental impact, integration needs for CCS etc.,
- the potential future breakthrough capture technologies that have the potential to achieve significant costs savings,
- Competitiveness of different fossil fuels with and without CCS as a function of fuel cost and carbon price
- Comparison and evaluation of the state of art of alternative storage options – e.g. basalts, mineralisation etc.,
- Comparison and evaluation of the state of art of alternative mitigation options – e.g. air separation, bio char etc.,
- capture from mobile sources

On all aspects the IEA GHG will look to develop critiques on state of the art and what has been learnt to date for member’s guidance. This is a new activity that has not been part of the core plan before.

2. To help facilitate implementation of potential mitigation options,

One of the key roles that the IEAGHG undertakes is to provide “evidence based information” on issues such as liability, storage potential risks, Heath, safety and environment, HSE issues etc., to international, regional and national bodies developing regulations and standards such as UNFCCC/SBSTA, IMO etc., This role will continue through Phase 6 as appropriate.

Another key activity will be to continue to help facilitate the development of best practise guidelines for CCS both technical and non-technical (i.e. communications) and guidance for regulatory development such as monitoring, modelling and verification needs for quantifying leakage etc. This because they share similar objectives since both IAs deal with cleaner fossil fuels may mean that more emphasis will be needed in this activity area in Phase 6 as the technology moves nearer to the market place although other bodies may play a more active role in a national/regional context.

The IEA GHG will continue to assess potential barriers to implementation (identified in Tasks 1 and 3) and develop studies/activities to address these barriers as required. It is expected that there may be more emphasis in this activity area in Phase 6 as the technology moves nearer to the market place.

Two areas that have been addressed in the previous phase that will continue in phase 6 are:

- Building a core of technical expertise for the future, by continuing the provision of annual international CCS summer schools,
- Addressing issues related to public awareness/attitudes to CCS through the social research network. There will be more emphasis placed on public awareness activities in Phase 6 than previously.

Another aspect of the work in Phase 6 will be for the IEAGHG to contribute technically to capacity building activities led by the IEA/GCCSI in developing countries as appropriate.

3. To help facilitate international collaborative activities,

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3 2nd/3rd generation capture technology are technologies that are developments of existing capture processes like improved solvents scrubbing processes and technologies currently at the research/pilot phase like membranes and solid adsorbents.

Document amended 20/08/2011 – J.Gale
One of the IEAGHG’s major successes has been the development of a portfolio of international technical research networks (3 on capture and six on storage in Phase 5) aimed to assess key issues associated with the development and deployment of CCS. The key activity in this task is the international research networks; the activity area will be maintained and built upon as appropriate during Phase 6. These networks have been very effective at attracting top researchers from around the globe to meetings, which underlies their success and confirms their importance. A general network strategy will be developed as well as strategies for individual networks. The aim of the strategy will be to ensure that the networks remain topical and help move CCS forward. The networks should aim to provide IEAGHG’s members on a regular basis with information on “what has been learnt” that feeds into Task 2. Network needs will be regularly evaluated and new networks activated as required on cross cutting issues such as impurities, operational flexibility etc.,

Due to operational reasons IEAGHG cannot undertake a limitless number of research networks and as new networks are identified others will need to be evaluated as to their continued value. Inevitably some existing networks will be shut down or merged during Phase 6.

Due to increasing demand, the pre-combustion capture and oxy-fuel research network activities will be expanded into conference series, which reflects increased research activities in these areas. Throughout Phase 6 we will continue to evaluate the demand/growth in these activities and reassess as appropriate. The IEAGHG will also consider how issues like environmental impacts of capture and CCS flexibility could be incorporated into these existing activities rather than create new networks.

The proliferation of practical R&D Projects means that it will be difficult for IEAGHG to associate with individual projects in the future due to resource limitations. The IEAGHG will instead look to associate with national/regional programmes to promote international co-operation, provide international reviews etc., and provide members with an overview of activities at this level. The IEA GHG will endeavour to ensure that the work from these national programmes gets fed into the research networks in Phase 6.

The IEA GHG will also continue to help facilitate member involvement into international research projects such as appropriate.

4 To disseminate the results of our work as widely as possible.

An important aspect of the IEAGHG’s activities is to ensure that the results of its work are disseminated as widely as possible. In Phase 6, IEAGHG’s existing dissemination activities will. These include:

- Web sites (www.ieaghg.org and www.ghgt.info)
- The Greenhouse Issues newsletter
- The GHGT/OCC conference series and GHGT/OCC summary report every two years
- Public summary reports as appropriate and reports on members activities
- Annual reviews of IEA GHG activities for promotional purposes
• The International Journal on Greenhouse Gas Control (IJGGC). The IEA GHG will use IJGGC to commission regular invited reviews on the state of art of key components on CCS technology – only if the GM stays as Editor in Chief.

Greater emphasis will be placed in Phase 6 on the maintenance and updating of IEAGHG’s communication tools and building awareness of and the inclusion/incorporation of new communication tools, such as twitter feeds etc., as appropriate.

The IEAGHG will also look at building an e-learning component into its existing web site.

Operational Aspects

The broad technical scope of the IEAGHG is set out in the Strategic Plan. The detailed scope is defined by the Executive Committee (ExCo) which meets twice per year (spring and autumn).

With regard to the technical evaluation studies (Task1), prior to each ExCo meeting the IEAGHG provides members with a list of study options which are voted upon and then the technical scope discussed at the respective ExCo meeting. At each meeting members select 4 to 6 studies for IEAGHG to pursue depending on their likely costs.

Similarly activities related to tasks 2 and 3 are presented to members at each meeting and are discussed and reviewed.

These six monthly reviews of IEAGHG’s give members the opportunity to modify the focus as the phase proceeds.
ANNEX 1

IEAGHG Interactions with other Organisations

The IEA and IEA Related Bodies

As an IA operating under the auspices of the IEA, the IEAGHG also reports its work to the IEA through the Working Party of Fossil Fuels (WPFF). Since 2005, the WPFF has been implementing Phase II of its initiative on Zero Emissions Technologies (ZETs). The WPFF has recently broadened its scope and developed a strategy for its third phase (2010 to 2012) of the initiative, entitled ‘Zero Emissions Technologies and Future Fuels: Sustainability for Oil, Gas and Coal’. The working platforms in this strategy are: a). Next Generation Fossil Fuel Technologies (including CCS); b). International Concerted Action on CCS for the G8; and c). Dialogue, Collaboration and Outreach (particularly with countries like, China, Brazil, Russia, etc.). The technical research work that IEAGHG undertakes relates directly to the technical interests within the WPFF and should complement the broader context of the WPFF’s engagement and outreach activities.

The research that IEAGHG undertakes can also be utilised by the IEA in its policy orientated documents and road maps such as the recent IEA CCS Road map. The IEAGHG is cooperating with the IEA CCS Unit and is developing a working relationship with the Unit. The IEAGHG was a cofounder of the IEA Regulators network with the IEA CCS unit, we are jointly operating a CCS costs network, we are inputting directly both through technical input and through our research work into reports being issued by the IEA CCS unit. The IEAGHG now reports the technical study results to the IEA CCS unit from key reports to allow them to assess the policy implications from the IEAGHG study work and how these policy implications might be reported to the IEA itself.

There are some 40 IA’s in operation, IEAGHG collaborates and exchanges information with these on an ad hoc basis. The IEAGHG cooperates with the IEA Clean Coal Centre more actively, because they share similar objectives since both IAs deal with cleaner fossil fuels. IEAGHG and IEA CCC have undertaken a number of joint reports and organised a number of joint workshops. Both organisations share information on their activities to avoid duplication and overlap.

The IEAGHG also interacts with other IA’s such as the Bio energy IA, the Geothermal IA, as appropriate to gain assistance in developing its work programmes on related/cross cutting research areas. The IEAGHG recognises that it cannot itself cover interactions with the other IA’s due to their sheer number. The IEAGHG has therefore enlisted the support of its contracting party members who also sit on other IA’s to assist it in its interactions with these groups. A number of IEAGHG’s current members have agreed to represent the GHG IA’s which currently include: ENARD, The Electricity Co-ordination Group, the CO2-EOR IA, the Geothermal IA and the Bioenergy IA.

The Coal Industry Advisory Board (CIAB) is a sponsor member of IEAGHG. The CIAB is a group of high level executives from coal-related industrial enterprises, established July 1979 to provide advice to the IEA on a wide range of issues relating to coal. Through membership of IEAGHG the CIAB can obtain technical information on the status of mitigation technology such as CCS which it can provide to its membership and utilise in its advisory role to the IEA.

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Carbon Sequestration Leadership Forum

The IEAGHG also cooperates with the Carbon Sequestration Leadership Forum (CSLF). The CSLF was established in June 2003 and its charter at that time gave it an operating lifetime of 10 years. The purpose of the CSLF is to facilitate the development of improved cost-effective technologies for the separation and capture of carbon dioxide for its transport and long-term safe storage; to make these technologies broadly available internationally; and to identify and address wider issues relating to carbon capture and storage. This could include promoting the appropriate technical, political, and regulatory environments for the development of such technology.

The IEAGHG has an agreement with the Technical Group of the CSLF whereby the IEAGHG has an observer role. Through this role the IEAGHG provides information on its current activities and to the CSLF Technical Group and provides a mechanism for this group to suggest activities that could be funded by the IEAGHG through the member’s common research fund. In this way, the IEAGHG can both advise and directly support the activities of the CSLF Technical Group. One study has so far been undertaken by this collaborative action route.

The CSLF has recently updated its technical road map on CCS, in collaboration with the Global Carbon Capture and Storage Institute, and to which IEAGHG was a contributor. The IEAGHG considers that its strategic plan complements the CSLF road map by addressing key areas of research that are needed to help develop and implement CCS globally.

Global Capture and Storage Institute

The Global Carbon Capture and Storage Institute (GCCSI) were established in April 2009 with direct support from the Australian Government. The GCCSI which has a 5 year tenure (2009 - 2014) currently has the support of some 225 members comprising both national governments, leading corporations, non-government bodies and research organisations. The aim of the GCCSI is to play a pivotal role in facilitating the development and deployment of safe, economic and environmentally sustainable commercial-scale CCS projects. The GCCSI will advise on the technologies that will capture, transport and store emissions, and provide expert insight on the costs and benefits of carbon solutions and the operational and legislative requirements needed to achieve success.

The GCCSI is a sponsor member of the IEAGHG and conversely the IEAGHG is also a member of the GCCSI. In this way information is shared by both parties and both parties assist in steering each other’s activities.

The IEAGHG also has a research provider agreement (covering the period 2009-2012) with GCCSI whereby the IEAGHG provides GCCSI with technical support for its activities by undertaking near market research to assist in identifying barriers to the implementation of CCS demonstration projects allowing GCCSI to develop strategies to overcome such barriers.

CCUS-MEF

The IEAGHG has been participating in the Carbon Capture, Use and Storage Action Group (CCUS), at the request of the IEA CCUS unit feeding in information on geological storage activities. The CCUS will feed back to the third Clean Energy Ministerial in 2012.

EU Activities

Document amended 20/08/2011 - J.Gale
The IEAGHG is a member of the technical and policy groups of the EU Zero Emissions Platform (ZEP) and has co-operated on a jointly funded study on the costs of storage with ZEP. THE IEA GHG is a member of the Advisory Council for the EU Demonstration plant network and has participated in the activities of the FENCO-ERA programme.

**Other National Activities**

For the USDOE, IEAGHG has been running a twice yearly international peer review of the multi-million dollar Regional Carbon Sequestration programme and is now participating in an advisory capacity on the recently launched National Risk Assessment Programme. For the USEPA IEAGHG organised an international peer review of its environmental framework tool. The IEAGHG is currently chair of the International Advisory panel for the Dutch national CCS research programme (CATO-2).

Many of these interactions will continue into the new phase.
Introduction
COP-16 in Cancun surprised everyone by making progress on CCS in the Clean Development Mechanism (CDM). The Cancun Decision said that CCS would be eligible if a set of some fifteen issues could be addressed in the context of possible new CDM rules for CCS. It put in place a work programme leading up to COP-17 in Durban in December 2011. This work programme consists of submissions from Parties and observers, a synthesis report of these submissions, a technical and legal workshop, and the UNFCCC to prepare draft new rules (‘modalities and procedures’) for CCS to be in the CDM. Many countries and observers submitted submissions, mostly positive or constructively critical.


Workshop in Abu Dhabi
The workshop presentations and discussions covered: storage; risk assessment; modelling; monitoring; groundwater and other environmental impacts; short term and long-term liability; transboundary issues; and views of Parties and NGOs. In doing so, the workshop addressed the long-standing technical issues in UNFCCC negotiations on CCS in developing countries.

There were many good hard questions to the experts from the leading CCS-sceptic negotiators from Grenada (who co-chaired) and Brazil, and from others. These were very open and forthcoming in their concerns, criticisms and questions, and got good scientifically-based and detailed answers. The importance of the IPCC GHG Guidelines (2006) was emphasised. Most discussion arose around long term liability, and the different options to manage that. It is possible that as a solution no one option may be specified for CDM, just that it is addressed by each project. Analogy with wind turbine long term liability (for fires) was made, in relation to CO₂ releases caused by earthquakes (the former not of concern to CDM). The worst case scenario of “massive catastrophic release” was clarified technically as not possible. It became clear also that there is legal uncertainty of liability if a site leaks out of a national jurisdiction into international waters. With risk assessment, prescribing just one technique or methodology was also thought wrong, when many and multiple options are available. Use of ISO 31000 was referred to as a general framework for risk assessment.

The ppts of the presentations by experts are now available at http://unfccc.int/methods_and_science/other_methodological_issues/items/6144.php. These also include Andrew Howard’s concluding slides on how this will be used by UNFCCC to develop the draft modalities and procedures to be negotiated upon in Durban. A report of the workshop will be produced by UNFCCC.

In terms of IEAGHG contributions, IEAGHG made many suggestions for speakers drawing upon the considerations on the Cancun Decision issues which were intentionally covered in the three storage Network meetings this year (Modelling, Monitoring, Risk Assessment). In terms of actual talks, as well as Tim Dixon talking on Transboundary issues and the London Convention, from IEAGHG networks there were two presentations from Andy Chadwick on CO₂ Storage Overview and on Monitoring, from Richard Metcalfe on Risk Assessment, and
from Katherine Romanak on Groundwater and Environmental Impacts. As they were new to UNFCCC, they were briefed with background material and also on the misunderstandings and misleading information not uncommon in the UNFCCC environment. Andy’s response to a question from Grenada on the Economides paper was a particular highlight. The IEAGHG report on CDM Market Impacts (2008) was also used in discussions.

The negative aspects were that it left the issue of liability unsatisfactorily addressed according to one leading sceptic, although this could be viewed as more of a policy issue and hence for negotiations in Durban. Also Greenpeace and CDM Watch lowered the overall high standard of information by misrepresenting London Convention work, fortunately IEAGHG was able to correct the participants.

IEAGHG’s view is that overall the workshop achieved a positive outcome. The workshop successfully enabled leading negotiators to get down to technical detail not achieved before, and so addressed the outstanding technical issues for CCS in the CDM (and developing countries), providing a good foundation for the negotiations at CoP-17 in Durban in December.

**Next steps**

The UNFCCC will use the report from the workshop and the synthesis report as the basis for draft new modalities and procedures for CCS in CDM. These will be discussed and negotiated over by SBSTA at COP-17, and SBSTA will make recommendations for a decision to the CMP-7 plenary also at Durban.

For COP-17, IEAGHG will again work closely with GCCSI, IEA, and CCSA. IEAGHG (Tim Dixon) is expected to participate at COP-17, funded under the contract from GCCSI. It is anticipated that GCCSI will provide a side-event on CCS, and that the morning briefings on CCS provided at COP-16 by GCCSI using IEAGHG will be repeated due to their popularity.
Introduction
At the 39th meeting the ExCo discussed a proposal for IEAGHG to undertake a study on costs of power plants with CO₂ capture. The proposal was initially focused on post-combustion capture but it was clarified that it could be broadened to cover all three of the major CO₂ capture techniques. The proposal was rejected by the Members and the following comments were included in the minutes of the meeting:

- Members questioned what the additional benefit of this study would be and were cautious over the added benefit over the EU ZEP work.
- USDOE has completed several investigations in this area, and created baseline data on which to model new plants against. From their experience, it is worth looking at the contractors who have worked on this before, as we could piggy-back on completed work.
- Members questioned the value as there are many other cost estimates being carried out, and therefore moving this to a different level would be the added-value option; maybe this could review and critique the work completed before, to gain more of a valuable report.
- Would we would consider cost variations on regional sensitivities, as this would be seen as an added benefit to the work already completed.

The Chair summarised that “we need a review initially and it should assess all three capture options and be reported back when possible”. This note is intended to provide background information to stimulate discussion and decision making by Members at the 40th ExCo meeting. It considers the need for capture costing studies, the other organisations that are undertaking costing studies, the pros and cons of IEAGHG continuing to do costing studies and a review of possible future work by IEAGHG.

The need for capture cost studies
Cost is probably the most important barrier to commercial application of CO₂ capture. For this reason undertaking technical and economic assessment studies on plants with CO₂ capture has been one of the main activities of IEAGHG since its inception in 1991. Studies on the costs of capture are needed by energy policy makers, researchers and companies who supply and operate plants. The studies are used to help policy makers and companies to decide whether CCS should be part of their future energy supply systems and businesses. The studies also help to determine the relative merits of different capture technologies and help to focus R&D on improved processes. High level summary cost information is sometimes sufficient for policy makers but companies and researchers often require more detailed information. Some companies that are already active in CCS, including some of IEAGHG’s sponsors, undertake their own capture cost studies but for the many companies that are considering entering the CCS business, independent public domain studies such as those carried out by IEAGHG are particularly valuable.

Scope and cost of IEAGHG’s capture cost studies
Before considering whether IEAGHG should continue to undertake capture cost studies and if so what type of studies we should do, it is worthwhile describing our typical studies.
IEAGHG’s capture cost studies usually involve technology selection and plant definition, estimation of plant performance and thermal efficiency and estimation of capital and operating costs and costs of electricity generation for plants with and without capture. Costs of CO₂ capture are calculated by comparing plants with and without capture. Sensitivities to a range of technical and economic criteria are usually assessed. For studies on novel capture processes, the costs of a reference plant based on a conventional capture process need to be estimated as a benchmark to calculate the improvements in performance and costs of the novel process on a consistent basis.

IEAGHG’s capture cost studies are usually undertaken by engineering contractors, who make use of information from capture process licensors and their own databases of equipment and installation costs. IEAGHG’s studies are usually for “nth-of-a-kind” plants based on known technologies. Some other organisations estimate costs for “first-of-a-kind” plants such as demonstration plants which include significant extra costs, for example due to conservative equipment design, high engineering and permitting costs and limited availability of plant suppliers etc. First-of-a-kind plant cost estimates are important for commercial decisions regarding demonstration plants but they are not a good guide to the costs of large scale use of CCS.

The scope of capture costing studies has tended to increase over time. In the early days of IEAGHG, when CO₂ capture technology was at an early stage of development and acceptance, relatively simple low cost studies were appropriate. Since then the level of knowledge on CCS has increased and the technology has moved closer to commercial application, so more detailed costing studies are expected. For example, early capture cost studies only assessed base load operation as that was considered to be the only role for CCS but in some countries it is now being seen to be necessary to also consider flexible operation, which involves significantly more analysis of plant performance and costs.

Financial resources are potentially a significant barrier to future work on capture cost studies by IEAGHG, because of IEAGHG’s modest budget and the need to carry out studies on many different aspects of CCS. Costs of IEAGHG’s recent engineering costing studies have typically been close to £100k. It is considered that IEAGHG has obtained good value for money in most of its capture plant engineering costing studies. The fact that IEAGHG’s studies are widely disseminated is viewed by some contractors as a major benefit because it enables them to publicise their capabilities in the rapidly expanding business area of CCS and consequently they have been willing to provide studies at below cost.

IEAGHG has participated in multi-partner costing studies, including the Canadian Clean Coal Power Coalition’s phase 1 studies and the EU Dynamis project, both of which had larger overall budgets. Although these studies provided useful information on costs of capture, IEAGHG has not been able to provide detailed information to its members due to confidentiality and consequently it does not propose to be involved in similar studies in future.

**Other organisations estimating costs of capture**

During most of that time since IEAGHG’s inception few other organisations have published detailed engineering assessments of the performance and costs of plants with CO₂ capture. For example at the time of the IPCC Special Report on CCS, completed in 2005, IEAGHG’s reports on costs of CO₂ capture, along with reports by US DOE, EPRI and universities were the main sources of cost data that could be used by the authors. However, since then the number of organisations working on capture cost estimating has increased, including organisations with access to substantially greater financial resources than IEAGHG such as various EU collaborative R&D programmes (ENCAP, Dynamis etc), the EU Zero Emissions...
Platform (ZEP), US DOE, EPRI and various private companies such as Alstom. However, with the exception of the DOE studies, only summary information from these studies appears to be available in the public domain. Even more detailed front-end engineering and design (FFED) studies have been undertaken by companies to estimate costs of proposed commercial scale capture demonstration plants but usually no cost information from these studies is made publicly available for commercial reasons. IEAGHG therefore remains one of the few public domain sources of original detailed engineering costing studies on CO\textsubscript{2} capture.

Most studies on CO\textsubscript{2} capture have been for power generation plants. Detailed public domain studies on capture in other industries are either sparse or non-existent, despite the expectation that other industries will account for a large proportion of future CCS\textsuperscript{1}.

Possible future work by IEAGHG on capture cost estimation

Whether IEAGHG should continue to undertake studies on capture cost estimation is a strategic decision that should be discussed by the ExCo. Major reasons why IEAGHG should or should not undertake such studies are summarised below.

Reasons why IEAGHG should continue to do studies on costs of CO\textsubscript{2} capture

- IEAGHG has an established reputation for unbiased costing studies, not linked to any particular country or technology supplier, and our reports continue to be valued by a large number of organisations and researchers\textsuperscript{2}.
- Few detailed original studies on costs of CO\textsubscript{2} capture are available in the public domain. Although more detailed studies have been carried out by other organisations they are rarely made available in the public domain, except in a highly summarised form.
- Some of the existing public domain studies are either derived from the same original studies or they are carried out by the same contractor, and they are likely to be based on the same source data. Having capture cost data from a variety of original sources provides greater confidence in CCS costs.
- There are some important aspects of capture costs, such as implications of variable operation and potential use of CCS in industries and smaller scale applications, so there is still scope for significant original work by IEAGHG. IEAGHG’s flexible work programme enables it to identify and respond to emerging issues before they become widely considered by others.
- Undertaking studies on capture plant performance and costs provides in-depth knowledge which contributes to IEAGHG’s overall expertise. Withdrawal from this area of work could result in IEAGHG becoming increasingly marginalised in the field of CO\textsubscript{2} capture and being seen as essentially a CO\textsubscript{2} storage organisation.

Reasons why IEAGHG should not do studies on costs of CO\textsubscript{2} capture

- Other organisations with greater financial resources than IEAGHG are doing studies on capture costs.
- Costs of plants in general are highly uncertain because of current global economic conditions, and any costing studies will soon become out of date.
- The relative costs of the leading capture technologies appear to be similar based on currently available information. Only when commercial plants have been built will real significant cost differences become apparent.

\textsuperscript{1} According to the IEA’s CCS Roadmap, 45% of CCS in 2050 will be in industries other than power generation.

\textsuperscript{2} For example, a paper which summarises IEAGHG’s costing studies is the most cited paper in the 60 editions of Energy, the International Journal published in the last 5 years.
- Estimating costs of novel “second generation” capture technologies is highly uncertain due to uncertainties in process performance and the use of novel materials and equipment whose costs cannot be accurately estimated. Once technologies have been developed to a stage where accurate costing can be undertaken, commercial considerations may limit the amount of information that is available for public domain costing studies.
- Although IEAGHG could re-focus its costing study work onto industries and potential longer term applications of CO₂ capture outside of power generation, past experience indicates that such studies are not the core interests of most of IEAGHG’s members and consequently they are unlikely to be selected by the ExCo.

Options for future IEAGHG costing work
If Members decide that IEAGHG should continue to undertake studies on capture costs, some options are described below.

Summarise other organisations’ capture costs
IEAGHG has in the past carried out its own detailed costing studies. A possible alternative future role for IEA GHG could be to provide summaries of detailed costing studies undertaken by other organisations. However, it should be noted that this role is already being fulfilled by other organisations, for example the IEA recently published a good review of recent published capture costs.

Participate in a CCS costs network
A workshop on costs of CCS, covering the entire chain of capture, transport and storage, was held in Paris in March 2011. The workshop is summarised in the Appendix. The participants at the workshop decided that it would be worthwhile to organise a network of experts to facilitate on-going discussion on CCS costs. IEAGHG decided that it would not take on the role of organising this costs network because it is already organising several other networks and it does not want to increase this already heavy commitment. However, IEAGHG will continue to be one of the members of the network steering committee.

Because there is great interest in CCS costs, the potential membership of the network is large. In order to limit the size of meetings and maximise the amount of discussion the steering committee decided to restrict membership of the network to only key people who are actively working of CCS costing. Interested parties would need to describe what they could bring to the table as input to the network. It is therefore important that IEAGHG continues to carry out its own CCS costing work to fulfil this criterion.

The main activity following on from the workshop will be to discuss CCS costing methods and measures, which is area where IEAGHG has done significant work in recent years.

Carry out detailed studies on coal fired power plants with capture
IEAGHG could continue the work it has done in the past on engineering costing studies on current technology power plants with CO₂ capture. In 2003-5 IEAGHG carried out studies on the leading post combustion, pre-combustion and oxy-combustion capture processes in power plants and subsequent studies have been mainly derived from these studies. These studies are now considered to be out of date due to subsequent technology developments. IEAGHG is currently doing a study on CO₂ capture at natural gas fired power plants, with active support from two leading post combustion capture technology suppliers, but new studies are also needed on coal fired plants. New studies on these leading capture options would be useful in their own right and they would also be needed as baseline plants for any studies on advanced
capture technologies. It is recommended that the three leading capture technologies in coal fired power plants should be assessed in a single study to ensure consistency.

An alternative approach would be for IEAGHG use ‘current technology’ capture plant costing studies carried out by other organisations as the baseline for its own future studies on advanced capture technologies, capture plant flexibility etc. The only study in the public domain that contains a reasonable amount of detail is believed to be the DOE-NETL fossil fuel baselines study. Use of this baseline study would have the advantage of providing some consistency between NETL and IEAGHG’s studies. Ideally IEAGHG would use the same contractor as NETL but this would negate IEAGHG’s principle of using competitive tendering for its studies and it may not be cost effective. If the same contractor could not be used there is a risk that IEAGHG and its contractor would not have access to all of the details and assumptions necessary to carry out its studies on a consistent basis to the baseline plants.

Advanced capture technologies
Most of the detailed published studies on capture costs have concentrated on first generation technologies such as MEA post combustion scrubbing. Several organisations are offering improved post combustion capture solvents and two such solvents are being assessed in IEAGHG’s on-going study on costs of capture at gas fired power plants. To provide a realistic assessment of the future application of CCS it is important that capture costs are based on such processes.

A wide range of advanced ‘second generation’ capture technologies including solid sorbents, cryogenics and membranes are also being developed. In many cases the developers of these processes and their funding agencies are undertaking costing studies but details are not usually made widely available. IEAGHG could focus its capture cost studies on second generation processes but availability of data may be a major constraint, either because sufficient practical results are not yet available or because of commercial confidentiality. The cost advantages of second generation capture technologies have to be assessed in relation to the costs of first generation technologies, assessed on a consistent basis. If IEAGHG ceases to undertake, or have detailed access to, studies on first generation capture technologies it becomes difficult to do meaningful studies on second generation technologies.

Regional cost variations
At the 39th ExCo meeting Members expressed interest in regional variations of CCS costs. Even within countries there can be substantial differences in costs due to differences in climate, raw material availability and transport, equipment delivery costs, labour productivity etc., but the most significant differences are likely to be between developed and less developed countries. There is currently relatively little information available on regional differences in costs of CCS and uncertainties are high. The GCCSI has recently published variations in overall CCS costs for 11 countries. Some bi-lateral studies such as the UK-China NZEC study have also provided some cost data and a paper published by Alstom has provided a significant amount of high level information on costs in Europe, North America and South-East Asia.

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3 Cost and performance baseline for fossil energy plants, revision 1, DOE/NELT-2010/1397, Nov. 2010.
4 The contractor that undertook the NETL baseline study has in the past refused to tender for IEAGHG’s studies because the funding available is not sufficiently great.
5 In the IPCC report and the recent IEA summary report on capture costs, the only reference to a post combustion capture costing study that was based on solvent other than MEA was an IEAGHG study that was based on KS-1 solvent.
6 Cost assessment of fossil power plants equipped with CCS under typical scenarios, Power-gen Europe, 2011.
At a simple level the relative costs of plants with capture in different countries are likely to be about the same as the relative costs of power plants in general. A more detailed assessment would require knowledge of the types of equipment and services used to build each type of capture plant and the capabilities of countries to supply the equipment and services. The effects of different ambient conditions and fuel analyses would also need to be taken into account. IEAGHG could in principle undertake a detailed assessment of regional variations of capture costs but the cost of doing this would most likely be beyond IEAGHG’s resources. Other organisations, including ones with greater direct involvement with developing countries, may therefore be better able to carry out detailed studies on regional costs of capture.

**CCS in industry and smaller scale applications**

Most studies that have been carried out by IEAGHG and others have been on costs of capture in power generation. However the IEA’s Carbon Capture and Storage Roadmap predicts that almost half of CCS in 2050 will be in industries other than power generation, especially production of synfuels, iron and steel, cement, chemicals and gas processing. In 2008 IEAGHG published a study on capture at cement plants and is currently doing a study on capture at steel plants. Some other organisations have done or are doing studies on capture in industry, particularly the major European ULCOS collaborative project on capture in the steel industry and the CCP on oil refineries but detailed results from most studies are not available in the public domain. It has been difficult for IEAGHG to obtain ExCo approval for studies on CCS outside of the power generation and oil and gas industries because other industries are not the core interests of most of IEAGHG’s members and sponsors.

A difficulty with doing studies on capture costs in industry is that the plants are often more complex and site specific than power plants, so costing studies will be more expensive and less generally relevant. An alternative approach would be to produce a ‘toolbox’ of costs of major capture components and their sensitivities to important criteria, which would enable site owners to estimate costs for their own individual sites. However, this approach may fail to identify some of the significant costs at industrial sites. Major new greenfield industrial plants are rare in industrialised countries, so it would be necessary to assess capture retrofits, the costs of which are even more difficult to estimate. There are potential opportunities for collaboration and possible co-funding of studies by industry organisations but some industries prefer either to undertake their own private studies (such as the steel industry’s ULCOS consortium) or they are reluctant to embrace CCS, because they see it as an unacceptable cost.

For smaller scale static sources of CO₂ and some larger mobile ones such as ships, there will be a choice between using CCS directly and using energy carriers (principally hydrogen or electricity) produced either from large scale plants with CCS or for other energy sources (renewable or nuclear). Either way, this is potentially a major market for CCS. IEAGHG has undertaken a study on the costs of pipeline collection of CO₂ from distrusted capture plants but the relative costs of providing CCS-derived hydrogen and electricity to end users and the costs of distributed CO₂ capture has not been adequately assessed and there is scope for further work. There is also scope for study of second generation capture technologies that are better suited to distributed users than the first generation technologies that will be used in large scale plants.

**Electricity system costs**

Most existing studies on CCS costs have focussed on base load operation but it is becoming clear that CCS plants will have to co-exist with other low carbon technologies such as renewables and nuclear and the characteristics of these technologies and the normal variability in consumer electricity demand will affect how CCS plants are operated and their economics.
There are two aspects to assessing CCS in electricity systems; assessing the costs of flexible operation of CCS plants and assessing the value of CCS plant flexibility. The former can be estimated in engineering costing studies and the later requires the use of electricity system models.

IEAGHG is currently completing an engineering costing study to assess the costs of improving CCS operating flexibility but there are a large range of technical options and there remain significant unknowns. Some detailed work to address these issues will be undertaken by capture technology developers and academic institutions but there may nevertheless be scope for IEAGHG to make a useful contribution in some areas.

It is not proposed that IEAGHG should undertake its own studies on electricity systems, to assess how CCS plants will be called upon to operate and the value of CCS flexibility. However, the CCS and renewables divisions within the IEA secretariat are about to start collaborative work on modelling CCS in electricity systems with high amounts of renewables and IEAGHG has been asked to contribute information from its capture costing study. Continuation of this collaborative work, which involves no funding by IEAGHG, is recommended as the best way of assessing system costs and operating requirements of CCS plants.

Conclusions

Cost is probably the most important criterion for commercial application of CO₂ capture, so it is recommended that the Programme should continue to work on this subject to maintain its involvement in all major aspects of CCS. The extent of IEAGHG’s future work on costs of CO₂ capture depends on the ExCo’s views on the Programme’s priorities. Recommendations for specific activities are:

- IEAGHG should participate in a network of experts on CCS costs, including in particular the associated discussions on costing methods and measures.

- IEAGHG should investigate the possibility of making use of NETL’s existing costing studies as the baseline for its own future studies. This will involve discussions with NETL and its costing study contractor. If there is not a satisfactory and cost-effective outcome, IEAGHG should put forward a proposal to the ExCo to carry out a new baseline study on coal fired power plants with the leading capture technologies (pre, post and oxy-combustion capture). This would provide a baseline for IEAGHG’s future studies on advanced capture technologies and other aspects of CO₂ capture.

- IEAGHG should put forward proposals to the ExCo for costing studies on advanced capture technologies in power plants on a case-by-case basis, depending on the expected availability of the data that would be required to carry out such studies.

- Subject to agreement in principle at the ExCo meeting to support such studies, IEAGHG should put forward proposals to the ExCo for studies on CO₂ capture in various industries and applications other than power generation.

- IEAGHG should continue to assist the IEA with its work on economics of electricity systems with CCS and renewables. IEAGHG should consider doing further studies on technical and cost aspects of CCS plant flexibility particularly if it is required to support this collaborative work.
APPENDIX

CCS Costs Workshop
A two day workshop on costs of CCS, covering the entire chain of capture, transport and storage, was held in Paris in March 2011.

The workshop was attended by 38 invited experts who are working on CCS cost estimation and it was organised by a steering committee consisting of Howard Herzog (MIT), John Davison (IEAGHG), Richard Rhudy (EPRI), Matthias Finkenrath (IEA), Clas Ekstrom (Vattenfall), Chris Short (GCCSI) and Ed Rubin (Carnegie Mellon University). Keynote presentations were made on:

- Audiences and uses for CCS cost estimates
- CCS costing methods and measures
- Status of CO₂ capture costs
- Status of CO₂ transport costs
- Status of CO₂ storage Costs

Each keynote presentation was followed by short presentations by three respondents and then a discussion session. These sessions were followed by breakout sessions on capture, transport and storage costs and finally the benefits of establishing a CCS cost network were discussed.

It was concluded that a network between CCS cost experts would be useful for information exchange. Ideas for related activities included addressing the lack of common terminologies and methodologies, improve general understanding of costs and work towards best practices or guidelines. A network could help to collect and organise relevant studies and information, and to communicate the current status of CCS costs more clearly. Future activities could include identifying gaps in knowledge, peer review cost evaluations and relate costs to technological development status and challenges. A broad range of potential members was identified in the context of a CCS costs network, such as the power, oil and gas industry, equipment manufacturers, academia, NGOs, engineering companies, governments and other energy-intensive industries. Membership could be based on an application process during which interested parties would need to describe what they could bring to the table as input to the network. It was tentatively decided that a further meeting would be held in spring 2012, probably in the USA.

The GCCSI has set up an area on their website, restricted to network members, to handle network communications. A draft report of the workshop, which includes the presentation slides, is posted on this website and a final version is expected to be available shortly.
Introduction
This study was undertaken in house to identify and quantify opportunities for Carbon Capture and Storage (CCS) and renewable energy technologies to be combined in a synergistic way and to identify any options which would tend to leave a permanent legacy for the renewable power generation industry. Several interesting options were studied and the key option of providing renewable thermal energy to compensate for the parasitic losses incurred by post combustion CCS was studied in some detail. The options investigated were:

- Concentrated solar thermal energy for CCS solvent regeneration and other power plant heating duties
- Hydrogen from Gasification/CCS as emission free support fuel for Concentrated Solar Power (CSP) thermal power plants
- A compressed air energy storage (CAES) system to provide load following capability for a Gasification/CCS/Hydrogen/CCGT power plant
- Use of concentrated solar heat for high temperature chemical reactions in support of CCS- calcining reactions and hydrogen production.
- Use of surplus wind energy for water removal from CO₂ storage reservoirs

Findings
The use of solar energy for CCS solvent regeneration and other power plant heating duties is the most promising combination. The amount of energy which might be collected close to a large 1GW power plant sited in a typical location was considered. Such locations are more likely to be in temperate climates where insolation levels are far lower than those at desert sites favoured for CSP applications. It was also considered that the solar collection should occur in a band around the site and that the furthest arrays should be no more than 2km distant. In temperate climates on sunny days at peak radiation times it is possible to gather enough energy to defray all of the CCS losses and several internal low temperature feedwater heating duties. However over 24-hours only part of the parasitic losses can be covered. The net result is that plant fossil fuel efficiency would improve by up to 3%. To do more requires thermal storage which would be expensive and on the limit of feasibility. A further consideration is the ratio between diffuse and direct radiation since only direct radiation can be used in highly concentrating solar thermal systems. At prime solar sites in low latitudes as much as 80% of the insolation is direct radiation. This figure falls to as little as 40% in northern latitudes. Investigations show that it is rather inefficient in both land area use and overall power conversion efficiency to provide thermal energy using heat storage or by backing out the extracted steam normally used for solvent regeneration and boiler feed water heating. This is at first sight a surprising result. The reason for the former is that there are exergy losses in heating and cooling the thermal storage medium and the full potential of linear solar arrays to generate high temperatures is not utilised. The reason for the latter is that daily cycling of the extraction rate of steam cause slight reductions in steam turbine efficiency. Even though these are very small they apply to a large proportion of the power. It is thus found to be far more efficient to install a dedicated steam turbine suited to processing the heat derived from the solar arrays.

Furthermore the investigations suggest that direct steam generation at moderately high temperatures in linear Fresnel arrays makes the best use of the practically available collection.
area around the plant. The role of the host CCS plant is limited to that of managing the warm up and standby of the solar turbine. The solar turbine provides an opportunity for CO₂ capture to be interrupted at times of high power demand without loss of thermal efficiency since it can be used for efficient conversion of extracted steam leaving the main turbines operating at maximum efficiency. The legacy left by the CCS plant is a small but effective solar power plant which would be capable of stand alone operation with little modification.

Of the other options investigated the two involving supply of hydrogen generated by a Gasification/CCS process to high temperature CSP and to CAES systems are the only ones which exhibit potential. However the first option makes poorer use of the hydrogen in conversion to power than a stand alone IGCC/CCS plant. The alternative of using natural gas as a supplementary fuel for CSP will be more economical but would create significant CO₂ emissions and again would make less efficient use of the gas than a stand alone CCGT plant. The CAES option may be able to utilise hydrogen with the same efficiency as an IGCC/CCS but there is not enough data on efficiencies to determine if this is the case. In both options a hydrogen store would enable capacity variations to be smoothed out and hence enhance overall power conversion efficiencies.

The other two options investigated do not seem to be viable. High temperature solar chemical conversion processes are still in their infancy. Heat and material transport requirements make integration infeasible. The option to use surplus wind energy to power extraction of water from CO₂ storage reservoirs to create additional storage volume or enhance injection rates is viable. However the power requirements are extremely small and therefore not significant as far as power balancing is concerned.

It is recommended that further work is considered to characterise the use of CSP in post combustion capture. Several quite optimistic papers have already been published on this subject. The scope could include:

- Survey power plant sites to establish land available and solar intensity patterns.
- Detailed analysis of steam turbine performances at the off load conditions under which such schemes require them to operate
- More detailed calculation and verification of true efficiencies of the various alternatives
- In depth consideration of all the environmental impacts and secondary land use implications

It is recommended that if further work is undertaken on the life cycle analysis of CCS in the near future that reduction of impacts through integrating renewable energy is not considered as its application is too uncertain.

It is recommended that further work is undertaken to understand what the essential supplementary fuel requirements of high temperature CSP systems are. It would also be worthwhile to establish the true efficiency with which supplementary fuel is converted to power in a CAES system.
**IEA GREENHOUSE GAS R&D PROGRAMME**

**40th EXECUTIVE COMMITTEE MEETING**

**CO₂ GEOLOGICAL STORAGE COSTS PHASE 2**

**Introduction**

IEAGHG’s storage cost calculator study was approved at the 37th Executive Committee meeting. At the 38th Executive Committee meeting, IEAGHG’s General Manager (Mr John Gale) informed members that IEAGHG had reached an agreement with the EU ZEP (European Technology Platform for Zero Emission Fossil Fuel Power Plants/Zero Emissions Platform) to share the costs of updating their existing cost calculator with new input from ZEP members.

**ZEP/IEAGHG Storage Costs report**

IEAGHG was a partner with ZEP in the report titled ‘The Costs of CO₂ Storage’. Three reports were published by ZEP in 2011 – looking at the costs of capture, transport and storage – along with an overall summary report for all three. The European-based reports give realistic cost estimates (based on ZEP members’ extensive knowledge) of complete value chains estimated for new-build coal- and natural gas-fired power plants.

The results of ‘The Costs of CO₂ Storage’ report indicate that the location, type of field, reservoir capacity and reservoir quality are the main drivers for costs in the storage of CO₂. The trends recognised were that onshore storage is cheaper than offshore, depleted oil and gas fields (DOGF) were cheaper storage reservoirs than saline aquifers (SA) – particularly when they have reusable legacy wells, and the highest costs (and widest cost range) were achieved when storing in offshore saline aquifers. The report acknowledged that there was a greater storage capacity in Europe offshore than onshore, especially for DOGF, and a greater capacity in saline aquifers than in DOGF. Costs varied significantly, from €1-7 per tonne of CO₂ in onshore DOGF, to €6-20/tonne in offshore saline aquifers.

An external party was contracted by ZEP to create the cost model (a Microsoft Excel spreadsheet) used to populate the above report with cost figures. The cost model was finalised in October 2010 and was considered as strictly confidential and not allowed to be shared outside of the Core CCS Cost workgroup. Some Executive Committee members have expressed their concern at not being able to see the underlying data, assumptions and spreadsheet model.

**Phase 2**

In July 2011, IEAGHG finalised the technical specification for Phase 2 of the storage costs study (see appendix 1 for full technical specification). Part one of this intended study is to extend the ZEP/IEAGHG storage costs report to other key world regions for CCS (North America, Australia, China and East Asia, the Indian Subcontinent, the Middle East, Central and South America, Russia and Central/North Asia, Africa). This extended report will assess costs for deep saline aquifers and depleted oil and gas fields.

Part two of Phase 2 will involve developing a web-based cost calculator, which is intended to be a similar form/type as the storage monitoring tool currently hosted on the IEAGHG website. The tool will allow users to derive a range of estimated storage costs for specified scenarios, based on data input by the user for key parameters.
IEAGHG envisage that the contractor will use the ZEP/IEAGHG spreadsheet model as a basis to extend the report to other regions and develop the cost calculator. Much of this data would have to remain confidential, as per the agreement for the ZEP/IEAGHG report.

IEAGHG asks the Executive Committee whether they are happy to proceed with Phase 2 as above, or instead change the technical specification so the contractor would develop a fully transparent CO₂ storage costs model.

Appendix 1 – CO₂ GEOLGICAL STORAGE COST CALCULATOR Technical Specification

Introduction

The financial cost of any Carbon Dioxide Capture and Storage (CCS) project is likely to be one of the key deployment factors, influencing design, operation, duration and overall feasibility of a project. Whilst storage costs are widely anticipated to be lower than capture costs for many point source anthropogenic emissions, they still form a significant component of overall CCS costs and moreover are subject to uncertainty due to factors including an absence of established regulatory regimes in many jurisdictions and limited operational experience of industrial scale injection.

During 2010, IEAGHG co-funded an assessment of potential storage costs undertaken by the Zero Emissions Platform (ZEP). This work has culminated in publication during 2011 of a joint IEAGHG/ZEP report on projected European storage costs.

The main aim of this study will be to build on the recent ZEP/IEAGHG report by applying the storage costs assessment to other key CCS regions around the world. A second aim of the study will be to create a web-based tool, to be hosted on the IEAGHG website, which will allow users to derive estimated storage costs for specified storage scenarios.

Technical Background

The ZEP/IEAGHG study assessed potential commercial deployment of CCS across Europe and identified six principal storage scenarios as follows:

- Onshore depleted oil and gas fields (DOGF) with legacy wells;
- Onshore DOGF with no legacy wells;
- Onshore deep saline formations (DSF) with no legacy wells;
- Offshore DOGF with legacy wells;
- Offshore DOGF with no legacy wells;
- Offshore DSF with no legacy wells.

For each of the above scenarios, full life-cycle costs were assessed.

The analysis of storage costs was made using a spreadsheet model adapted from a previous CCS costing study. The spreadsheet was provided on a confidential basis by a third party and is not published with the ZEP/IEAGHG study report. Input parameters for the model (i.e. required quantities and costs of key storage elements such as geophysical surveys, well installations etc) were determined by a team of experts from ZEP member industrial organisations.

The ZEP/IEAGHG study found that many factors affect predicted storage costs, including site location (e.g. onshore versus offshore), storage capacity, injectivity, legacy wells, and the presence or otherwise of existing, reusable infrastructure. Costs varied from onshore DOGF as the cheapest scenario (1 – 7 Euros per tonne) through to onshore DOGF as the most expensive (6 to 20 Euros/tonne). These variations in cost are primarily the result of the natural variability of storage site characteristics, rather than uncertainties associated with cost elements.
Scope of Study

The first objective of the study is to extend the ZEP/IEAGHG analysis to other key world regions for CCS, namely:

- North America
- Australia
- China and East Asia
- The Indian Subcontinent
- The Middle East
- Central and South America
- Russia and central/north Asia
- Africa

The study will assess storage costs only for DSF and DOGF. Storage costs for coal seams, basalts, shales and other geological media will not be considered. Storage directly associated with operational CO2-EOR will also be excluded from the study analysis due to the technical and economic complexity of these sites.

The ZEP/IEAGHG spreadsheet model should be used as the basis for assessment of storage costs. The spreadsheet model is to remain strictly confidential and will not be published with the final study report. The contractor will need to assess the likely quantities and costs of various project elements for each region and identified storage scenario.

Future trends in cost and availability of materials, goods and services may also need to be considered under the study, and the potential influence these factors may have on future costs of geological storage should be described.

The second part of the study will be to develop the web-based cost calculator. The exact form of this tool will be developed by the contractor in consultation with IEAGHG. It is envisaged that the tool will allow users to derive a range of estimated storage costs for specified storage scenarios, based on data for key parameters input by the user. The storage monitoring tool currently hosted by the IEAGHG website provides an example of the type of functionality sought. The contractor may be able to use the ZEP/IEAGHG spreadsheet (or a simplified version) as the ‘engine’ for the tool, although the spreadsheet must not be accessible to the user due to confidentiality restrictions.

The successful contractor will need to have relevant expertise in areas such as the economic and technical aspects of CO2 geological storage, and the contractor will be provided with copies of recent, relevant IEAGHG studies and details of other IEAGHG contractors working on similar or related study areas to ensure compatibility of data, and consistent terminology usage.

In addition to providing consistency with the recent ZEP/IEAGHG report, results from the following IEAGHG studies will need to be considered by the contractor:

- Injection Strategies for CO2 Storage Sites, CO2CRC, 2010-04
- Gap Analysis for CO2 Storage Deployment, Geogreen, in progress.

Reporting

A draft report, containing the results of the study, will be produced. An electronic copy of the draft report will be delivered by the date specified in the Tender Instructions. IEAGHG will send copies of the draft report to an expert review panel for comment within 1 month. Appropriate comments will be passed on to the contractor as soon as possible. The contractor will modify the report to take these comments into account and will deliver the final report within one month of receiving the comments.
The final report will also be supplied electronically, on a PC CD-ROM or by electronic transfer, in Microsoft Word and PDF formats (including all diagrams, illustrations, tables etc.). All diagrams, pictures and illustrations must also be supplied as *.tif, *.jpg or *.gif files at a resolution no less than 300dpi, unless they have been created in Corel Draw, PowerPoint or Excel, in which case copies in the original format are acceptable. If pictures are inserted into PowerPoint then original *.tif files should also be supplied separately. Photocopies of photographs and illustrations are not acceptable.

The final report (and any material supplied with it, and including this specification) is the property of IEAGHG and its contents must not be reported or published in any form, written or electronic, without the permission of the IEAGHG.

In addition to the final report, a paper (up to 10 pages) summarising the key findings of the study should be produced for open publication, either in a journal or for presentation at a conference. The conference or journal will be agreed in consultation with IEAGHG.

The form of deliverable for the web-based storage cost calculator tool will be discussed with IEAGHG as the study progresses.

All copies of the ZEP/IEAGHG spreadsheet (paper and electronic) must be returned to IEAGHG or destroyed at completion of the contract. Strict confidentiality with regards to the spreadsheet will be maintained by the contractor throughout the contract.

Progress Meetings

Allowance should be made for up to three meetings (including a project launch meeting) at the offices of the contractor carrying out the study. These meetings may not be necessary given good progress and agreement of the various issues by fax, e-mail or other means. The contractor should indicate whether they would be able to hold progress meetings by video conference if required.

The contractor should nominate in their proposal their proposed frequency and mode of communication for the progress meetings. IEAGHG will be responsible for the costs of its representative attending the meetings.

Form of proposal

The proposal should include the names and qualifications of the persons to be involved in the work. A schedule of the proposed work should be described together with the fixed total cost (in UK pounds sterling) for the work described, together with a breakdown of each individual's contribution (in hours/weeks or days).

If the contractor has not previously carried out work for the IEAGHG programme, references should be given of two independent parties familiar with the work of those tendering for this contract.
Introduction
This discussion note was prepared in-house in response to concern resulting from publication in the USA of an academic paper claiming that methane emissions arising from the production of shale gas could be sufficient to make unconventional natural gas from that source more greenhouse intensive than coal. Such a claim runs counter to the conventional wisdom that converting an application from coal to natural gas invariably results in a reduction in the greenhouse gas emission consequences of the application.

This review has identified that there is a shortage of representative public domain data on the shale gas industry and conflicting claims of appropriate assumptions. A simple framework has been developed for carrying out full fuel cycle analyses, which has been populated with indicative data.

The main reason for the disquieting claim that shale gas could be more greenhouse intensive than coal arises from the controversial use of a high Global Warming Potential for methane in the short term.

Full Fuel Cycle Greenhouse Footprint of Unconventional Natural Gas Production

Summary
The use of high volume hydraulic fracturing (fracking\(^1\)) for the production of shale gas, notably in the USA, results in methane emissions that are additional to the methane emissions arising from the production of conventional natural gas. The United States Environmental Protection Agency (USEPA) is charged with reporting the US Greenhouse Gas (GHG) inventory to the UNFCCC secretariat. In order to carry out that duty, the USEPA, with very little industry data, developed a methodology, published in 2010, for assessing the additional methane emissions arising from the completion of unconventional gas wells. That methodology derived a methane emission factor, which was not challenged by the shale gas industry at the time, of 9,175 Mcf per well completion.

In April 2011 Professor Robert Howarth from Cornell University published a paper based on the USEPA methodology and considering alternative global warming potential values for methane, which concluded that shale gas could be comparable with coal in its greenhouse gas footprint. This claim raised considerable concern in the US shale gas industry.

In May 2011, a rebuttal of Prof Howarth’s findings carried out by the US Department of Energy’s National Energy Technology Laboratory and, following the USEPA methodology, resulted in a lower estimate of the greenhouse footprint of shale gas supplied to large consumers, such as power stations, by using alternative assumptions, but there was still a significant increase over the greenhouse footprint of conventional natural gas.

In August 2011 a private report “Mismeasuring Methane” from IHS CERA was published, which examined the basis of the USEPA methodology and found that the key emission factor of 9,175 Mcf per well completion was overestimated compared with industry best practice. There are several factors involved in the assessment of the additional emissions of methane from unconventional gas production facilitated by fracking, which vary from case to case:

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1 An alternative spelling used in the Shale gas industry is “fraccing”
• The amount of gas produced during well completion that cannot be dispatched for sale;
• The proportion of that gas that is flared rather than vented;
• The duration of gas production from a completed well before reworking of the well needs to be carried out;
• The initial production from the completed well; and
• The rate of decline in the production of gas from an unconventional gas well.

Different assumptions concerning these factors are the main reasons for different messages concerning the comparative greenhouse footprints of conventional natural gas and shale gas. However, the main reason for Howarth’s disquieting conclusion that shale gas could be more greenhouse intensive than coal arises from his controversial use of a high Global Warming Potential for methane in the short term.

This debate is set against a background of increasingly confrontational disagreement between environmentalists and the shale gas industry, particularly in the USA. That disagreement is principally focused on incidents of adverse impact of fracking on water quality and community amenity. There are also several jurisdictions that have imposed a moratorium on the use of fracking technology.

Introduction

A special report (IEA 2011) accompanying the IEA World Energy Outlook 2010 asks “Are we entering a golden age of gas?” That detailed report builds a “Golden age of gas” scenario, which quantifies global demand and supply pathways. The IEA report states: -

• The factors driving natural gas demand and supply increasingly point to a future in which natural gas plays a greater role in the global energy mix.
• When replacing other fossil fuels, natural gas can lead to lower emissions of greenhouse gases and local pollutants.
• The global natural gas resource is vast and widely dispersed geographically.
• Unconventional natural gas resources are now estimated to be as large as conventional resources.
• Unconventional gas now makes up about 60% of marketed production in the United States.
• Use of hydraulic fracturing (fracking) in unconventional gas production has raised serious environmental concerns and tested existing regulatory regimes.
• Based on available data, we estimate that shale gas produced to proper standards of environmental responsibility has slightly higher “well to burner” emissions than conventional gas.

In contrast, a paper by Professor Bob Howarth from Cornell University (Howarth, 2011) suggests that surface plant methane emissions associated with fracking for shale gas production are at least 30% greater than, and perhaps more than twice as great as, those from conventional gas. Howarth, 2011 also estimates that the Greenhouse Gas (GHG) footprint of shale gas can be comparable with that of coal when considered over the conventional 100-year timeframe, when an increased Global Warming Potential value due to consideration of aerosol effects is used. When considered over a 20-year time frame with the higher Global Warming Potential (GWP) for methane, Howarth, 2011 indicates that the greenhouse footprint of shale gas obtained with fracking could possibly be more than twice as great as the typical greenhouse footprint of coal.

Additional analyses of the comparative greenhouse footprints of conventional and unconventional natural gas have been produced, for example by the National Energy Technology Laboratory of the US Department of Energy (NETL 2011). These analyses show that the marginal fugitive emissions of methane from shale gas fracking operations, which are
additional to emissions from conventional natural gas production operations, depend on a number of variables.

This note presents an initial scoping assessment of relative Greenhouse footprints of conventional natural gas and unconventional natural gas and presents it in the context of the alternative Global Warming Potentials and a nominal greenhouse footprint of coal.

An additional issue that has not been widely canvassed and is unquantifiable is the possible migration of methane gas from the fracking zone or the well casing later appearing as diffuse fugitive methane emissions at the surface. This note discusses the consequences of not achieving perfect hydraulic isolation of the target shale formation, which is a prerequisite for the IEA scenario. In addition, in the global context, the consequences are assessed of energy use for liquefaction and regasification of natural gas that is exported in the form of LNG. These two issues were not considered in either IEA 2011, Howarth, 2011 or NETL 2011.

**FFC Methodology**

The Full Fuel Cycle (FFC) methodology is adopted for this comparison of emission factors, as described in Appendix A. The FFC emission factor provides a measure of the greenhouse footprint (i.e. combustion emissions plus pre-combustion emissions) of an energy source at the point of supply to the consumer.

Using the FFC methodology outlined in Appendix A, a generic the FFC emission factor for delivered coal is about 100 kg CO$_2$-eq/GJ. This round number provides a useful benchmark for comparison with other delivered fuels. A generic FFC emission factor for conventional natural gas is typically in the range of 60-70 kg CO$_2$-eq/GJ. Hence natural gas is generally considered to be more greenhouse friendly than coal.

The FFC methodology does not take any account of the attributes of fuel affecting the efficiency with which that energy source might be applied. For example, electricity can be generated from natural gas more efficiently than it can be generated from coal, thus providing an addition greenhouse benefit from the use of natural gas. However, when considered for a smaller scale application, such as an industrial boiler or home heating, there is no such advantage. Neither coal delivered by truck, nor natural gas delivered by pipeline is in a form suitable for meeting the demand for mobile energy sources.

Table 1 shows a list of potential sources of precombustion emissions arising from the supply of natural gas to large and small consumers.
Table 1 Pre-combustion Emission Sources for Natural Gas

<table>
<thead>
<tr>
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<th>Emission Source</th>
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<tbody>
<tr>
<td>A</td>
<td>Methane permeating from mobilized gas underground directly to the atmosphere</td>
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<tr>
<td>B</td>
<td>Methane produced during fluid flowback after fracking</td>
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<tr>
<td>C</td>
<td>Routine venting and equipment leaks at well site (field production)</td>
</tr>
<tr>
<td>D</td>
<td>Intermittent emissions during liquid unloading operations at a well site</td>
</tr>
<tr>
<td>E</td>
<td>Emissions during gas processing at a central gas collection facility</td>
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<tr>
<td>F</td>
<td>Emissions from plant for liquefaction and regasification of gas transported as LNG</td>
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<tr>
<td>G</td>
<td>Emissions from high pressure pipelining and storage of natural gas</td>
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<tr>
<td>H</td>
<td>Emissions during low pressure pipeline distribution of natural gas to customers</td>
</tr>
</tbody>
</table>

The first of these precombustion sources of GHG is discussed in Appendix B. The scale of methane release to atmosphere via route A, if any, is unquantifiable because it is entirely dependent on unknown site specific factors.

Historical estimates of methane emissions from the US natural gas industry during a period of rapid expansion of unconventional gas production, as presented in the US GHG inventory are discussed in Appendix C.

A derivation of generic benchmark factors B to H is discussed in Appendix D. Alternative Global Warming Potentials for methane are listed in Table 2 and discussed in Appendix E.

Table 2 - Alternative Global Warming Potential Values for Methane

<table>
<thead>
<tr>
<th>Source Description</th>
<th>GWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPCC 1996 - Second assessment report - 100 year time horizon (This is the value currently used for carbon accounting)</td>
<td>21</td>
</tr>
<tr>
<td>IPCC 2007 - Fourth assessment report - updated - 100 year time horizon</td>
<td>25</td>
</tr>
<tr>
<td>IPCC 2007 - Fourth assessment report - updated - 20 year time horizon</td>
<td>72</td>
</tr>
<tr>
<td>IPCC 2007 plus aerosol effect - 100 year time horizon</td>
<td>33</td>
</tr>
<tr>
<td>IPCC 2007 plus aerosol effect - 20 year time horizon</td>
<td>105</td>
</tr>
</tbody>
</table>

A quantified comparison of estimated FFC emission factors, based only on factors B to H for conventional and unconventional gas is presented graphically below, with step off cases to illustrate the benefits of additional flaring and the effects of alternative GWP assumptions and the impacts of transporting gas in the form of LNG.

Analysis - Sources B to H

Excluding consideration of loss of containment of gas underground (Source A) the following analyses attempt to quantify all the other contributions to natural gas precombustion emissions listed in Table 1. Many of the factors have very wide potential ranges. For clarity a single median value of the fraction of the natural gas flow lost at each stage is suggested. Those fractional median losses are then compounded in the determination of an indicative median FFC factor. However, it is emphasized that there can be substantial variance around these estimates.

This initial analysis is primarily based on available data reflecting shale gas production and gas processing and transporting practices in the USA. At the present time the regulatory regime in the USA is being tightened up. For example, the New York Department of Conservation has just issued its 1537 page draft Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program for consultation. Some
countries and regions will have lower emissions due to tighter legislative standards and stricter environmental controls imposed on operators. Conversely, some countries will have weaker enforcement of standards and less pressure on operators to take measures beyond those dictated by an economic or safety imperative. For the purpose of this initial scoping discussion note, it is assumed that current US practice is middle-of-the-road and, since US engineering contractors operate worldwide, can be taken as a proxy for average worldwide gas industry practice.

Excluding consideration of loss of containment of gas underground, analyses based on factors presented in Appendix D, attempt to provide a benchmark indication of all the other contributions to natural gas pre-combustion emissions and to explore opportunities for additional flaring of methane. The results of this analysis are shown in Figures 1 to 4.

The analysis in Figure 1 is based on conventional gas industry practice, often required by legislation, that routine emission from production of natural gas are captured and flared where practicable.

It is suggested that short term intermittent emissions of methane from field development activities, which are not normally required to be captured unless for local environmental or safety reasons, could be captured and flared for greenhouse gas emission mitigation reasons. The potential benefit of such additional flaring is shown in Figure 2.
Figures 3 and 4 show estimates of the median FFC emission factors for natural gas and shale gas considered over a 20-year time horizon, with and without additional consideration of the aerosol effect of methane in air, based on the assumptions set out in Appendix D.

**Figure 2**

**Figure 3**
Figure 5 shows the impact on precombustion emissions of unconventional natural gas that is subsequently transported internationally in the form of LNG. In this case flaring of well-site emissions is included and the 20-year GWP horizon is adopted. In this case a 1.2% loss of containment of gas underground (source A) migrating to the surface over time would give the delivered fuel gas the same greenhouse footprints as coal.

The data for Figures 1, 2, 3, 4 and 5 are tabulated in Appendix D.
Observations
This analysis yields the following generalised indications:-

- That the median greenhouse footprint for conventional natural gas is typically nearly two thirds of the benchmark greenhouse footprint for coal; when these fuels are used in equivalent combustion applications.
- That the greenhouse footprint advantage of conventional natural gas over coal would be reduced by about 10% when gas is produced by unconventional methods from shale.
- That the greenhouse footprints of shale gas and natural gas would be about the same when a high level of flaring of intermittent emissions from shale gas development operations is practiced.
- That when methane emissions are considered over a 20-year time frame, the advantage of conventional natural gas over coal is about halved compared with consideration over a 100-year time horizon.
- That when methane emissions are considered over a 20-year time frame, the greenhouse footprint of shale gas approaches that of coal.
- That when the worst case methane GWP is considered, shale gas has the same greenhouse gas footprint as coal.
- That exporting of shale derived gas in the form of LNG, when produced with a high level of flaring at the wellsite, when considered over a 20-year time horizon would have a reduced greenhouse advantage over coal. That greenhouse gas advantage would be eliminated by a loss of underground containment of the gas amounting to 1.2% of the gas produced.

N.B. In Howarth 2010, there is no consideration of migration of methane underground. Howarth’s suggestion that the shale greenhouse footprint might be double that of coal is derived from taking the upper ends of the ranges of uncertainty in the methane emission from surface operations in combination with the worst case GWP assumption.
APPENDIX A

Full Fuel Cycle Analysis Methodology

A way of comparing the GHG footprint of fuels is the Full Fuel Cycle (FFC) emission methodology, which differs from Life-Cycle Analysis (LCA) methodology in that it does not include the energy consequences of construction of the necessary fuel processing equipment. The FFC emission factor is expressed in terms of kg of CO$_2$-equivalent per Gigajoule of fuel delivered to the end use application. In this assessment the GJ of delivered fuel is considered on the higher heating value basis. The FFC emission factor includes emissions from combustion of the fuel and also all energy use emissions and fugitive emissions associated with exploration, development, production, transport and processing of the fuel prior to delivery to the consumer.

The combustion emission factors for black coals are typically in the range of 88-92 kg.CO$_2$/GJ, and around 95 kg.CO$_2$/GJ for lignite. The precombustion GHG emissions from coal mining and transport typically include own use of fuel and fugitive emissions of coal bed methane, which are typically in the order of a 10 kg.CO$_2$-eq/GJ addition for black coal and a 5 kg.CO$_2$-eq/GJ addition for open cast lignite. Therefore a generic FFC emission factor for both coal and lignite is in the region of 100 kg.CO$_2$-eq/GJ. This round number provides a useful benchmark for comparison with other fuels.

The combustion emission factor for pure methane is 50 kg.CO$_2$/GJ on a higher heating value basis. This gives rise to the common perception that natural gas has about half of the GHG footprint of coal. However, natural gas resources are seldom pure methane. Natural gas typically contains significant amounts of CO$_2$, ethane, ethylene, propane etc., after recovery of propane and butane (as LPG) and light condensate naphtha (gas liquids). Associated CO$_2$ and non-methane hydrocarbons in reticulated natural gas result in a higher combustion emission factor, which typically makes the combustion emission factor for pipeline natural gas about 53 kg.CO$_2$/GJ (Baines 1993).

In addition to the emission of CO$_2$ from end use of natural gas as a fuel, there are additional emissions of methane arising from gas production and processing activities, and CO$_2$ from own-use of gas as an energy source, which is carried out by the natural gas industry as a consequence of bringing the natural gas product to the customer. (See Table 1 in the main text). Pre-combustion emissions typically contribute to the FFC emission factor for conventional natural gas being 60-70 kg.CO$_2$-eq/GJ.

In this discussion note the unit kg.CO$_2$/GJ is used where the only GHG emission considered is CO$_2$. When the CO$_2$ equivalent GHG effect of methane emissions is included then the term kg.CO$_2$-eq/GJ is used. The Global Warming Potential (GWP) that is used to convert methane emissions to CO$_2$-equivalent emissions is discussed in the main text of this note.
APPENDIX B

Methane Migrating from a Fractured Gas Resources to the Surface

A conventional natural gas field comprises an accumulation of fossil hydrocarbons in a natural geological trap, as illustrated on the left in the above diagram. The existence of the gas resource proves that the conventional natural gas cannot escape through faults fissures and aquifers to the surface; otherwise it would be long gone. When fracking of the conventional gas field is carried out to improve production rates, natural gas that is mobilized would still be constrained by the natural geological trap and would remain underground until drawn off through the gas production well. Therefore, in the case of conventional natural gas resources, fracking of them to increase production rates can reasonably be assumed not to create potential for methane to permeate from the disturbed gas resources directly to the atmosphere.

In the case of shale gas, the hydrocarbon source rock is targeted. Immobile methane is retained in gas-rich shale adsorbed onto the residual solid kerogen, where it is held by high hydrostatic pressure. Any mobile gas or hydrocarbon liquids would have migrated over geological time either into a conventional geological trap or to the surface. There is no indication that an overlying sealing layer is intact to contain shale gas that is mobilized by drilling and fracking.

Shale gas is produced by the use of directional drilling to create a longitudinal well following the contours of the shale formation. Reduction of the down hole pressure then results in methane desorbing from its source rock into the well. However, only gas in the immediate vicinity of the well would be accessed at commercially viable rates. Therefore fracking is used to reduce the permeability of the shale rock around the well and to increase the methane gas production rate.

In view of these considerations, it is considered possible for a small portion of the shale gas mobilized by the drilling and fracking activities to escape into underground cracks and aquifers and, possibly over a long period of time, to migrate to the surface. Such dispersed gas permeation to atmosphere might not cause an observable acute environmental effect of concern, but if the efficiency of gas containment is less than 100% there could be potential for additional anthropogenic greenhouse gas emissions arising from unconventional gas production activities.
The IEA WEO 2010 report lists some points of best practice in shale gas production including:

"Ensure that the well and the shale formation remain hydraulically isolated from all other strata penetrated by the well. This means ensuring both the physical integrity of barriers between the well and those other strata and that no communication is opened between the shale formation and the surrounding strata. To prevent contamination of water supplies, gas wells and the shale formation itself need to remain hydraulically isolated from other geological formations, especially freshwater aquifers. This must be ensured both in design and well construction (which includes hydraulic fracturing) and the long term production process during the life of the well."

These absolute requirements for perfect containment suggest a level of monitoring and control in excess of that which would be motivated by maximization of commercial gas production. Furthermore, such requirements would present severe challenges for regulatory regimes.

The potential loss of containment underground of mobilized gas as a fraction of unconventional gas production is unknown and unknowable, perhaps even to the operators. It would be highly site specific and would depend strongly on the diligence of the gas production operators and their willingness to abandon and seal a well in the event of any dispersion into adjacent aquifers being detected. For the purpose of considering the impact on the GHG footprint of unconventional gas production it might be useful to consider sensitivity to a parameter for "In-ground loss of containment of gas", where "loss of containment" refers to the situation where gas could migrate to the surface in a matter of years rather than millennia.

Anecdotal evidence indicates that this parameter is non-zero. In particular incidents of elevated levels of methane in potable groundwater have raised widespread concern in areas where fracking is practiced for shale gas and for shallower coal seam methane. The potential for in-ground shale gas methane migration to the surface is indicated by a company that manufactures continuous ground gas monitors with remote data loggers, which were developed for use at landfills. This company advertises their products in the Shale Daily bulletin with a caption advising operators to manage their methane mitigation risks.

**Analysis - Source A**

The loss of containment of mobilized gas underground, if any, cannot be estimated. Therefore indicative figures are presented here on the basis of emissions per percentage point of loss of containment of the gas. The time taken for any mobilised gas to migrate to the surface will be highly case specific. Permeation rates of mobilized gas through unfractured strata might take millennia to reach the surface. However, mobilized gas might migrate to the surface through faults, fissures and connected aquifers on time scale commensurate with the GWP time horizon. Hence, consideration of loss of containment could be given to circumstances where mobilized gas could potentially migrate to the surface in a matter of years rather than millennia.

Table B1 shows the potential additional impact on the FFC emission factor for unconventional natural gas in terms of the increase in GHG emissions from Source A per percentage point of loss of containment of gas underground for various values of GWP. These scenarios comprise the IPCC’s 100 year and 20-year time horizons and also include a step-off case considering the aerosol effect, as was adopted in Howarth, 2011.
### Table B1

**Source A. Increase in FFC GHG emission factor per percentage point loss of gas containment**

<table>
<thead>
<tr>
<th></th>
<th>Timeframe of GWP definition</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 years</td>
<td>20 years</td>
<td></td>
</tr>
<tr>
<td>IPCC 2007 GWP&lt;sub&gt;methane&lt;/sub&gt;</td>
<td>25</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>• kg CO&lt;sub&gt;2&lt;/sub&gt;-eq/GJ per % loss of containment</td>
<td>4.8</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>IPCC 2007 GWP&lt;sub&gt;methane + indirect aerosol effect&lt;/sub&gt;</td>
<td>33</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>• kg CO&lt;sub&gt;2&lt;/sub&gt;-eq/GJ per % loss of containment</td>
<td>6.4</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX C

US Inventory data

In the US context, emissions of methane by the natural gas industry are explicitly reported in the USEPA national GHG inventory. These emissions are not measured directly, but are calculated from standard emission factors for items of equipment that are in use. The reported methane emissions for sources C, E, G and H are presented in Figure C1. The accompanying CO₂ emissions from own-use of gas as a fuel are not separately identified in the US GHG inventory.

Figure C1 indicates a gradual reduction in estimated methane losses from processing, transmission and storage and distribution over time. However, the largest source of reported methane emission, from field production activities, shows a significant upswing over recent years. This is consistent with the rapid increase in exploitation of shale gas in the US and the greater methane emissions associated with the completion of unconventional gas wells.

The complex methodology used by the USEPA in deriving the data for US GHG inventory, in particular the high emission rate reported for 2006, is a matter of current debate. The USEPA methodology is presented in a Background Technical Support Document (EPA 2010), but some of the assumptions and the credibility of the data sources are challenged in a recent review “Mismeasuring Methane” (IHS – CERA 2011). A reliable agreed basis for assessment of fugitive methane emissions from unconventional natural gas field production has not yet been established.

Notwithstanding this significant uncertainty, this report attempts to assemble indicative data for the components of precombustion emissions in order to provide a benchmark against which variability of performance and refinements of methodology can be assessed.
APPENDIX D

Losses as a Fraction of Gas Flow

B1. Methane produced during fluid flowback after fracking

After a gas well has been drilled and cased there is an additional process in the case of unconventional gas production, which is hydraulic fracturing (fracking) of the hydrocarbon bearing rock. This step is absent from conventional gas well production. The fracking process as practiced in the Marcellus Shale development is described in Maryland 2010 as follows:

"Physical fracturing occurs after the well is cased and the equipment is in place. A fracturing engineer perforates the casing in the farthest 300 to 500 feet of the wellbore first, causing holes to form in the cement and fractures to form in the shale. He then injects 300,000 to 500,000 gallons of slick water (water mixed with chemical proppants and sand or silicate) at high pressure into the wellbore from the surface to extend the fractures caused by perforating. After the water has fractured the shale formation, sand is injected to keep the fracture lines from closing and the natural gas flowing. The fracturing engineer repeats the same process for each subsequent 300 to 500 foot section of the horizontal section of the wellbore. A 4,000 foot well could require 2.4 to 7.8 million gallons of water."

After the well has been hydraulically fractured it is cleaned up and the fracking fluid needs to be removed ready for production. Flowback of the fracking fluid is allowed to flow from the well under the gas pressure or is pumped out. It is reported that about one quarter to one third of the injected fluid is discharged from the well as flowback fluid; i.e. about 1 to 2 million US gallons (3,750 – 7,500 m³) for the above example.

During the fluid flowback stage the gas-liquid ratio discharged from the well increases. The USEPA estimate of methane discharged from a fracked gas well during the flowback stage is 9,175 Mcf (177 tonnes CH₄) per completion. Under 3000 ft of hydrostatic head in the fracture zone, that would correspond to 2,800 cubic metres of methane; i.e. an indicative average downhole gas:liquid ratio of 0.4 to 0.8 for the above example, which does not seem to be unreasonable.

The USEPA figure is the simple average of 4 data points 700, 6,000, 10,000 and 20,000 Mcf per completion derived in a questionable way by USEPA from public presentations. The validity of the derivation of this critical number is challenged by the oil shale industry. However, no more reliable basis for assessment of methane coming out of the well during the flowback stage has been identified in the public domain. The NETL 2011 assessment quotes 11,643 Mcf per completion for a horizontal shale well, based on EPA methodology. Howarth 2011 cites an uncontested methane production of 13,000 Mcf for completion of a Barnett shale gas well.

In view of the above consideration of gas:liquid ratios it appears that the USEPA average figure, despite its crude derivation, is likely to be reasonably indicative of the order of magnitude of methane accompanying the flowback fluid during completion of a shale gas well after fracking.

The other contentious issue with regard to methane produced with fracking fluid flowback is the extent to which that methane can be captured and flared. Current industry best practice is for methane that cannot be delivered into a pipeline for dispatch to a gas processing plant to be flared at well site, whenever practicable. Environmental legislation is moving towards establishing that principle as a general requirement. However, flaring of gas that is highly variable in quality and quantity in a remote location is not straightforward. For example, it would require a gas supply for a pilot burner flame. Spark ignition of methane in air requires
a concentration between 5% and 15%. Safety procedures regarding fugitive methane generally focus on dilution and dispersion of methane to keep concentrations in air below the lower flammability limit of 5%, rather than gathering the gas and maintaining its concentration in air for unproductive burning. In remote locations, in the absence of regulations or local safety imperatives, economic drivers would tend to favour venting methane rather than flaring.

The assessment by NETL (NETL 2011) is based on 15% of methane from flowback fluid being flared. The USEPA (2010) methodology is based on 51% of methane from flowback fluid being flared. The HIS-CERA (2011) report claims that the current industry best practice is to flare all methane arising from fracking flow-back operations.

For the purpose of this general overview, flaring of flowback methane is assumed to be 15% for the reference case, with a step off case based on 80% flaring of the flowback methane.

The methane emissions from well completion occur before any gas production is confirmed. To determine the marginal greenhouse gas emission increment due to fracking the typical lifetime yield of unconventional natural gas from a well needs to be identified. Well lifetimes of 20 to 40 years are quoted, but such longevity of only achieved by periodic reworking the well; i.e. carrying out another complete hydraulic fracturing operation. NETL 2011 indicates that reworking the well results in well completion methane discharges equal to the original discharges. Therefore the lifetime yield of the well is considered over the period before reworking is needed, which might typically be about 6 years.

Occasionally the development of a shale gas well may not result in any commercially viable quantities of gas being produced. At the other end of the spectrum, the most productive shale gas wells are reported as having initial gas yields over 10 million cubic feet per day. However, the production rates from such prolific wells decline rapidly and could be producing at only 20% of the initial flowrate and the end of the first year with a further 50% decline in production over the second year. Such a prolific well might yield 4 billion cubic feet (bcf) of gas before the need for reworking of the well.

Howarth, 2011 quotes data for a Barnett shale well with a lifetime yield of 1.2 bcf of gas. The example cited in the NETL 2011 assessment is a well yielding 3 bcf of gas over 30 years, but with 3.5 workovers, indicating a yield before workover of less than 1 bcf.

USEPA data indicate that in 2007 the average production of gas from unconventional gas wells was less that 0.1 bcf per year well, indicating a life-time yield less than 0.6 bcf. However, on-going developments and knowledge in the shale gas industry will have led to improvements in the success rates of shale gas exploitation in recent years.

For the purpose of this scoping assessment, it is assumed that a typical current shall gas well development might have a lifetime yield of 1 bcf of gas; i.e. 1.1 PJ. Thus, if the methane produced with the flowback fluid is 9,175 Mcf, then that represents 0.92% of the total gas produced.

B2. CO₂ from drilling energy
Shale gas wells are typically deeper and longer than conventional gas wells and therefore involve more drilling. Assuming that a 10,000 ft shale gas well can be drilled in 40 days using a rig consuming 150 US gallons of diesel per day, the associated CO₂ emissions would be 60 tonnes, equivalent to a loss of 0.09% of gas produced. In contrast, drilling a 3000 ft conventional gas well might have one third of that equivalent gas loss.

C. Field production emissions
The NETL study reports 0.096 lb CH4/MCF fugitive emissions from pneumatic devices and other sources at the well-site for both conventional and unconventional gas production. This corresponds to 0.27% fugitive losses, of which virtually none can be captured and flared. Howarth reports wellsite leaks as 0.3% to 1.9%. The low end of this range, i.e. 0.3% is adopted with no flaring.

D. Intermittent emissions during liquid unloading

Additional venting occurs during “liquid unloading.” Conventional wells frequently require multiple liquid-unloading events as they mature to mitigate water intrusion as the reservoir pressure drops. Howarth 2011 asserts “Though not as common, some unconventional wells may also require unloading”. In contrast, the NYDEC 2011, USEPA 2010 and NETL all assert that liquids unloading is not applicable to unconventional gas production.

Howarth, 2011 reports that empirical data from 4 gas basins indicate that 0.02 to 0.26% of total life-time production of unconventional wells is vented as methane during liquid unloading. Since not all wells require unloading, a range at 0 to 0.26% is assumed, with a median value of 0.13%. The NETL 2011 study indicates that 0.25% of life time production from a conventional well would be lost during liquid unloading episodes.

It is proposed in GAO 2010 that this source of vented methane could be captured and flared to reduce its greenhouse impact. For consideration of the impact of additional flaring it is assumed that 80% of this gas could be captured and flared.

E1. Methane loss in gas processing

Figure C1 shows that in recent years the own use of gas for processing as reported\(^2\) had a methane emission factor of 0.69 kg,CO\(_2\)-eq/GJ. These data are based on standard factors for continuous leaks and losses of gas, both by design and due to wear, from gas handling equipment at a centralized gas processing plant. These factors are for fugitive methane emissions and do not include CO\(_2\) emissions from any capture and flaring of fugitive methane gas, which is considered to be impractical. In accordance with UNFCCC reporting conventions these data will have been derived using the GWP of 21 for methane. Accordingly, the fractions of processed gas lost as methane from equipment during gas processing activities are estimated to be 0.22% in the US context.

E2. CO\(_2\) emission in gas processing

There will also be own-use of natural gas as a fuel in gas processing activities. The emission from that source will be as CO\(_2\) and is not included in the data presented in Figure C1. It is assumed that 80% of the gas throughput reduction occurring at gas processing plants is attributable to own-use of gas as a process fuel.

F. Emissions from plant for liquefaction and regasification of gas transported as LNG

The conversion of natural gas into a liquid at -161°C is an energy intensive process. Therefore inclusion of transport of natural gas as LNG in the supply chain would add to the FFC greenhouse footprint of that fraction of the natural gas supply that is shipped as LNG. Emission factors for natural gas liquefaction are reported by Griffin,2007 as 11-31 lbs,CO\(_2\)-eq/GJ. This corresponded to an overall thermal efficiency range of 91% to 73%. Other sources indicate that current state-of-the-art integrated gas liquefaction plants can achieve 91-92% thermal efficiency, i.e. the upper end of the range suggested in Griffin, 2007. Therefore 9% gas flow loss is assumed for the liquefaction step with a further 1% throughput loss in the regasification step. Tanker transport of LNG would also result in GHG emissions, but, since all fuel sources are subject to transport considerations; this element is assumed to

\(^2\) Reported under the UNFCCC with a GWP for methane of 21.
be accounted for in the Source G analysis. Thus an additional gas throughput loss of 10% is assumed for all gas that is transported as LNG.

The IEA WEO 2011 report identifies LNG technology as a critical component of future gas supply systems. LNG capacity currently coming on stream is reported to be able to transport about 0.3 Tcf of natural gas per year, which is about 10% of the global natural gas demand of about 3 Tcf. Therefore in terms of the global natural gas supply network the use of LNG for transport would on average consume about 1% of all gas. It is assumed that all the gas used in LNG processing would be burned to CO₂.

In the USA all unconventional natural gas production is currently used in the domestic market. In general, shale gas would be used for domestic reticulation and not transported as LNG. However, the shale gas bonanza, particularly from the Marcellus shale play, is such that it has been suggested that the US might become a net gas exporter via LNG. If that were to eventuate then any such gas delivered overseas would have an additional greenhouse gas emission penalty equal to 10% of the gas dispatched; i.e. 11% of the gas delivered.

G. Methane losses during transport, storage and distribution of natural gas

The US GHG inventory data presented in Figure 1 shows 1.9 kg.CO₂-eq/GJ of emission as methane from transmission and storage and 1.3 kg.CO₂-eq/GJ as leaks from gas distribution networks. Together these amount (at GWP =21) to a loss as methane of 1.05% of natural gas supplies to US customers.

Howarth, 2011 cites data from world-wide sources with a range of estimated losses from 0.2% to 10%. They conclude that a conservative range for all transport, storage and distribution losses is 1.4% to 3.6%, with a median value of 2.5%, which is consistent with an estimate in Hayhoe, 2002. If 1.05% of gas loss is attributed to fugitive methane losses, then 1.45% of the gas flow is assumed to be consumed used in booster compressors etc.

Flaring

Where significant methane leaks or discharges occur in a single location it may be practicable to capture those emissions and route them to a flare, or possibly to a useful combustion device. Where unburned release of that methane would constitute a safety hazard or an adverse local environmental effect then capture and flaring of the escaping methane would be required and can be considered as normal practice. Capture and flaring of methane losses greatly reduces the GHG emission consequence of that source of emission.

There are many situations in which the venting of methane to atmosphere does not constitute a safety hazard or cause an adverse local environmental effect. Capture and venting of those discharges to air would then normally only be installed at additional cost if there were a mandatory requirement to do so or a commercial incentive, such as carbon charge avoidance. It is assumed that 80% of the intermittent emissions from flow-back and liquid unloading activities could potentially be captured and flared with an appropriate legislative requirement or economic incentive. However, capture and flaring of these sources is not included in the reference case.

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<thead>
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<th>Table D1</th>
<th>Reference Case - FFC Emission Factor for Natural Gas and Shale Gas</th>
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<tbody>
<tr>
<td></td>
<td>Conventional Gas</td>
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<td>% loss</td>
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Summary of Analysis
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<th>Source of emissions</th>
<th>GWP</th>
<th>25</th>
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<tr>
<td>B. Methane produced during flow-back CO₂ from drilling rig (equiv)</td>
<td>-</td>
<td>-</td>
<td>0.92%</td>
</tr>
<tr>
<td></td>
<td>0.03%</td>
<td>0.02</td>
<td>0.09%</td>
</tr>
<tr>
<td>C. Routine venting and equipment leaks at well site (field production)</td>
<td>0.3%</td>
<td>1.35</td>
<td>0.3%</td>
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<tr>
<td>D. Intermittent emissions during liquid unloading</td>
<td>0.25%</td>
<td>1.12</td>
<td>0.13%</td>
</tr>
<tr>
<td>E. Methane emissions during gas processing CO₂ emissions from gas processing</td>
<td>0.22%</td>
<td>0.98</td>
<td>0.22%</td>
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<tr>
<td></td>
<td>0.88%</td>
<td>0.48</td>
<td>0.88%</td>
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<tr>
<td>F. Emissions from plant for liquefaction and regasification of gas transported as LNG</td>
<td>1.0%</td>
<td>0.54</td>
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<td>G. Methane emissions from pipelining CO₂ emissions from transmission</td>
<td>0.63%</td>
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<td></td>
<td>1.44%</td>
<td>0.77</td>
<td>1.44%</td>
</tr>
<tr>
<td>H. Emissions during distribution of natural gas to customers</td>
<td>0.43%</td>
<td>1.84</td>
<td>0.43%</td>
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<td>Combustion emissions</td>
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<td><strong>Total</strong></td>
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</tbody>
</table>

**Caution** For simplicity, this analysis is based on the mid points of wide ranging source data and is therefore subject to substantial uncertainty. Actual pre-combustion emission factors in real cases could be substantially smaller or larger.
Table D2 – Other cases - Case for FFC Emission Factor for Natural Gas and Shale Gas

<table>
<thead>
<tr>
<th>Kg CO₂-equivalent per GJ hhv gas</th>
<th>Case 2 – Extra flaring</th>
<th>Case 3 – 20 year horizon</th>
<th>Case 4 – high GWP case</th>
<th>Case 5 - LNG export</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural gas</td>
<td>Shale gas</td>
<td>Natural gas</td>
<td>Shale gas</td>
</tr>
<tr>
<td>GWP</td>
<td>25</td>
<td>25</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td>Extra flaring</td>
<td>yes</td>
<td>yes</td>
<td>No</td>
<td>no</td>
</tr>
<tr>
<td>Source of emissions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B. CH₄ during flow-back</td>
<td>0.02</td>
<td>1.17</td>
<td>0.02</td>
<td>10.17</td>
</tr>
<tr>
<td>CO₂ from drilling rig (eq)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. Routine venting and</td>
<td>1.35</td>
<td>1.33</td>
<td>3.88</td>
<td>3.84</td>
</tr>
<tr>
<td>equipment leaks at well site</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D. Intermittent emissions during</td>
<td>0.34</td>
<td>0.17</td>
<td>3.23</td>
<td>1.66</td>
</tr>
<tr>
<td>liquid unloading</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E. CH₄ from gas processing</td>
<td>1.47</td>
<td>1.45</td>
<td>3.32</td>
<td>3.28</td>
</tr>
<tr>
<td>CO₂ from gas processing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F. Emissions from LNG plant for</td>
<td>0.54</td>
<td>0.00</td>
<td>0.54</td>
<td>0.00</td>
</tr>
<tr>
<td>gas transport as LNG</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G. CH₄ from pipelining</td>
<td>3.47</td>
<td>3.47</td>
<td>8.68</td>
<td>8.68</td>
</tr>
<tr>
<td>CO₂ from transmission</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H. Emissions during distribution</td>
<td>1.83</td>
<td>1.83</td>
<td>5.30</td>
<td>5.30</td>
</tr>
<tr>
<td>to customers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustion emissions</td>
<td>53.00</td>
<td>53.00</td>
<td>53.00</td>
<td>53.00</td>
</tr>
<tr>
<td>Total</td>
<td>62.01</td>
<td>62.43</td>
<td>77.97</td>
<td>85.94</td>
</tr>
</tbody>
</table>
APPENDIX E

Global Warming Potential

The UNFCCC GHG inventory conventions for the Kyoto Protocol first commitment period are based on consideration in the IPCC Second Assessment Report (IPCC 1995) of the relative radiative forcing effects of methane and CO₂ over a 100 year timeframe. This accounting convention corresponds to the use of a GWP for methane of 21.

In the IPCC Fourth Assessment Report (IPCC 2007) the likely effects of methane in the atmosphere were reassessed and it was determined that methane has a 25 times greater direct effect on the climate than an equal mass of CO₂ when considered over a 100-year timeframe and 72 times greater effect when considered over a 20-year timeframe. Nevertheless the GWP of 21 for methane is currently retained for established carbon accounting purposes.

Methane released into atmosphere slowly oxidizes over time to CO₂ and water vapour. CO₂ released to the atmosphere is eventually dissolved in the oceans or is absorbed by mineral weathering or net afforestation. The rate of depletion of atmospheric methane is more rapid than the depletion of CO₂. Cumulative global warming potentials of 25 over 100 years and 72 over 20 years correspond to an instantaneous GWP of 109 with depletion of methane at 5% per annum and depletion of CO₂ at 0.3% per annum.

Howarth, 2011 refers to Shindell, 2009, which determines that when the indirect effects of methane on atmospheric aerosols are taken into account, the GWP of methane should be increased to 33 over a 100 year timeframe and to 105 over a 20-year timeframe. IPCC 2007 also acknowledged the aerosol effect, but did not quantify it.

For the purpose of this comparative assessment of the greenhouse footprint of shale gas, the current IPCC best estimate of 25 as the GWP for methane over 100 years is adopted for the reference case and 72 and 105 step off cases.

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References

EIA 2010  http://www.eia.gov/naturalgas/reports.cfm?t=72
Griffin 2007  Comparative Life Cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation. Paulina Jaramillo, W. Michael Griffin, H. Scott Matthews
SHIP TRANSPORT OF CO₂: REVIEW OF WORK UNDERWAY

Introduction
CO₂ has been transported as a refrigerated, pressurised liquid in small ships (around 1000 tonnes) for many years to supply the food and chemicals industries. In 2004 IEAGHG published one of the first studies to assess larger scale ship transport of CO₂ for geological storage. This report has been widely referenced, including in the IPCC Special report on CCS. Since then the level of interest in CO₂ shipping has grown, for example a conference on CO₂ shipping in 2010 attracted over 100 participants mainly from the shipping industry. Other organisation have recently carried out studies on including ships, barges and pipelines in CO₂ transport hubs for example at Rotterdam and there have been proposals to use ships to transport CO₂ from CCS demonstration projects, including a proposed EU-funded project in Finland which was cancelled in 2010.

At the 38th ExCo meeting Members approved a proposal to undertake a further study on ship transport of CO₂, to update the performance and cost information in IEAGHG’s 2004 report and to assess a greater number of operating scenarios and cost sensitivities. The start of the study has been delayed due to resource constraints and other priorities but IEAGHG now has the capability to start the study. However, in the time since the proposal was approved a substantial amount of new information on ship transport of CO₂ has been published, including recent reports by the ZEP and GCCSI. These two reports cover most of the scope of IEAGHG’s proposed study. There is also other work underway including the European 7th Framework R&D project called COCATE which runs from 2010 to 2012 and which includes assessment of collection of CO₂ in the Le Havre region in France and ship transport to Rotterdam. The funding for the overall COCATE project is €4.5M, around 100 times greater than the resources available for an average IEAGHG study. Some other studies looking at ship transport scenarios for particular locations have also been published recently in journals.

To avoid unnecessary duplication and to make best use of IEAGHG’s resources it is proposed that IEAGHG should either not proceed with its proposed study on CO₂ shipping or it should refocus the study onto assessment of novel ship transportation technologies, as discussed below.

IEAGHG report PH4/30
IEAGHG’s report published in 2004 includes outline design, performance, emission and cost data for ships capable of transporting liquid CO₂ at 7bar and -50℃. Three ship sizes: 10kt, 30kt and 50kt were assessed. Operating scenarios for various distances were assessed, ranging from the short distances that would be required for transport between local capture and storage sites or transport hubs (e.g. 200km) to intercontinental distances, e.g. the 6000km that would be required to transport CO₂ from Japan, where storage capacity is limited, to Australia where capacity may be more abundant. The sensitivity to ship speed was also assessed, as this has a

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significant impact on costs and CO₂ emissions. Costs of ship transport were compared to costs of pipeline transport, obtained from an earlier IEAGHG study. The costs for transport of 6.2 M tonnes/year of CO₂ are shown in Figure 1. These costs are based on the assumption that CO₂ is supplied to the liquefaction plant by a pipeline operating at 100bar.

![Figure 1  Comparison of ship and pipeline transport costs, IEAGHG study](image)

Shipping requires substantial fixed costs for CO₂ liquefaction, CO₂ buffer storage at the port, ship loading and unloading and other port costs but the costs of ship transport increase only gradually as the transport distance is increased. For example, the cost of transporting CO₂ for 2000km is only 50% greater than the cost for 200km. The breakeven between the costs of ship and pipeline transport is around 700km for offshore pipelines and 1500km for onshore pipelines, although it should be noted that in practice the distances for transporting CO₂ between two points would not necessarily be the same for ships and pipelines.

**ZEP report**

A techno-economic summary report on CO₂ transport was published by the EU’s Zero Emissions Platform (ZEP) in mid-2011. The report considers pipelines and ships, with particular emphasis on networks transporting 10-20Mt/y of CO₂. The networks consist of:

- Onshore feeder pipelines or a combination of an offshore feeder pipeline and a ship feeder route
- A trunk route consisting of an onshore or offshore pipeline or ship transport
- Onshore or offshore distribution pipelines connected to geological storage sites.

In a scenario that involved ship transport of CO₂ from an on-shore terminal to an offshore distribution point, the breakeven transport distance between ship and offshore pipeline transport was about 1500km (assuming 100% utilisation). This is greater than in IEAGHG’s 2004 study but this is due to the greater quantity of CO₂ (20M t/y of CO₂ compared to 6.2M t/y in IEAGHG’s study) which gives greater economies of scale for the pipeline option than the ship option. The total cost of ship transport for 1500km was about €15/tCO₂, compared to $14/t in IEAGHG’s study. The higher cost in the ZEP study reflects general cost inflation, offset somewhat by greater economies of scale. Another scenario in the ZEP study included ship transport of 2.5M t/y of CO₂, which cost €13.5/t for 180km and €19.8/t for 1500km. This confirms that the cost of ship transport is relatively insensitive to distance.

Sensitivities of costs of offshore pipeline and ship transport to distance, utilisation, operating cost (OPEX) and capital cost (CAPEX) are shown in Figures 2 and 3 (note the different scales in these charts). The base case in these Figures is 10M t/y of CO₂ and 500km distance.
These Figures show that pipelines are proportionately more sensitive to utilisation than ships. One of the advantages of ship transport is its flexibility to accommodate changes in throughput because ships can be easily redirected to and from other projects around the world, provided ship transport of CO₂ becomes reasonably widespread. The ZEP study assessed the impacts of under-utilisation of pipelines during the ramp-up of CO₂ availability. As an illustration, costs for 100% utilised ships and 50% utilised pipelines are compared in Figure 4, which is based on a maximum throughput of 10M t/y. The profile of ramp-up of CO₂ availability would obviously be highly site specific but in this case the breakeven distance between pipeline and ship transport is around 500km. In practice the pipeline utilisation may be less than 50% in the early years of operation but approach 100% utilisation in later years. Even when a transport network is fully developed the annual average utilisation may be less than 100% due to the variability of power plant load factors throughout the year.
GCCSI report
A report on ship transport of CO₂ was produced for the GCCSI by Tebodin Netherlands consultants and engineers in 2013, building on work for the Rotterdam Climate Initiative. The report assesses the CO₂ Liquid Logistics Shipping Concept, developed by Vopak and Anthony Veder, which are companies involved in tank storage and ship transport of liquefied gas, including CO₂. Ship designs were prepared by Ulstein, a Norwegian ship design company.

The report provides a detailed technical assessment of the whole chain of CO₂ ship transport, including:

- Onshore CO₂ pipeline
- CO₂ compression, dehydration and liquefaction
- Barge transport of liquid CO₂
- Buffer storage of liquid CO₂
- CO₂ boil-off gas handling
- CO₂ terminal layout
- CO₂ ships
- Ship off-loading and injection, including CO₂ heating

Two different designs of 30,000m³ liquid CO₂ ships (conventional and X-bow designs) were presented and compared. In general the conventional design was preferred.

The number of permutations of CO₂ availabilities, storage sites and transport arrangements is large and it was only possible to consider a few scenarios. The report presents costs in relative terms rather than absolute (€/t CO₂) terms, so the results cannot be compared directly to the results of the IEAGHG and ZEP studies.

The breakeven distances between ships and pipelines are shown in Figure 5. This shows that the cost of pipelines increases with distance much more than the cost of ships, which is consistent with the conclusions of the IEAGHG and ZEP studies. The breakeven distance between ship and offshore pipeline transport is about 150km, which is less than in the IEAGHG and ZEP studies but the breakeven distance depends strongly on technical and economic assumptions, including the interface between pipelines and ships in networks.
The study also assesses barges for river transport of liquid CO₂. Liquefied gases have been transported in barges for many decades. An advantage of barge transport is that it could minimise the need for overland pipelines and thereby reduce permitting difficulties for CCS in some densely populated countries. The breakeven costs of barges and onshore pipelines are shown in Figure 6. Barges are shown to be cheaper than pipelines for distances greater than about 200km.

Examples of other published work on ship transport of CO₂
A paper by Decarre⁴ (IFP) et. al. assesses costs for ship transport scenarios. The economic breakeven between ship transport and pipelines for 5.6Mt/y of CO₂ is about 1100km for onshore pipelines and 350km for offshore pipeline.

A paper by Yoo et. al. (Daewoo Shipbuilding and Marine Engineering) proposes a novel design for a 100k m³ CO₂ transport ship⁵. Costs for 600km transport are presented and the 100k m³

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ship is shown to have lower costs than a 30k m³ ship (a typical size in most other studies) for quantities greater than around 7Mt/y.

A paper by Haugen et. al. discusses CO₂ transport options for a Vattenfall power plant in Denmark. Costs for 170km transport of liquid CO₂ by ship or barge are around €17/t.

**High pressure ship transport of CO₂**
The paper by Haugen also briefly discusses the possibility of transporting CO₂ by ship at high pressure (100bar) in hundreds of vertical pressure ‘bottles’ fabricated from standard 42” pipe. Pressurised CO₂ could be fed to a ship directly from an onshore pipeline, avoiding the need for a liquefaction plant. Transport of pressurised CO₂ currently lacks regulatory qualification but the paper says that several companies are nevertheless pursuing this concept. Although not mentioned in the paper it may be possible to transport CO₂ in ships using coils of high pressure pipe (Coselle design) or pressure vessels made of composites, both of which are being actively considered for transport of natural gas. The advantages of pressurised gas transport compared to liquid transport are expected to be mostly for relatively short distances. Pressurised gas transport would avoid the need to build a CO₂ liquefaction plant, which would be an advantage particularly for relatively short duration projects or projects with variable CO₂ flowrates. This could include using ships while availability of CO₂ increases sufficiently to justify building a large pipeline and also as a back-up in case of problems with pipelines and storage reservoirs, particularly during the early stages of operation. High pressure ship transport of CO₂ could be the subject of a revised scope study by IEAGHG.

**Conclusions**
Substantial work on assessment of ship transport of liquid CO₂ has recently been published by ZEP, GCCSI and other organisations and further work is underway.

The technology for ship transport of liquid CO₂ is proven and the costs are known reasonably accurately. The shipping industry is willing to provide commercial transport of liquid CO₂ if or when the market requirement arises.

The economic breakeven between ships and pipelines depends strongly on the quantity of CO₂, the utilisation and other parameters. Pipelines are expected to be the lowest cost option for transport of large quantities of CO₂ over relatively short distances, which will account for most CCS. Ships may be competitive for longer distances and/or smaller quantities, for projects with variable CO₂ flow rates or short durations. Barges may be preferred to onshore pipelines for cost or permitting reasons in some circumstances. The operating flexibility of ships and barges can help to reduce the commercial risks of CCS projects.

To avoid excessive duplication of work it is proposed that the study on ship transport of CO₂ that was approved at the 38th meeting should not proceed or it should proceed with a revised scope of work. The alternative scope could concentrate on assessment of technology development, regulatory requirements and potential cost advantages of high pressure transport of CO₂ in ships.

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**IEA GREENHOUSE GAS R&D PROGRAMME**

**40th EXECUTIVE COMMITTEE MEETING**

**REVIEW OF WORK UNDERWAY ON ALTERNATIVE CAPTURE SYSTEMS**

**Introduction**

Conventional carbon capture and storage systems provide a benchmark against which to compare alternative concepts for reducing the climate consequences of fossil fuel use. IEAGHG in-house reviews of some alternative capture concepts has been aimed at screening ideas that are put forward with a view to identifying those concepts that may have advantages compared with CCS and therefore warrant further detailed investigation.

This area of investigation was prompted by publication this year of a report “Direct Air Capture of CO₂ with Chemicals - A Technology Assessment for the American Physical Society Panel on Public Affairs”

The final report of the Australian Novel CO₂ Capture Task Force has been published recently and proposes further practical research on algal bio-sequestration of industrial CO₂, mineral carbonation, soil carbon effect in forestry, Biochar and life-cycle analysis.

Mineralisation is being considered under a separate IEAGHG project.

Topics that have been considered in-house by IEAGHG include:-

**Seawater/limestone scrubbing**

A concept is proposed in which CO₂ would be scrubbed from a flue gas by contacting it with seawater in the presence of limestone. The captured CO₂ would be in the form of calcium bicarbonate dissolved in the discharged seawater. This concept would use the ocean as the storage location for the captured CO₂. An initial assessment suggests that over time the discharged water would equilibrate with the atmosphere and lose the captured CO₂.

**Liming the ocean**

If a molecule of lime (calcium oxide) is dissolved in seawater then it will absorb two molecules of CO₂ from the atmosphere to form calcium bicarbonate in solution. The production of that lime in a lime kiln would release one molecule of CO₂. In a practical system the capture/release ratio might be about 1.5:1. A co-benefit would be reduction of ocean acidification. However, the energy requirement per tonne of CO₂ captured could be about 5 times greater than the energy penalty of CCS.

**Burial of wood**

If logs of wood are stacked in an engineered underground depository that is flooded with water, then the anaerobic decomposition of the wood to methane might be reduced to a much lower level than is reported to occur in a conventional landfill. Practical research would be required to validate this concept.

**Biochar**

Gasification of biomass can result in the production of a stable biochar, which could be used as a soil enhancer, thus providing a route for carbon from the atmosphere into the earth. There are on-going research programmes to study the effects of various types of biochar on soil. A key question is the long term residence time of carbon in the soil.

**Biomass Energy with CCS (BECCS)**

Integration of a biomass combustion process with conventional CCS could result in net negative CO₂ emissions. Studies are on-going to establish whether there are
synergies from the integration that point this being a better application of CCS capacity than its conventional application to fossil fuel combustion with a separate conventional bioenergy plant.

**Direct CO₂ capture from air**

A theoretical paper considering a conceptual industrial CO₂ scrubbing process acting on air containing 400 ppm CO₂, determines that the cost of CO₂ capture and compression might be in the order of $500/tonne of CO₂ captured. This is in reasonable agreement with an estimate of $600/tonne developed in the APS report. This sets a theoretical upper limit to the cost of CCS.

**Conclusions**

No alternative technologies have been identified which warrant further investigation by IEAGHG at this time. However, a watching brief on alternative technologies should be maintained.
Introduction
IEAGHG currently have a number of public summary brochures available, aimed at explaining aspects of the CO₂ Capture and Storage process to a non-technical audience. These brochures are now at least 4 years old, and as such may be a little out-dated, and reflect the old logo and corporate style. It was therefore determined that it would be worthwhile to update these, checking any references at the same time and updating facts and figures with more recent results.

At the same time, we were approached by two University undergraduate students, looking for some work placements over the summer holiday period, and it was proposed that these students were set a task that would assist in the update of these brochures. Each student was asked to address the same task, without knowledge of the others work, to determine whether the difference in backgrounds and university subjects had any influence on the task results.

The Task
The task was to determine the initial questions that come up when introduced to the area of CCS with little or no prior knowledge. The students were asked to come up with a list of questions they would require answered if a CCS project was proposed in the vicinity of their home. The basic premise of this was to identify the questions asked, and follow this up with an analysis of our existing public summary brochures to determine if we are currently addressing the topics that are likely to be of relevance.

Secondly, the students were asked to research the information readily available through the internet, to determine what information is likely to be accessed by members of the public, and we intend to use the analysis of the two reports to reassess and update our public summary brochures.

Students Reports
The following section is comprised of the 2 reports produced by the placement students, listing the questions they came up with, along with the answers and information sources they used. The reports shown here are what was produced by the students; we will amalgamate and clean up the content and issue this as a technical review as a precursor to the revised public summary brochures, updating the current information, and extracting the relevant pieces of information from this technical review.

Not all of the information represented here is confirmed and reliable, but it does represent what is available when searching for information. It is likely that this information contains inaccuracies and misquotes, but this will form the basis of the questions we need to ensure we are addressing. Any instances of erroneous information, facts and figures are prime examples of why we need to revisit the public summary information; to ensure that the correct information is easily accessible by those seeking information through the internet.

Report 1
How expensive is CCS? Who Pays? And will it cause an increase in power prices?
Estimates say that a CCS plant large enough to capture 90% of the carbon dioxide emissions from an average sized power plant would cost around £1 billion. CCS is to be partly funded
by the Government and partly funded by the private sector however the need for private sector funding is urgent. In Scotland the government has granted £1 billion of funding for a CCS plant, £500 million of which will go on building the power plant with CCS, and £500 million will go on the general running costs of the power plant itself. It is believed that CCS will have very little effect on power prices, adding only 5p a week to each energy consumers bills over a period of ten years (that’s £2.60 a year, and in a household of 4 people that’s £10.40 a year)

How Would Climate Change affect us directly?
If global temperatures rise between 1.1 and 6.4 degrees, it could have a detrimental affect on the earth, causing changes like:
- Sea levels could rise 18-59cm by 2100, causing flooding in coastal areas like some of East Anglia
- The ocean will get more acidic, causing harm to coral reefs and fisheries
- Extreme weather events like flooding, droughts, tropical storms, heat waves and wildfires will become more common place, causing an increase in UK home insurance by up to 4%
- Increasing temperatures and changing rainfall patterns could cause a drop in crop yields, causing an increase in fruit and vegetable prices
- The risk of extinction of 20-30% species, causing a knock on effect to other species
- Increased coastal erosion

Is Carbon Dioxide Safe when it is put into the Ground?
There is already a lot of experience when it comes to injecting carbon dioxide deep underground, as it has been done for over 30 years in enhanced oil recovery projects and storage projects which are ongoing. An example of an ongoing carbon dioxide storage project is Sleipner in the North Sea, 160 miles west of Stavanger in Norway, where they have been injecting carbon dioxide into a saline aquifer above the Sleipner gas field safely since 1996.

Carbon dioxide is initially trapped underground by structural or hydrodynamic trapping. Structural trapping involves the use of geological formations such as an impermeable barrier of cap rock, which acts as a seal keeping the carbon dioxide trapped in the rock.

Hydrodynamic trapping occurs in saline formations where fluids migrate slowly over long distances, and carbon dioxide can undergo a series of geochemical interactions with the rock and water in the formation.

Over a long period of time the carbon dioxide will very slowly begin to react with the mineral matter in the rock, to form very stable, solid carbonate minerals, like calcite. Carbon dioxide mineralisation is an ongoing natural process, which provides a safe long term repository for carbon dioxide.

Many formations like oil and gas reservoirs have naturally stored carbon dioxide and other gases for millions of years.

What is Carbon Dioxide? What does it do? And why does it need to be Captured?
Carbon dioxide is a colourless, odourless gas that is one part carbon and two parts oxygen, and is found virtually everywhere. We exhale carbon dioxide and plants absorb carbon dioxide, and through photosynthesis convert it to oxygen, which they release back into the atmosphere. Most carbon dioxide was removed from the atmosphere as early organism's
evolved photosynthesis, locking away carbon dioxide as carbonate minerals in oil shale, coal and petroleum in the earth’s crust, leaving 0.03% carbon dioxide in earth’s atmosphere.

Natural sources of carbon dioxide occur in the carbon cycle, where billions of tons of atmospheric carbon dioxide are removed from the atmosphere by natural ‘sinks’ like oceans and growing plants, and are emitted back into the atmosphere through natural ‘sources’ like plant decay and volcanic eruptions:

When in balance the total carbon dioxide emissions and removals from the entire carbon cycle are equal, maintaining global temperatures. However, since the Industrial Revolution in the 1700’s, human activities such as the burning of oil, coal and gas and deforestation have increased the amount of carbon dioxide in the atmosphere by up to 40%:

![Graph showing parts per million of carbon dioxide over time](http://www.pbs.org/wgbh/warming/art/graph4.gif)

The atmosphere contains many greenhouse gases which trap heat, and to ensure the earth’s temperature remains constant the balance of these gases in the atmosphere must not be upset. Carbon dioxide is one of the most important greenhouse gases, and its increase in concentration in the atmosphere, due to an imbalance in the carbon cycle is causing ‘enhanced greenhouse effect’. Greenhouse effect happens because radiation from the sun enters the earth’s atmosphere, and greenhouse gases in the atmosphere like carbon dioxide prevent some of the radiation from leaving the atmosphere. The trapped radiation then heats up the earth, however the more greenhouse gases that are present means more heat radiation will be trapped causing an ‘enhanced greenhouse effect’.

Therefore it is vital we prevent large amounts of carbon dioxide emissions from entering the atmosphere and trapping more of the sun’s radiation.

**Where does the Energy for CCS come from?**
The energy for CCS comes from the power plant itself. Initially the CCS technology will use between 10-40% of the energy produced by the power plant, however over time the amount of energy needed for CCS from the power plant will decrease as it becomes more energy efficient

**How will the Sites be monitored for Carbon Dioxide concentrations? And how long will they need to be monitored for?**
Sophisticated monitoring techniques have already been developed for underground natural gas storage, and can easily be transferable to CCS. The extensive monitoring systems will be put in place before, during and after large scale carbon dioxide injection:

- **Pre-operational Monitoring** - Carbon dioxide levels are monitored to establish the pre-existing carbon dioxide levels
- **Operational Monitoring** - Injection procedures are monitored to ensure everything is done safely
- **Closure Monitoring** - To make sure the site is performing is expected
- **Post Closure Monitoring** - Continued monitoring to make sure the site is performing as expected, this type of monitoring will continue for several decades

There are 3 specific areas where monitoring will be carried out:

- **Sub-surface Monitoring** - Monitors the movement of carbon dioxide in the storage site and the stability of the cap rock
- **Near-surface Monitoring** - Monitors soil, well water and ground water to ensure carbon dioxide is not leaking
- **Atmosphere Monitoring** - Monitors the carbon dioxide in the air

Long term safe storage requires on-going measurement and monitoring of sites.

One of the most important safety considerations for carbon dioxide leakage is that from wellbores. However the risk of leakage through man made wells is expected to be minimal, as the enclosure of these wells is already dictated by rigorous regulations in place governing the oil and gas industry.

**How is Carbon Dioxide transported between Capture and Storage?**

Except when the source is located directly over the storage site, the carbon dioxide needs to be transported to the storage site. Carbon dioxide from industrial sites is transported primarily by one of two methods, depending on the distance the carbon dioxide has to travel. If under 1000 km carbon dioxide is transported as concentrated streams through pipelines at high pressure (like those used in the USA since the early 1970’s for enhanced oil recovery), if over 1000km carbon dioxide is transported as a liquid in ships. Carbon dioxide can also be transported by rail cars or road tankers in insulated tanks at low temperatures and pressures, however this is less economical than using pipelines or ships. Transporting carbon dioxide is currently the least complicated part of CCS in regards to technology and evaluating costs.

**How much Carbon Dioxide can be stored?**

CCS can reduce a power plants overall carbon dioxide emissions into the atmosphere by approximately 80-90%. The US Department of Environment predicts potential storage in the US to be at 3,600 – 12,900 billion metric tonnes (annual emissions of carbon dioxide in the US are currently about 5,814 million metric tonnes per year), allowing at least 600 years worth of carbon dioxide storage.

**What threats can CO₂ pose to the environment?**
Carbon dioxide is found in the Earth’s atmosphere at a concentration of 390 parts per million as of 2010\(^1\). It is a greenhouse gas, which occurs naturally - yet is created at an accelerated rate by numerous human activities such as transport and heavy industry. There is an observed correlation between such greenhouse gases and global temperatures. Therefore the main threat that CO\(_2\) poses to the environment is that increasing levels (caused by human consumption) will speed up the global warming process, which can cause side effects such as drought, desertification, rising sea levels and extreme weather events\(^2\).

**What is the scale of the problem?**
Climate change is a global problem\(^3\), and effects are likely to be noticed across the world. However, particular areas are more vulnerable than others\(^4\):
- **The Arctic** - warming will cause accelerated melting of ice caps, increasing sea levels and threatening habitats.
- **Small Islands** - such as Micronesia and The Maldives are at risk of disappearing completely due to rising sea levels.
- **Equatorial regions** - heightened threat of drought and heatwave, leading to devastating human losses.
- **Coastal populations** - 634 million people live in areas greatly at risk of coastal flooding. Frequency of these events is likely to increase.

**How urgent is it to address the problem?**
The problem needs to be treated with a great sense of urgency. It is cheaper in the long run to invest in technologies such as CCS, and alternative renewable energies now, rather than have to account for the problems caused later\(^5\). It is important to act now before the problems escalate even further.

**What will happen if nothing is done?**
There is a 75% chance that global temperatures will rise by up to 3 degrees Celsius in the next 50 years, and a 50% chance that they will rise by 5 degrees Celsius\(^6\). The Stern Review outlines a number of eventualities that could occur if nothing is done:
- Melting glaciers will increase flood risk in localised areas
- Crop yields will decline due to droughts and heat waves
- Rising sea levels could leave 200 million people permanently displaced
- Up to 40% of species could face extinction
- More extreme weather patterns, which could ultimately lower global GDP by 1%
- A 3°C rise in global temperature could decrease global economic output by up to 3%, with the poorest countries losing up to 10%
- Insurance premiums rise due to increased frequency of extreme weather events

**How is CO\(_2\) captured?**
There are three ways that carbon can be captured:
- **Post-Combustion**\(^6\): Carbon dioxide is removed from the flue gas at the end of hydrocarbon combustion. Most commonly, the gas is absorbed by an amine solvent, or by quicklime- then the CO\(_2\) can be driven off and separated for transport and storage.

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\(^1\) US Dept. Commerce (http://www.esrl.noaa.gov/gmd/ccgg/trends/)
\(^3\) Greenpeace UK (http://www.greenpeace.org.uk/climate/problems)
\(^5\) Nicholas Stern (http://news.bbc.co.uk/1/hi/business/6098362.stm)
\(^6\) Scottish Centre for Carbon Storage (http://www.geos.ed.ac.uk/sccs/capture/postcombustion.html)
- **Pre-Combustion**: Carbon dioxide is removed before combustion, to produce hydrogen. Hydrogen combustion releases no CO$_2$, with water being the main by-product. The hydrocarbon fuel is converted to hydrogen and carbon monoxide to form a synthesis gas. The carbon monoxide is reacted with water to produce carbon dioxide. This is separated and compressed into a liquid ready for transport.

- **Oxy-Fuel Combustion**: This is where hydrocarbon fuels are burned in pure oxygen, rather than natural air, resulting in a more complete combustion. The exhaust steam is 90% CO$_2$, with the rest being oxygen- which can easily be separated by condensation processes.

**How is the captured CO$_2$ transported?**
Unless the storage site is directly below the source, transport is required. The captured carbon dioxide is generally transported through pipelines, as these are usually cheaper than alternative methods. Millions of tonnes are already being transported by approximately 5,800 km of pipelines across the USA. It is transported in a liquid state, after it has been captured. Ships can also be used to access areas such as the North Sea oil fields. Trains and tankers can also be used, but these are generally less economically viable options, depending on the distance that needs to be travelled.

**How is the captured CO$_2$ stored?**
Carbon dioxide, normally in its supercritical form, is directly injected into geological formations such as saline aquifers, exhausted oil/gas fields and unmineable coal seams. Approximately 40 million tonnes of CO$_2$ in the USA are injected into old oil fields each year. Using oil fields is an attractive option because the geology is generally well understood, and remaining oil may be displaced and sold to offset the cost of injection. However, they have a limited capacity compared to aquifers. Saline aquifers contain highly mineralised salt water that has no use to humans. In the past they have been used to store some chemical wastes. They are advantageous due to their large capacity and common occurrence, reducing transport costs.

**What makes a site suitable for carbon storage?**
There are a number of factors that determine the suitability of a site to store carbon dioxide. Firstly, it needs to have a large capacity, in order to hold the maximum amount of carbon dioxide possible. Secondly, it should be accessible and close to the source if possible, in order to minimise costs incurred through transportation. Thirdly, if possible it should be located in an area of low tectonic activity, as there is a small possibility of leaks, should an earthquake occur.

**How long has this technology been available?**
The process of injecting CO$_2$ into geological features as a long term means of storage is a relatively new concept, despite the technology behind it being available for many years, and carbon dioxide being injected for other purposes. The first commercial example of this was at Sleipner, 1996, where carbon dioxide is stripped from natural gas and stored in a deep...
saline aquifer. Since then a number of other major projects have been initiated, such as the Weyburn project in Canada, which stores the equivalent of 8 million cars worth of carbon dioxide each year, and is currently the largest CCS scheme active. The Carbon Capture and Sequestration Technologies Program at MIT first conducted research into capture and storage in 1989, and is globally recognised as a leader in this field.

How effective is CSS?
Power plants that use CCS technology can cut their emissions by 80-90%. However, excess energy needs to be created by the plants in order to operate the carbon capture technology. Usually this involves increased burning of hydrocarbon fuels. The energy requirement of the plant would be increased by 10-40%, meaning that to store more carbon; more must be consumed in the first place.

How much does the technology cost to set up and run? Who pays?
Estimates show that on a global scale the set up costs will be approximately 2% of global GDP. In the UK, if the costs were passed on to the consumer, it would cost around £200 per person per year (about 2p on each electricity unit). The government is offering subsidies to schemes such as the CCS add on to the Kingsnorth power station. They have made £1 billion available to this project. There are also estimates to suggest that it would cost $80-100 per tonne to capture, transport and store carbon dioxide correctly.

Are there any negative side effects of CCS?
CCS is a costly programme to initiate. If companies are to maintain their profit margins the costs must be passed on to the consumer, either through increased energy bills, or government taxation to raise revenue for subsidies. Only large scale CCS projects are viable because of these costs. However, there are no other real negative drawbacks to CCS, as storage is reliable, safe and relatively straightforward. It is thought that in the USA alone, there is enough space to store captured carbon for the next 600 years.

Are there any alternative techniques to tackle the problem?
The main alternative to tackling the CO₂ problem is carbon recycling. This is the process whereby created CO₂ is mixed with water and electricity, under a platinum catalyst to produce formic acid and other by-products. This formic acid can be used as an energy source for low power applications such as mobile phones and iPods, as well as having uses in other industries such as aviation and steelworks. This means the carbon does not need to be stored, but can be reused instead, and the recycling process be repeated almost indefinitely. The other main alternative is to use renewable energy sources, which do not create any carbon emissions in the first place, such as wind power, HEP, and solar power. Nuclear fission is another, more controversial alternative.

13 http://www.sintef.net/Projectweb/IK-23430000-SACS/
14 http://www.ptrc.ca/weyburn_overview.php
16 IPCC (http://www.bellona.org/ccs/Artikler/the_ccs_potential)
17 climatechange.110mb.com/nations-carbon-capture-storage.htm
18 Research councils UK (http://www.co2storage.org.uk/)
19 The Times (http://business.timesonline.co.uk/tol/business/industry_sectors/natural_resources/article6128615.ece)
21 CCS101 (http://www.ccs101.ca/ccs-basics/faqs/)
22 ERC (http://www.mantraenergy.com/Tecnology/ERCTechnology.aspx)
Conclusions
There is a lot of information available on the internet, and it seems that there are some questions that are likely to be asked of CCS projects that we are not currently providing answers for. It is possible that the data in question is not available, but we need to be proactive in addressing this; if there are gaps in the available data, we need to acknowledge this, and explain what is being done to remedy this, rather than ignore the question altogether.

The public summary brochures will be revised over the course of the next 3 months, and the new brochures will be circulated to members before publication.
IEA GREENHOUSE GAS R&D PROGRAMME  
40th EXECUTIVE COMMITTEE MEETING  
QUANTIFICATION TECHNIQUES FOR CO2 LEAKAGE

This study was undertaken by CO2GeoNet, led by Imperial College London. The final report has been received following external review and revision.

An attached draft overview has been prepared for member’s reference. The overview will be distributed to members for comment and discussed at the 40th ExCo meeting.

*Note references are provided in the full report
QUANTIFICATION TECHNIQUES FOR CO\textsubscript{2} LEAKAGE (IEA/CON/09/167)

Background

On the whole, the primary focus of CO\textsubscript{2} storage monitoring techniques has been to monitor plume behaviour in storage formations, and to detect leakage to the biosphere. However, for emissions trading under the EU ETS and for national GHG inventory purposes it is necessary to quantify leaked emissions to the atmosphere should leakage occur, and there is a low level of understanding of the capabilities, accuracies and uncertainties of measurement techniques for this application. Quantification of leakage was identified as a significant gap in the coverage and knowledge base of the IEAGHG storage networks in the Joint Network Meeting in June 2008, and the IEAGHG Environmental Impacts of Leakage workshop held in September 2008 highlighted there is potential for quantitative measurements to a level of accuracy required although inconclusive. Both the EU ETS work on monitoring and reporting guidelines for CCS and the EU CCS Directive working group concluded there is insufficient knowledge in this area; hence, it is pivotal for policy, regulations and for the development of monitoring technologies to ascertain the current state of knowledge in this field and understand possible future developments to meet requirements.

Scope and Methodology

A contract for this study was awarded to CO2GeoNet, with a project team led by Imperial College, London. The primary aim was to identify and review potential methods for quantifying CO\textsubscript{2} leakages from a geological storage site from the ground or seabed surface. The contractor was asked to identify techniques that can measure CO\textsubscript{2} leakage, reviewing techniques that have the potential to measure CO\textsubscript{2} leakage into the atmosphere and into the water column, for both point-source and dispersed leakage scenarios; once identified, provide a detailed review of quantification performance including sensitivity cost and future developments; suggest quantification improvements of a monitoring portfolio; review current requirements and provide recommendations. The contractor was also asked to liaise with the British Geological Survey to ensure results are reflected in the updated IEAGHG Monitoring Selection Tool.

The contractor provides a description of the technologies that can measure CO\textsubscript{2} leakage from potential point and/or diffuse sources, reviewing the quantification performance of these methods, discussing potential improvements for quantifying CO\textsubscript{2} leakage through the implementation of a monitoring portfolio approach. The review focusses on methods relevant for monitoring the marine and terrestrial aquatic environments, the atmosphere, shallow subsurface and ecosystems for leaked emissions as defined for requirements in the EU ETS and GHG inventory guidelines; recognising the importance of deep subsurface monitoring techniques for targeting the storage formation and overburden to identify potential pathways and migration in advance which are briefly discussed as part of monitoring portfolios.

Results and Discussion

Techniques to detect and quantify CO\textsubscript{2} leakage

Due to the nature of a CO\textsubscript{2} geological storage site, techniques to detect any potential leakage or likely pathway will be necessary prior to deployment of direct or indirect instrumentation for quantification. Deep subsurface methods with therefore be important to identify any potential leakage before it reaches the near subsurface, atmosphere or water column. Baseline monitoring is needed before any compartment is altered by the effect of CO\textsubscript{2} injection or exposure, especially as large spatial and temporal variation of background levels is likely to contribute the larges level of uncertainty. Modelling is also key to the planning of monitoring programmes; hence methods to help constrain model parameters and reduce uncertainties will

*Note references are provided in the full report*
add value. Preference should be given to methods that are concurrently employed for performance monitoring, are favourable in terms of cost and benefit, are most reliable and accurate, can be deployed in conjunction with other techniques, can be operated with minimum human effort, are robust and have added benefit in improving calibration of models. Detectability and sensitivity of a monitoring method is not just dependant on the technology but also the implementation mode when used in a specified calibration range and of course, different technologies will be suitable for different conditions and environments.

Table 1 in the main report presents the suitability of available methods for CO\textsubscript{2} detection and quantification considering the rate of CO\textsubscript{2} that can be quantified using the proposed techniques. This table will be integrated into the IEAGHG Monitoring Selection Tool.

**Marine and terrestrial aquatic environment monitoring**

Similar to surface atmospheric monitoring, CO\textsubscript{2} once in the water column will be rapidly dispersed by currents or dissolution and dilution. An understanding of baseline concentrations and variability as well as the local physical oceanography is crucial for interpretation of monitoring data. As there is likely to be a small signal in a large volume of water, methods with large spatial coverage provide the opportunity to detect but may be limited for quantification due to poor resolution; therefore monitoring strategies may be designed to focus on detection initially, and if a leak is suspected then techniques for flux quantification may be deployed directly or indirectly.

Side scan sonar was initially deployed from ships, and later applied to towed vehicles and autonomous underwater vehicles (AUV). The bathymetric data is obtained by active sonar, generating high quality photograph-like images which can resolve features as small as 1cm; hence can detect small changes in morphology should seabed surface topography be effected by any potential CO\textsubscript{2} leakage. Side scan sonar could also be used to detect CO\textsubscript{2} seeping into the water column, which has been demonstrated in natural seepage of shallow methane gas. With high sensitivity, they have been identified to have high potential for subsea hydrocarbon leakage detection systems (Carlsen and Mjaaland, 2006) with coverage in the range of some tens of metres for subsea oil and gas production systems (Hellevang et al., 2007), and such systems could be adapted for CO\textsubscript{2} leakage monitoring, as demonstrated in deep sea environments (e.g. Brewer et al, 2006).

Sonar system surveys, which are likely to be cost-effective, have the potential of covering a wide spatial area in a short period of time, and applying such to AUVs may be promising for monitoring, detecting and further quantification though multibeam systems may have limited resolution. Multibeam sonar, consisting of an array of narrow single beam echosounders with a frequency range of tens to a few hundred kHz, shows similar potential with limits in resolution which may not detect small pockmarks or minor fluxes. Combining multibeam sonar with optical methods, acoustic tomography and flow sensors could assist in quantification of flux, and a swarm of AUVs equipped with multibeam sonar and sensors could survey a large area on a regular basis which though costly would be effective. Long-term in-situ monitoring however requires a stationary system such as GasQuant: a lander based hydroacoustic swath system developed to monitor temporal variability of bubble release at seep, recording bubbles crossing the horizontally orientated swath, capable of monitoring an area of 2km\textsuperscript{2}. An energy supply is of course crucial for any long term system and a system such as GasQuant could be linked to storage technical installations. With areal coverage of thousands of square kilometres, the Long Range Ocean Acoustic Waveguide Remote Sensing (OAWRS) for bubble detection may be suitable for initial surveys though has low resolution therefore would be limited for detailed quantification.

Geochemical methods are the only techniques that can directly quantify CO\textsubscript{2} seepage in the form of bubbles which dissolve as they rise or as dissolved CO\textsubscript{2} migrating with deep-origin waters. Composition of the leaking gas may elucidate its source and help determine the flux.
rate, and samples of the gas can be collected and analysed close to the potential leakage point before dissolution into the water column; either in-situ or in the laboratory with leakage rates estimated by conducting profiles and using associated current velocities to calculate mass flux. Laboratory analysis is useful for improved sensitivity or for analysing components in-situ techniques cannot, though in situ analysis reduces potential sampling artefacts and as a continuous method has the possibility of collecting large amounts of data. A CTD probe is commonly used for measurements such as these, however ROVs are more flexible, and equipped with sensors an ROV can be deployed once sonar has identified a possible leakage site, measuring the size and shape of plume by manoeuvring the ROV in and out of the plume; or if also equipped with scanning sonar, can potential map the plume. Alternatively, sensors could be mounted on AUVs offering good spatio-temporal resolution. Various types of sensors have been applied for commercial and research probes including non-dispersive infrared (NDIR), electrochemical, mass spectrometers, direct-absorption spectroscopy and calorimetric sensors. An example of such sensors is the SAMI 2; which uses a diffusion membrane and a wet chemical approach, as the dissolved CO2 diffuses across the membrane onto a pH indicator where it transforms into carbon acid, changing the solution pH; and can measure pCO2 in the range of 150 to 750ppm, with a response time of 5 minutes, precision greater than 1ppm, accuracy of ±3ppm, long term drift of less than 1ppm in 6 months, and can be deployed up to 500m depth.

A technique lying between in situ and remote analysis of dissolved gas is the equilibrator technique with good spatio-temporal coverage, involving the towing of a long hose behind a ship, with a ‘fish’ at the end of the hose which maintains a constant sampling depth and a pump which continuously transfers water to the ship, passing it through the equilibrator which strips dissolved gases from the water for analysis via either infrared or gas chromatography. This method has been used for the detection of pipeline leaks and seepages from oil and gas reservoirs (e.g. Logan et al., 2010).

Benthic chambers also offer potential for direct quantification of flux rates from the sediment to the water, which consist of an enclosed volume with one end open for deployment on the sediment surface by divers in shallow water or ROVs or landers. However, these measurements are highly point specific and errors can occur due to spatial heterogeneity. As elevated CO2 levels near the seabed and in ambient water will affect marine ecosystems, monitoring of seabed fauna could also be measured using AUVs or long-term time lapse video recording. Threshold values currently being researched in projects such as the EU FR7 RISCS and EC02, may represent a useful tool for the evaluation of biological impacts and in turn, quantification of potential CO2 leakage.

Atmospheric monitoring

Similar to the marine environment, leaked emissions of CO2 to atmosphere may be quickly dispersed, and may prove difficult to detect using techniques favouring wide areal coverage and low spatial resolution. Surface monitoring instrumentation is therefore best placed in areas where potential leakage pathways have been identified during risk assessments. There are a number of techniques tested and in development with potential for quantification of CO2 flux, including the eddy covariance method (ECM) and long open path diode lasers.

The eddy covariance method offers relatively large spatial coverage, using statistics to compute turbulent fluxes of heat, water and gas exchange, and is one of the most effective methods to measure and determine gas fluxes in the atmospheric boundary layer; and has been proposed as a potential method for monitoring CO2 storage sites (e.g. Oldenburg et al., 2003). ECM is an established technique with low to moderate largely associated with the requirement of significant specific knowledge regarding the application of mathematical corrections and processing workflows. ECM works by a gas flux determined as a number of molecules crossing a unit area per unit time, and the gas flux is based on the covariance between

*Note references are provided in the full report*
concentration and vertical air movement/speed. Measured flux rates lie within the typical range of natural CO₂ emissions from soils and land cover (tens of g/m²/d) and higher emission rates can be easily determined, e.g. Werner et al. (2003) measured release rates between 950-4460 g/d/m² at the Solfatara volcano, Sicily. However, whether ECM can detect potential leakage from a storage site depends on the ratio between the integral CO₂ flux from the footprint area and the seepage rate from the point source, for example seepage rate of 0.1 t/d from a ZERT release experiment wasn’t distinguishable from background CO₂ emissions, whereas a release of 0.3 t/d significantly increased the flux compared to the baseline (Lewicki et al., 2009).

With a finer spatial resolution than ECM, various open-path sensing techniques have been developed, measuring path-integrated concentration of a target gas between two points near the ground surface, with a measurement interval ranging from tens to hundreds of metres. These methods have been used to locate gas emission and estimate leakage rates to atmosphere from point or non-point sources such as landfills and coal mines (e.g. Piccot et al., 1996; EPA, 2006); and more recently have been applied to monitoring of CO₂ geological storage sites (e.g. Trottier et al., 2009). There are a number of different systems, including Open Path Tuneable Laser (TDL) and Open Path Fourier Transform Infrared (FTIR) which to date have been applied to CO₂ monitoring. As the location and quantification of various gaseous pollutants is an issue, not only for CO₂ monitoring, the US EPA has published a protocol for the use of open path optical techniques applied to emission monitoring (EPA, 2006). Longer path lengths ensure larger areas are monitored however also result in loss of resolution and greater dilution of the leakage signal, therefore shorter path lengths are beneficial highlighting this method requires identification of a defined location. The method is well adapted for long-term unattended monitoring, as the lasers can be mounted on automated rotating platforms and most have an internal reference cell for self-calibration.

Leakage quantification can be performed by approaches applying models to the resultant data such as vertical radial plume mapping (VRPM) (EPA, 2006) which employs multiple non-intersecting beam paths in a vertical plane down-wind from a leak to define a plume map, and the flux through the vertical plume is calculated by combining the plume map with the wind speed and direction. Another approach uses a background Lagrangian stochastic (bLS) model (particle tracking) assuming an ideal surface layer based on Monin-Obukhov similarity theory (MOST) appears the most promising, assuming all required wind statistics can be determined from a few key surface parameters, is valid when source and measurement point lie within a horizontal homogenous surface layer and distance between these two points is sufficiently short that the particles remain in this surface layer. Controlled methane release experiments have yielded estimates within 5% of the true value at flux rates of 16-48 t/day (Flesch et al., 2004) and 3-6 t/day (Loh et al., 2009), in agreement with modelled minimum detectable rates of 1.7-7 t/day (Trottier et al., 2009; compared with modelled minimum detectable flux rates of 950 – 3800 t CO₂/day (Trottier et al., 2009) and an over estimation by 87% during controlled leakage of 43-100 t CO₂/day (Loh et al., 2009), hence similar results with CO₂ have produced larger errors due to more background variability and lower sensor sensitivity.

Short open path lasers, are very similar to long open path, with the difference of the equipment being mounted on ground or airborne vehicles for mapping of point sources compared to fixed installations; with TDL the most commonly applied method for CO₂ monitoring. Response times are rapid with little memory effects hence can be conducted at high speeds. Although the CO₂ unit is less sensitive than that for CH₄, the sensor has undergone recent technological advances, improving performance, and the tuneable diode laser can now measure up to 2000 nm, enabling 5 ppm CO₂ sensitivity and a range of 10,000 ppm. The ground based CO₂ unit measures once every second at recommended speeds of 20 to 100 km/h. Such has been tested at natural seepage sites such as Latera (Italy) and Laacher See (Germany) (Jones et al., 2009; Kruger et al., 2009); as well as during surface gas monitoring at the In Salah Gas project in

*Note references are provided in the full report.*
2009 using a Boreal Laser open path CO₂ detector linked to a gasFinder FC, mounted at 38cm above the ground on a Toyota Landcruiser, which used a detector wavelength of 2 µm with a 5-10ppm CO₂ sensitivity (Jones et al., 2011). Airborne methods for CO₂ detection and quantification may prove difficult due to low sensitivity, the influence of wind conditions and CO₂ will tend to remain closer to ground level.

Short closed path detectors involve the introduction of a gas sample into a chamber via a pump or diffusion and the quantification of a specific gas component by passing light across the chamber and through the sample. This is similar to long and short open path laser due to the use of optical sources and detectors, but differs due to the measurement chamber, allowing for greater portability and reduced interference though can have lower sensitivity and has slower response time. As they are of relatively low cost, are flexible, robust and could be deployed in large numbers, they show promise for use in a monitoring network. It consists of an infrared source and an infrared detector separated by a measurement cell, with recent advances including an internal reference cell for calibration. There are two types of infrared detectors: non-dispersive (NDIR) and dispersive. In NDIR, all the light from the source passes through the sample, after which it is filtered prior to detection; however in a dispersive system a grating or prism is used prior to the sample to select a specific wavelength. NDIR are the most commonly used detectors for field application and are often used in soil gas and CO₂ gas flux surveys which is discussed in near surface monitoring.

In terms of atmospheric monitoring, Lewicki et al. (2010) concluded NDIR sensors showed great promise if deployed around areas of higher potential for leakage, and Loh et al. (2009) showed an enrichment of greater than 4 ppm above background levels for CO₂ was needed for detection and quantification of CO₂ flux, in comparison with CH₄ which only required an enrichment of 0.02 ppm. Additionally, Wimmer et al. (2011) noted elevated concentrations were not observed at heights greater than 2.5 cm except directly above the leakage point when deploying NDIR; highlighting detecting and quantifying CO₂ flux may be challenging. Short closed path tuneable diode lasers (TDL) can have better sensitivities and faster response times, with the added benefit of the potential for real-time isotopic analysis; however these tend to be more expensive.

**Shallow subsurface monitoring**

Near surface gas chemistry offers two relatively low cost methods of monitoring and quantifying CO₂ leaked emissions: gas flux measurements at the ground surface and gas concentrations or isotopes in the shallow sub-surface (typically from a depth between 0.5 and 1m), and are commonly deployed together. Gas flux measurements are generally conducted using either the closed chamber (CC) or dynamic closed chamber (DCC) techniques, involving monitoring of gas changes over time within an accumulation chamber placed on the soil surface, with samples collected manually in the CC method or continuously (commonly every second) via an in-line detector in the DCC method and such autonomous monitoring can be very valuable for collecting baseline data. Soil gas samples are typically collected using small lightweight soil probes, involving driving a hollow steel tube into the ground and drawing soil air to the surface for analysis, or alternatively, sampling methods involve direct push, power hammered, augured or drilled systems but these are more costly, less portable and slower. In dry permeable ground such as in arid environments, deeper sampling at several metres depth may be essential to avoid atmospheric contamination (Gole & Butt, 1985). The samples can be analysed in the field, using portable equipment or stored in airtight containers for laboratory analysis, examining CO₂ plus other gases due to possible association with the reservoir (e.g. CH₄), as well as performing isotopic analysis to determine the origin of the gas i.e. to distinguish between naturally occurring CO₂ and that which may be originating from storage the reservoir. However, CO₂ isotopes may be limited as delta 13 Carbon values of CO₂ from burning of fossil fuels are similar to those from plant or microbial respiration; hence tracers are being examined for monitoring and quantification purposes, for example at the West Pearl

*Note references are provided in the full report*
Queen depleted oil formation in SE New Mexico study site where a Perflourocarbon tracer (PFT) was added to injected 2,090 tonnes of CO$_2$ and was used to quantify a CO$_2$ leakage rate of $2.82 \times 10^3$ g CO$_2$/yr (Wells et al., 2007).

Two main factors influence the success of soil gas and gas flux surveys for quantification: the methods much locate the leak and define its physical extent which can be addressed statistically, and the methods must be able to separate baseline flux from leakage flux rates for which baseline subtraction approach can be used or analyse for tracer species in soil gas which can be associated with the injected CO$_2$ and relating their concentration to CO$_2$ at the surface. Timeliness is also key hence it is important soil gas and gas flux measurements are integrated into a wider monitoring program. Sampling on a grid, interpolating between points, conversion to total flux for the measurement area and subtracting near-surface contributions, would typically be the process for quantification, for example, controlled leaks of 0.1 and 0.3 t CO$_2$/d at the ZERT site were accurately quantified with the latter 0.3 t CO$_2$/d leak quantified at a mean $\pm$ 1 standard deviation of 0.31 $\pm$0.05 t CO$_2$/d (Lewicki et al., 2010).

In the near surface environment, CO$_2$ flow is likely to occur as bubbles migrating vertically along a fault or borehole, and in such a case, gravimetric and EM/ERT methods may be deployed whilst simultaneously monitoring the reservoir, and can potentially be used for detection in groundwater. Continuous or time-lapse gravimetric methods may theoretically be able to characterise volumes of gas in the order of a few hundreds of tonnes in the shallow subsurface depending on saturation, though it is not established for CO$_2$ monitoring and may be prohibitively expensive. Airborne EM is well established in groundwater exploration studies (e.g. Siemon et al., 2009) however applicability may be limited due to noise from a variable water table and high natural CO$_2$ flux. Ground-based sampling would be needed to establish the cause of any enhanced conductivity, and for quantification a numerical simulator could be used to predict the groundwater impact of an ingestion of CO$_2$ in terms of a change in total dissolved solids (TDS), using an empirical relationship between TDS and EM to estimate the amount of CO$_2$ dissolved in the groundwater which is a subject of current research.

Hydrochemical factors may be useful for both detection and quantification, particularly in inhabited areas with springs or streams, for example waters with elevated CO$_2$ levels emerging at the surface may visibly show signs such as bubbles or rusty deposits through mobilisation of iron and oxidation at the surface. Depending on the water composition, CO$_2$ may form numerous dissolved complex species which can be sampled and analysed. The relative accuracy of hydrochemical analyses is in the order of 1-3%, with detection limits of CO$_2$ being 2 mg/l and 3 mg/l for HCO$_3^-$.

Ecosystem and Remote sensing monitoring

Ecosystem-based monitoring can be used to quantify and detect potential leakage into near surface environments, particularly when undertaken in combination with soil gas surveys, though accuracy necessary to meet requirements may be difficult. Botanical, soil gas, microbiological and gas flux surveys at the natural CO$_2$ seepage site at Latera has observed significant impact in a zone a few metres wide centre of the vent, with acid tolerant grasses dominating near the vent core, microbial populations regulated by near anoxic conditions, and small changes in mineralogy and bulk chemistry (Beaubien et al., 2008). Such impacts on vegetation and soil geochemistry may possibly be detected using airborne spectral (or optical) remote sensing techniques (Chadwick et al., 2009). Thermal imaging may also potentially detect leakage if there is a measurable temperature anomaly. Higher spectral resolution is achieved with hyperspectral sensors which can be as precise as 1m. Bateson et al. (2008) used

*Note references are provided in the full report*
spectral datasets to assess several indices related to plant stress and estimated a threshold of around $60 \text{ g m}^{-2} \text{ d}^{-1}$ would be the minimum CO$_2$ flux rate that could be detected with spectral remote sensing methods. Such vegetation indices can however contribute to false positives and hence care should be taken on interpretation.

**CO$_2$ Leaked Emissions Requirements**

Under EU regulations, requirements for leaked emissions falls under the EU Emissions Trading Scheme (EU ETS); which, launched in 2005, builds upon mechanisms set up under the Kyoto Protocol, the Clean Development Mechanism (CDM) and Joint Implementation (JI) (EC, 2008); and for geological storage of CO$_2$ would now be triggered by the EU CCS Directive which entered into force in 2009. Article 16 of the EU CCS Directive 2009/31/EC lays out requirements in case of leakages or significant irregularities, ensuring should there be any leaked emissions there would be a surrender of allowances under the EU ETS. In June 2010, an amendment to the 2007/589/EC, establishing guidelines for the monitoring and reporting of greenhouse gas emissions, was amended to say leakage ‘may be excluded as an emission source subject to the approval of the competent authority, when corrective measures pursuant to Article 16 of Directive 2009/31/EC have been taken and emissions or release into the water column from that leakage can no longer be detected.’ A further amendment to Decision 2007/589/EC under Annex XVIII adds ‘Monitoring shall start in the case that any leakage results in emissions or release to the water column. Emissions resulting from a release of CO$_2$ into the water column shall be deemed equal to the amount released to the water column’ and defines an approach for quantification, stating ‘The amount of emissions leaked from the storage complex shall be quantified for each of the leakage events with a maximum overall uncertainty over the reporting period of ± 7.5%. In case the overall uncertainty of the applied quantification approach exceeds ± 7.5%, an adjustment shall be applied, providing an equation for leaked emissions reporting in such a case. The operator requirements for acknowledgement of uncertainties, using a cumulative approach as defined in the 1996 IPCC Guidelines (Reporting Instructions) indicates the greater the uncertainty the greater the penalty should CO$_2$ leakage occur.

Currently, there are no other national regulations requiring quantification of leaked emissions, despite some in place providing monitoring requirements; however, the US EPA has a proposed further rule, proposed in early 2010 (US EPA, 2010) which supplements the greenhouse gas reporting rule finalised in 2009, requiring carbon storage facilities to report their emissions by calculating the sequestered CO$_2$ by subtracting total CO$_2$ emissions from CO$_2$ injected in the reporting year. Such does not ask for specific procedures or methodologies to be implemented, but rather asks operators to develop and implement a site-specific approach to monitoring, detecting and quantifying CO$_2$ leakage. Additionally, the Australian Regulatory Guiding Principles for Carbon Dioxide Capture and Geological Storage, which were developed with the aim of establishing a national regulatory framework state ‘Regulation should provide a framework to establish, to an appropriate level of accuracy the quantity, composition and location of gas captured, transported, injected and stored and the net abatement of emissions. This should include identification and accounting of leakage.’

**Technique Uncertainties**

Given there is a specific requirement in the EU for defining the level of uncertainty in quantification estimation, it is important to consider the current knowledge on measurement instrumentation/technique uncertainties. Level of uncertainty will of course decrease with further refinement with increased application; however the natural system will always impose some level of uncertainty. For example, in surface water chemistry techniques, Mau et al. (2006) estimated 10 to 20% of their uncertainty was due to variations in the local background with over 50% due to current velocity variations. From reported research there is evidence to suggest some technologies in their current level of development may have uncertainty ranges

*Note references are provided in the full report*
exceeding the required range of ±7.5%, i.e. Trotta et al. (2010) estimated the largest uncertainties can range from 10 to 40% for different set-ups of eddy-covariance-based estimates of net ecosystem exchange; and uncertainty of CO₂ flux increases with increasing absolute magnitude of the flux (Hollinger & Richardson, 2005). Research is required to improve current understanding of sensitivities and uncertainty ranges of both individual technologies and combined monitoring portfolios.

**Expert Review Comments**

The contractor is currently compiling a document which describes how the revised version of this study report reflects the expert reviewers’ comments; hence this will be described in detail in the final overview.

**Conclusions and Recommendations**

The study results highlight for potential leaked emissions in the shallow subsurface, atmosphere and marine environment, monitoring portfolios should be focussed on identified leakage pathways, making use of deep subsurface monitoring technologies to recognise potential pathways; or else it will be necessary to deploy monitoring technologies with lower resolution and wide spatial coverage to detect any CO₂ seepage before deploying more sensitive measurement techniques for quantification. To quantify CO₂ flux, no one technology has been identified, and development of an efficient monitoring portfolio will depend on the specific environment.

The results show technologies suitable for quantification do exist, however certainly need further field testing and some currently proposed methods may prove unsuitable for quantification, for example ECM which though a powerful tool is expensive, complex and measurement errors and uncertainties is an issue which remains to be solved. Additionally, the study highlights that largest uncertainty ranges for some techniques may exceed that of current requirements, for example in surface water chemistry techniques and ECM, and it is recommended IEAGHG explore this further. For quantification purposes, further research should focus on defining sensitivities of instrumentation and uncertainty ranges, testing the technologies in a wide range of conditions for both controlled and natural releases of CO₂. Future research should also provide further insight into variability of baseline CO₂ flux which will be crucial for ascertaining suitability of techniques for specific environments, and EU projects such as the proposed CO2BASE project should help to build knowledge in this area. Some areas of the report are weaker than others due to data availability, such as technologies in the marine environment, therefore such should be re-examined in future relevant studies.

The study also provides a number of technology specific recommendations, provided within the final chapter of the report, which includes a need for further testing specific to CO₂ seeps for surface water chemistry techniques in order to assess method sensitivity, precision and costs for CO₂ monitoring; the need for further development of long open path lasers with more stable baseline signals and that can measure more than one pathway and improve results and greater distances; focus on deploying short open path lasers closer the ground surface to minimise potential anomalies and testing models to monitor tracer gases that have lower sensitivity; for shallow groundwater monitoring further research should examine integration of indirect methods such as EM to enable wider spatial coverage and for airborne EM further work should examine the discrimination of the effects of CO₂ leakage from alternative scenarios such as seawater intrusion.

*Note references are provided in the full report*
FEASIBILITY OF MONITORING TECHNIQUES FOR SUBSTANCES MOBILISED BY CO₂ STORAGE IN GEOLOGICAL FORMATIONS

Draft Overview

Background to the Study

Monitoring programmes for geological storage of CO₂ have been focussed on techniques for detecting leakage of CO₂. However, it has been recognised that CO₂ may mobilise other substances and can cause displacement of saline water. All of which could have an environmental impact in the event of leakage from the geological storage formation to potable water, the water column, soil and the atmosphere.

Several regulatory regimes, including the guidelines for CO₂ storage in the London and OSPAR conventions, require that any effects of such substances mobilised by the CO₂ and any displaced saline water be included in the effects assessment and potentially monitored. Therefore it is necessary to review what the feasibilities and current capabilities are of techniques which can monitor movement of other substances in geological formations and in the event of leakage.

The displacement of saline formation water may be caused by changes in formation pressure during CO₂ injection. This is particularly the case in deep saline formations. The extent of displacement is dependent on the geological setting and the injection scenario. A system may be considered to be ‘open’ or ‘closed’ depending on whether the target formation is compartmentalised by lateral flow boundaries (faults). In a ‘closed’ system, the boundaries limit fluid flow, whereas in an ‘open’ system there is a much greater pressure communication and hence fluid flow is more likely. It should be noted that many systems can be considered as ‘semi-closed’ with an intermediate pressure communication. Another factor is the number and location of injection wells, which may further complicate the resulting pressure fields within the formation.

Pressurisation could affect the caprock and fault integrity, and hence cause the creation of leakage pathways and it is possible that the displaced saline water may enter into an overlying potable aquifer.

The addition of CO₂ into a formation can cause changes in the pH and pE (redox potential) in the formation water. This may, in turn, cause changes in the solubility of various trace metals, especially those of redox sensitive metals, causing them to mobilise. Which substances are mobilised will depend upon the lithology of the target formation and that of the caprock, as well and the pH and pE. For example, in a poorly buffering (low CaCO₃) aquifer containing galena (PbS), it is likely that lead solubility, and possibly that of other toxic metals, will increase.

If leakage then occurs, the mobilised substances may enter the water column or soil, and may affect bacterial production and cause a significant change in the microbial community structure. The mobilised substances along with the CO₂ may also enter into any overlying potable aquifers, making them unusable.
It may also occur that additional substances, remaining from the capture process, may be injected into the target formation along with the CO₂. It is important to be able to monitor these in conjunction with the CO₂.

CO₂CRC, a consortium based in Australia and New Zealand, was commissioned by IEAGHG to undertake a study considering which substances that may be mobilised by CO₂ need to be considered in monitoring programmes and what technologies could be considered to detect them.

**Scope of Work**

The scope of this study was in two parts. The first part is, by using the existing literature to identify what substances should be addressed, i.e. which are those that could be mobilised by injected and stored CO₂ as well as those contained in the CO₂ stream (incidental associated substances from the fuel, capture, transport and injection processes). For example, CO₂ can cause changes in pH in sediments which could mobilise trace metals and other compounds to a higher level of bioavailability. These substances should also include displaced saline water. Then the potential scale and effects of mobilisation of such substances be assessed, so as to identify those substances which are most likely to require monitoring.

Secondly, the main part of the study would review and assess potential technologies and techniques for their feasibility of detection of these substances, and for detection of any environmental impacts they might cause in the event of leakage. Potential technologies and techniques would include both direct sampling, including for downhole applications, and remote monitoring techniques, and shall be reviewed for both onshore and offshore applications. The study should look at each technique and discuss its current and possible applications, which substances it applies to, sensitivity and resolution, costs and future developments.

It is expected that as well as a study report the contractor should be prepared to present the report and results at an IEAGHG Monitoring Network meeting.

CO₂CRC was asked to refer to the following recent or ongoing IEAGHG reports/studies 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:

- Development Issues for Saline Aquifer Storage, CO₂CRC, Report 2008/12
- Assessment of Sub Sea Ecosystem Impacts, Report 2008/08
- Potential Impacts of Leaks from Onshore CO₂ Storage Projects on Terrestrial Ecosystems, Report 2007/3
- Environmental Impact Assessment for CO₂ Capture and Storage, Report 2007/1
- Pressurisation and Brine Displacement, Permedia, project commenced, report 2010/15
- Effects of Impurities in CO₂ on Geological Storage, Natural Resources Canada, report 2011/04
- Potential Impacts on Groundwater Resources of CO₂ Storage, to be published 2011.
Findings of the Study

Monitoring Opportunities

The section of the study looked at what effects could be monitored and is divided into flow effects, geophysical effects, effects on the near surface biosphere, geochemical effects, hydrocarbons and organics and captured gas compositions.

Injection of supercritical CO₂ into a deep, confined aquifer will cause mobilisation of the pre-existing fluids and depending on the injection scenario may include some migration of the supercritical CO₂ plume. In addition, there will be some degree of dissolution of the CO₂ front into the formation fluid and interaction between these fluids and the rock matrix. This will cause some physical changes in the pre-existing flow properties which may be detectable and therefore have application in monitoring and verification activities. Formation water properties that may change are pressure, density, viscosity, temperature, chemistry/redox potential of the original formation water and pH changes, due to the presence of the CO₂ and potential reactions with the rock matrix.

Geophysical tools are known to work on- and off-shore and can be used to measure changes in salinity, density and pressure as well as the presence of CO₂ and CH₄.

Effects of on the near surface biosphere may be monitored and potential changes can be identified by considering natural analogues. Mobilised minerals and compounds can act as an active nutrient supply or toxic substance, either of which will have a pronounced effect, therefore monitoring for positive and negative effects on plant and bacterial communities may give an early warning of changes and eventual CO₂ presence.

Geochemical effects that could be monitored include the oxidation and reduction states of fluids and minerals and monitoring of changes to metals, metalloids and anions.

In CO₂ geological storage applications, there is the potential that buoyant CO₂ could leak from a deep storage formation and migrate to shallower aquifers used as a groundwater resource.

The addition of CO₂ gas to a shallow aquifer would result in an increase in the partial pressure of CO₂. This increase in PCO₂ would in turn result in an increase in dissolved CO₂ and therefore a decrease in pH. There are likely significant consequences of large changes in aquifer pH including; 1) dissolution of carbonate and silicate minerals, releasing contained metals/metalloids 2) dissolution of oxide and hydroxide phases (i.e., primarily Fe-, Mn-, and Al oxyhydroxides), which will release adsorbed or co-precipitated metals/metalloids and 3) desorption of metals from mineral surfaces by lowering the pH below the characteristic adsorption edge of different aqueous species on different aquifer materials.

A review of published studies and consideration of natural analogues was carried out to identify the species of concern. These differ depending on the reservoir type and the extent of mobilisation may differ according to, amongst other factors, the pH level, Fig. 1.

Figure 1 Ficklin-type diagram showing the influence of pH on mobility of transition metals associated with different styles (i.e. volcanogenic massive sulfide, sedimentary exhalative, porphyry copper, and kimberlite) of mineralisation under natural and acid-mine drainage conditions. Figure from Leybourne (2007).
There is an opportunity to utilise tools and technologies for monitoring hydrocarbons in CCS monitoring and verification programs where depleted oil and gas fields are used. Whether for EOR (e.g. Weyburn, Cranfield) or using abandoned or uneconomic fields (e.g. Otway) there tends to be significant quantities of hydrocarbons left as "oil-in-place". As a consequence, there may be free gas, free oil and residual hydrocarbons that will mix with the added CO₂, and these hydrocarbons can be taken up by the supercritical CO₂ plume and easily mobilised during storage in these environments. In addition to this hydrocarbons or functionalised organic compounds have been used as tracers.

Incidental substances can be present in CO₂ streams introduced from combustion fuels, capture, transport, industrial manufacturing and injection processes (e.g. as tracers). Depending on the processes involved, any additional substances/ contaminants may be present in varying abundances and with quite different chemical compositions. The most important effects are considered to be pressure changes from the effect of limited/no compressibility of non-condensables; chemical reactions, which are scaling/fouling of the injector, changes in pH, mineral reactions beyond the injector and mobilisation of cations/anions; then there is transport of contaminants, movement of contaminants as pollutants or tracers.

Potential Technologies

The approach taken in the study was to consider anything from soil surface to deep subsurface and includes physical, geophysical, chemical, biological and other approaches to identify tools. Potential technologies considered were divided into those that monitor flow or physical effects, geophysical effects, biological technology, geochemical effects, mobilisation of anions and monitoring of hydrocarbons and organics.

The significant advantage in the types of tools and systems described in the physical monitoring tools section is their ability to detect changes due to the presence of CO₂ some distance away from the CO₂ itself. This increases the percentage of reservoir (or aquifer) "covered" by the monitoring system, increasing confidence in the containment and allowing for the possibility of early detection and remediation.
The key parameter in this section is pressure. There are two reasons for this; 1) it is a mature technology with a range of options suitable for the types of monitoring environments required for CCS technology. It is off-the-shelf, cost effective, sensitive and robust for long term installations; 2) the movement of a plume of CO₂ will be accompanied by a propagating wave of pressure whose spatial footprint will far exceed the dimensions of the plume itself. The key parameter to consider in long-term pressure monitoring is the level of sophistication required for a specific site. The cost of installation, processing and interpreting increases with increasing complexity of the system and number of gauges installed. It is necessary to carefully consider what the monitoring objective is for each case.

The other systems described in the report, such as DTS (distributed temperature sensors) and ERT (electrical resistance tomography) have been demonstrated to have application to CO₂ monitoring, however, their longevity of these systems under reservoir conditions is also unclear and their cost may be prohibitive. For this reason, although they are potentially applicable to monitoring aquifers above the storage zone, it is unlikely they would be deployed here. The exception may be in specific, high risk locations. Fibre optic technologies have the potential for quite sensitive monitoring of acoustic, flow and temperature properties. This again produces large volumes of data which can be complex to handle, require sophisticated geological models to interpret, and considerable computing power to process. pH sensors are only beginning to be developed for deeper, hotter environments due to new applications in oilfield surveys but may not be deployable for longer term periods as yet without some testing.

Deeper geophysical methods measure the CO₂ plume or the shift in salinity/density/pressure that can be detected. Although other associated compounds may also be liberated, it is unlikely any of these are in large enough quantities to change the geophysical technique and its application. Shallow applications may have more flexibility in detecting other subtle parameters, but this is not certain.

Depth is, and will continue to be, a problem for most geophysical methods applied to CO₂ monitoring. In the shallow environment (<100 m) the measurement capabilities of geophysical measurements for detecting CO₂ leakage are improved significantly. 4D seismic is most valuable at all depths, but electromagnetics and gravity also have some value. Other seismic options such as microseismic, vertical seismic profiling have been able to resolve CO₂ migration and continuous monitoring techniques will probably have more long-term value and use in future CCS projects. Cross-well methods are very useful subsurface monitoring, but are limited in the resolution and spatial extent of the surveys being confined to the well locations. The use of magnetotellurics (controlled source in terrestrial settings) has potential for application to CO₂ monitoring, but has not been tested at a real CCS project site. Surface deformation monitoring is valuable, whereas other methods discussed such as MRS (magnetic resonance sounding), GPR (ground penetrating radar), magnetics, spectral and near surface gas fluxes do not appear to have extensive upside to development towards CO₂ monitoring.

Biological monitoring for CCS present challenges at depth, but is a relatively low cost and feasible option in the near surface environment. The gap in application of biological monitoring to CCS sites compared to chemical or geophysical methods is great, with only a few successful biological monitoring tests applied to natural analogues or shallow test injections. The most important finding in this section is the potential of newer monitoring tools for phylogenetic and functional gene characterisation of microbial communities that have not been tested in the “CO₂ storage realm”. These tools offer rapid and more thorough microbial characterisation than older methods and have the potential to show changes in microbial communities due to CO₂ leakage and associated issues such as pH changes and mobilisation of potentially toxic metals and metalloids. Once a link can be
established between species or functional genes that reflect CO₂ changes due to CCS leaks, refining specific microbiological signals into simple-to-use, field portable, rapid biosensors should become a reality. This is the next critical stage for advancing the science of biological monitoring for CO₂ storage.

For geochemical monitoring traditional ion selective electrodes (ISE) suffer from a number of drawbacks that make them largely unsuitable for long-term in situ monitoring of deep saline groundwaters. These disadvantages include issues of matrix matching, sensor drift, need for calibration, need for variable storage solutions for different analytes, use of internal reference solutions, and in some cases, detection limits that are too high for trace metals. The new thin and thick film deposition of sensors means that many of these problems are in the process of being solved, in particular detection limits, miniaturization, and reduction in the need for repeated calibration.

The most useful approach to long-term in situ monitoring for the alkalis, alkaline earths, transition metals and metalloids appears to lie in the area of ISE and ISE sensor arrays. The approach to take most likely involves identifying key analytes that represent a larger group of elements that typically have similar behaviour in groundwater and in response to changes in pH and aquifer mineralogy through carbonation reactions. Thus, Pb and Zn could be monitored as proxies for many of the transition metals. A La, Ce or Nd electrode would be suitable to monitor changes in rare earth elements (REE) and actinide concentrations (as these are commonly the most abundant REE in groundwater); many studies of the behaviour of the REE in solution are based on their ability to act as analogues of the actinides. An ISE for Fe would permit monitoring of dissolution and precipitation of Fe and Mn oxyhydroxides; these are key mineral phases that control the mobility and attenuation of many metals and metalloids (especially Cu, Pb, Co, Ni, As, Se). Finally, Ca, Na, Mg and K ISE, in conjunction with pH and CO₂(g), would permit monitoring of the extent of water-rock interaction and carbonation.

Changes in anion concentration as a result of CO₂ leakage could arise in a number of ways, including 1) mixing with saline waters, which would increase Cl, Br, and I concentrations, 2) lowering of pH resulting in enhanced water-rock interaction, which could release anions, 3) lowering of pH may result in increased adsorption of anions onto positively charged mineral surfaces, and 4) changes in redox conditions, resulting in changes in sulfide/sulfate values, reduction of nitrate or oxidation of ammonia. Thus, in situ monitoring of key anionic species is key to determining the influence of leakage of sequestered CO₂.

Many anion sensors employ the potentiometric (i.e., electrochemical) transduction mechanism i.e., ISE. The majority of anion ISE tools use a polymer receptor/membrane and polyvinyl chloride (PVC) is a commonly used polymer. In many cases, a plasticizer and ionophore is incorporated into the PVC membrane, and these are typically optimised to selectively interact with the anion of interest. Despite many displaying suitable analytical properties (i.e., sensitivity and selectivity), as with cation sensors there are problems related to drift and the need for calibration. Most polymer-based anion sensors have a relatively short lifetime (i.e., less than 3 months), which limits their application to long-term realtime monitoring.

As with cation ISE, anion ISE have traditionally suffered from a number of limitations that would hamper their use as long-term in situ monitors. However, along with rapid changes in ISE with respect to miniaturization and solid-state, lab-on-chip technologies, the key to in situ monitoring is likely to determine relative changes in aquifer chemical conditions, which would trigger more detailed sampling and laboratory analysis.
A great deal has been published on the development of sensor technologies and tools for monitoring hydrocarbons, however, very little has been applied to CCS monitoring applications. This is partly because many of the sensors are not particularly selective. Membrane based sensors are generally more selective compared to sensors that do not comprise a chemoselective material. However, those that employ an absorbing membrane are generally less stable at high temperatures/pressures and over long monitoring periods given that the membrane material can degrade with time. By contrast, fluorescence based detection tends to be very stable due to the robust nature of both the light source and the photometer. Of the sensors that have been developed commercially and in the scientific literature, it seems that fluorescence and piezoelectric (i.e. surface acoustic wave) sensors are the most sensitive and can detect the required levels (i.e. ppb). Although these sensors are relatively small and robust, it is not known how they will perform in the geological formation over long periods of time. The long-term drift (over a one year period) of these sensors have not been properly evaluated and this needs to be addressed in the future.

**Application of Study**

There is the potential for an increasing number of tools to be used to develop integrated multi-analyte sensors for real time qualitative and quantitative analysis, along with data acquisition and transfer. Some of the electrochemical and optical detection platforms appear more suited to adaptation and deployment as they are already relatively inexpensive, rugged, easily miniaturised, low in power requirement and sensitive. Solid state devices, such as new generation pH probes are beginning to have the sort of specifications required for deployment in deeper and more aggressive environments.

Pressure measurement is a fundamental component of any CCS monitoring system. Pressure transients are likely to occur ahead of any CO\textsubscript{2} plume (or other proxy) potentially allowing the detection of changes some distance away from the source of CO\textsubscript{2}. This increases the coverage of the individual components (i.e. wells) of the monitoring system and increases the likelihood of early detection and remediation.

Complexities do arise however in the use of these and other tools and technologies (e.g. DTS and fibre optics) as they can produce large volumes of data. Interpreting the data can be highly complex and, in the case of pressure, it can be affected by numerous processes depending on deployment in the storage reservoir or overlying permeable aquifers (e.g. localised perturbations due to extraction of water or production of hydrocarbons, seasonal variations and unknown recharge rates). Calibrating the data to detect CO\textsubscript{2} related anomalies may require considerable understanding of the systems involved and extensive computing software, facilities and expertise. These issues arise not only for pressure data, but for all cases where considerable data acquisition occurs.

Capital costs of pressure instruments are variable and dependant on the sophistication of monitoring required. In general, this is a mature field and there are specific tools available depending on the monitoring environment. Some of the newer technologies (for example fibre optics) may be expensive and their long term functionality and stability is unproven.

The geophysical monitoring in this report has tended to focus on alternative technologies commonly employed in shallower environments using mineral exploration and agricultural approaches. Many techniques do work in both the shallower and deeper environments.

Irrespective of the methods used to monitor the subsurface via geophysical methods, depth to “target” will always limit resolution for identifying leaks. As alternative approaches, electromagnetic and gravity surveys do appear to show some promise, as does magnetotellurics (though this method has
not currently been tested in a CCS environment). Crosswell seismic methods are limited in their spatial extent though may be valuable for testing wellbores as potential leakage conduits.

In the near term, where possible 4D seismic remains of great value, closely followed by surface deformation monitoring techniques. Both of these have been successfully employed independently in CCS projects at commercial scale (Sleipner and In Salah respectively).

Information on conducting extensive biological monitoring for CCS was limited. While this was found to be a challenging approach at depth, the relatively low cost of surface arrays (compared to geophysics) makes this technology appealing.

Few tests have been conducted (on vegetation or microbial systems) but there are successes from natural analogue and shallow release studies by way of “calibration”. As some of these tools have not yet been tested extensively in the CCS domain, the changes in vegetation or microbial community anticipated for these tools may not yet be identified and developed. Some tools e.g. phylogenetic chips, have shown potential after deployment in the mineral exploration domain and are anticipated to be of similarly good value to CCS. These tools could perform as low cost assurance monitoring tools, though testing is required to confirm their usefulness in other settings.

The geochemistry of subsurface fluids has traditionally been characterised by direct fluid sampling. Advances, such as the use of the U-tube or other sampling methods to obtain pristine samples at reservoir conditions have been complemented by analysis in the field (e.g. mass spectrometry of gases and tracers) or in laboratory environments (e.g. use of ICP-MS or other techniques). Finding deployable tools that might compete with laboratory instrumentation in terms of specificity and sensitivity have tended to limit the availability of tools for inorganic geochemical monitoring (i.e. both cations and anions, and other species for that matter). This is because many alternative tools simply cannot detect species to relevant levels that laboratory equipment can be tuned to see.

The advancement of ion selective electrodes (ISE) to higher sensitivities allow for the consideration of these tools for deployment that will return similar results to laboratory testing. Remote interrogation of these tools is possible, but automation of some of the chemical sensors remains challenging. There are some drawbacks however, as traditional ISEs currently suffer from sensor drift; the need for matrix matching; calibration requirements; the requirement of different storage solutions for different analytes; use of internal reference solutions and inappropriate detection levels for some species. But new advances in solid-state electrodes and sensor arrays have contributed toward improving some tools such that increased detection limits, miniaturisation and reduced calibration times are occurring. Targeting the right group of species for a given site could allow for the building of a powerful array incorporating other monitoring tools looking specifically for changes in particular metal concentrations, pH and CO$_2$(g).

The situation is similar for anion monitoring, with traditional ISEs suffering from the same suite of drawbacks. However, these too are undergoing rapid advancements in technology with lab-on-chip solutions being developed to miniaturise tools for future deployment.

Hydrocarbons and organic sensors were included due to their pervasive presence in the subsurface. In many situations, depleted oil and gas fields have and will continue to be targeted for CO$_2$ storage. Similarly EOR opportunities that aid in the economics of CO$_2$ storage (e.g. Weyburn or Cranfield) will mean that M & V will take place in locations with abundant hydrocarbon compounds present.
Many of the sensors available are not particularly selective to specific compounds, however this is not regarded as a concern for monitoring of depleted hydrocarbon reservoirs where a range of compounds may be present. However, it will be an issue if the sensor is required to monitor for a specific organic tracer compound (e.g. a perfluorocarbon).

Increased concerns about the mobilisation of organics (in particular BTEX compounds) into potable aquifers (related to recent coverage in coal seam gas [CSM] or shale gas activities) could become an issue for CCS. This means that tools or sensors may need to be deployed in shallow aquifers for public assurance at new or existing CCS sites. Furthermore, conflicts between competing activities in the same area could occur. In parts of eastern Australia (Great Artesian Basin), storage of CO$_2$ and recovery of coal seam gas may occur in proximity to one another. BTEX problems are already being encountered in the CSM industry in an area with potable groundwater causing considerable community concern.

While some small and relatively robust sensors for hydrocarbons are available, their long term drift and stability in aggressive environments may require further testing. It is anticipated that monitoring of overlying aquifers to show an absence of organics will be an increasing focus for assurance of potable water integrity.

**Expert Review Comments**

Expert comments have been received from 5 reviewers and CO2CRC are currently in the process of making the changes for the final report. Several reviewers have made detailed (often technical) comments which are difficult to summarise or collate, so we have encouraged CO2CRC to study the reviews carefully and consider all changes that may be appropriate; some comments could be addressed by adding suitable caveats to the text, or recommending further work/future studies.

Based on observations that were commonly made by reviewers and our own internal reading of the draft, the following areas need to be considered and suitably addressed in the final report:

1. Firstly we are very pleased with the overall quality of the report and amount of information contained within; however the scope of the study needs to be much clearer. There is much information contained within the study, but it needs to be made clear what substances should be monitored (those mobilised by CO$_2$) and how they can be monitored by the variety of methods described. The original specification requests a first part identifying which substances are of interest, followed by a second part describing what methods can be used to monitor them. Parts of the report read like a list of monitoring methods not necessarily useful for monitoring the mobilised substances.

2. Please include only the geophysical techniques that can be used to monitor mobilised substances, some methods are described only in terms of how well they monitor CO$_2$. If it is possible that they can be used to monitor mobilised substances this should be included.

3. The conclusions and executive summary should be more a summary/analysis of the findings as it is currently just a description of the work carried out. What substances can currently be monitored? What is likely to be able to be monitored?

4. Please make the distinction between potable aquifers and potential storage reservoirs clearer. IEAGHG usually use deep saline formation (DSF)
5. References need some cleaning up (see review 4 for specifics)

Despite some common thoughts/specific criticisms from many of the reviewers, the overall response has been positive and we are hopeful that the final report will be a worthwhile study that makes a significant contribution to this area of storage research.

Conclusions

While many tools and new technologies have been identified, many of these have not yet been tested either in a CO\textsubscript{2} storage environment, or even outside of a laboratory. Tools that have been deployed at previous and current sites have not been deployed across all sites. This may be due to costs and funding arrangements, or because they are not appropriate at some sites or there has been mixed experience with some tools or the datasets generated. Many of the current CCS sites have relied strongly on equipment from the oil and gas sector, where the tools are already appropriately rated for pressure and temperature, but may not always be tested in terms of longevity, ease of data retrieval or manipulating the extensive data generated.

In almost all cases, tools have been deployed to investigate the injection horizon, and some shallow aquifers, soil gas or atmosphere. Monitoring of the formation directly overlying the injection horizon has been limited to indirect measurements (i.e., geophysics). The one exception is at Cranfield where there is a specific monitoring zone above the first sealing unit because pre-existing wells in that zone could be equipped with monitoring tools relatively cost effectively. More focus with selected tools sampling the zone directly overlying the injection horizon is needed, as this may provide early warning of leakage or detection of substances that might be mobilised by that leak.

There has been little discussion in this document about the location of some of the tools with respect to placement in the annulus or placement within or out-with the well casing. It is acknowledged that the development of smart or intelligent wells will provide more opportunity for investigating new approaches with placement of tools in the future.

There is an ongoing drive towards miniaturisation, ruggedization, lower costs, lower detection levels and increasing electronic communications to report the data obtained and yet, there are few tools that have been tested or deployed, and so, this must be a future goal of this sort of research. Identifying the longevity, stability and operational costs (retrieval, replacement of power supplies, data processing and manipulation etc.) must be a future goal for the CCS domain in order to quantify the true cost of M & V and also assess the relevance of different tools in different settings.

The work here also demonstrates that the tools can be split into different technology readiness levels. For example, many seismic tools would be in the upper zone, where technology is mature, tested and deployed and only incremental improvements may be anticipated. By contrast, some tools, such as the biological tools would more likely fall in the lower to mid zone, where the tools may have been tried for other applications reasonably successfully, but would require further research to prove the feasibility of the tools in CCS M & V applications. Evaluating tools in terms of their technology readiness might be a good way to flag tools that could be trialled alongside proven technologies during future storage operations.

Any mechanism that provides low cost, large spatial coverage of a CCS site and assures us that the CO\textsubscript{2} is safely stored is an important outcome for the CCS domain, however significant testing and
augmentation of many tools may be required before we achieve a full toolbox of techniques that can fit any geological storage site.

**Recommendations**

Some technologies considered in this report are still in the early stages of development and it is unknown whether they will prove to be useful for monitoring of substances mobilised by CO$_2$. It is important that IEAGHG keep updated on the progress of testing, possibly through the IEAGHG web based monitoring tool. The monitoring tool will also need to be updated with the results from this report.

IEAGHG should ensure that adequate attention is paid to these topics through future storage network meetings and by the study programme.
IEA GREENHOUSE GAS R&D PROGRAMME  
40th EXECUTIVE COMMITTEE MEETING  

ETHICAL ATTITUDES AND UNDERGROUND CO₂ STORAGE  

This study is being undertaken by The University of Manchester Tyndall Centre. The draft report has been received and sent out for peer review.  

An attached draft overview has been prepared for member’s reference. The overview will be distributed to members for comment and discussed at the 40th ExCo meeting.  

*Note references are provided in the full report
ETHICAL ATTITUDES AND UNDERGROUND CO₂ STORAGE  
(IEA/CON/10/188)

Background

All new technologies face challenges with social acceptability, which can prevent or delay progress and implementation. Various studies have investigated public and/or stakeholder perception of underground CO₂ storage, reporting differing reactions, and the reason for such is poorly understood. For example, Shell’s proposed CO₂ storage project in the depleted gas fields of Barendrecht and Barendrecht-Ziedewij was cancelled in 2010 by the Dutch government claiming lack of local support, following significant stakeholder opposition; however, positive support has been seen elsewhere including for the TOTAL Lacq pilot project, following community engagement in Illinois and in the establishment of the CCS Promotion Association by Tomakomai City in Japan. Public perception of underground CO₂ storage is widely recognised as a key factor for success or failure of a project, therefore it is necessary to explore why such public perception differences exist.

The majority of social science research associated with underground CO₂ storage provides further understanding of perceptions to the technology and the technological risks; however underlying social issues which may explain perception are yet to be fully explored. Bradbury et al (2009)* noted some initial observations of such in a study analysing community perspectives in three of the US Department of Energy’s (DOE’s) Regional Carbon Sequestration Partnerships, with social factors such as past experience with government and existing low socioeconomic status being of greater concern than the risks of the technology itself. As people use their cultural frame of reference; such as their values and social interactions; when evaluating an issue, underlying morals or ethics may explain the different reactions in perception studies.

Scope and Methodology

A contract for this study was awarded to The University of Manchester Tyndall Centre. The core aim was to chart the value systems and ethical attitudes of the people and institutions that come into play when they have to make a judgement concerning the underground storage of CO₂; to provide a better understanding of the moral values and norms of the perceiver. The contractor was asked to investigate relationships between populations of different ethical profiles, discussing which are likely to concur and which are likely to be adverse to each other, as well as how external conditions may influence these relationships; to improve communication. Following this aim, the contractor was asked to undertake a literature review from the perspective of the ethical profession, ensuring presentation of the results maintained a neutral and objective perspective.

The contractor has undertaken a preliminary assessment of ethical attitudes to CCS to explore potential issues and lay the foundations to develop a more deliberate approach in future research. This assessment includes a review of selected literature describing the background to and importance of ethical analysis, with particular relevance to CCS, drawing and expanding upon methodologies used in ethical technology assessment to develop an initial scoping ethical matrix designed to support the mapping of the ethical landscape of CCS. The ethical matrix has then been applied, reviewing the ethical principles and positions of some relevant actors based on published and referenceable material. The application of this ethical matrix is not intended to be comprehensive or representative of the CCS ethical landscape, but rather demonstrates a range of responses and how these may be incorporated in such a matrix. A participatory and deliberative process was not possible for this first base scoping study, and following research could pursue this deeper analysis for further understanding.

*Note references are provided in the full report
As the development of the ethical matrix methodology itself is an important component of the results, this is described in the following results and discussion.

Results and Discussion

Literature Review

Environmental decision making is multi-faceted, and environmental management requires consideration of its many dimensions, though it is not uncommon for decision makers to assume science and technology can provide all the answers without explicitly attending to social and/or ethical concerns and such can lead to inequitable solutions by conferring undue power to experts and elites (Dahl, 1989). Science can provide the information needed to identify and explain problems, such as fossil fuel produced CO₂ emissions contributing to human induced climate change, and technology can provide practical measures to solve such problems, for example, storage of CO₂ in geological formations (Stenmark, 2002).

However, scientific or technical knowledge does not provide enough information to develop policy or to conclude whether a particular technical approach should be applied, with ethical implications of a new technology hence being embedded in a decision of whether and how it should be deployed. These ethical implications are considered in new and emerging science and technology (NEST); where NEST ethics identifies the debate around a technology starts with consequential arguments (whether its consequences are desirable or not), followed by criticisms of these arguments which brings in principles of equity and values, and then returns to consequential arguments in response (Swiersta and Rip, 2007), with those promoting or developing a technology find justification. Ethical debates see a move away from the consequentialist approach, from individual ethics to social ethics, considering the social processes (Devon, 2004), hence not only ethical roles of individuals are seen to be important, but also the collective response, requiring an inclusive approach to decision making.

In relation to Carbon Capture and Storage, the current research focus appears to remain on technical feasibility (Leggett, 2010), and contributions of social scientists has predominantly focused on exploring public perceptions possibly as the technology remains in an early stage of implementation; however awareness is growing that ethical and justice-based debates hold implications for the development of fair and effective CCS policy. There are few articles related to CCS and ethics. Leggett (2010) presents an overview of the ethical issues of CCS, specifically framing the debate in terms of liability, legal implications and justice; a presentation made to EU FENCO ERA NET workshop by Spahn and Taebi (2009) also explores justice and CCS; and NGO Corporate Watch evaluates various climate change mitigation options against ‘ethical benchmarks’ (CorporateWatch, 2008).

The moral and ethical dilemmas surrounding CCS are complex, potentially more so than comparable technologies such as renewable, as i) the benefits of CCS can be realised over a limited period, while ii) its effects, or fate of stored CO₂ persist over the long term and iii) it could potential prolong reliance on fossil fuels (e.g. Vergragt et al., 2010). Additionally, there are two concepts related to governance which are fundamental to the study of ethics of CCS: ‘social contracts’ and ‘procedural justice’. Procedural justice aims to improve the decision making process, to ensure all interested parties are full participants in the process, have the ability to express opinions, are treated with respect, are given enough information to make a decision and such decisions are responsive to information and correctable in the face of new information (Maguire and Lind, 2003). Theorists have diverse visions of the nature of social contracts, but they are underpinned by the notion that governance arrangements should be informed by the consent of the people (Weale, 2004), implying human relationships should be regulated by agreements which are achieved through deliberation and discussion (O’Brien, 2009). In the context of climate change mitigation, adherence to social contracts approach poses challenges and raises questions; further complicated when considering a new technology such as CCS; as the State has a contract with the people to protect them against catastrophic

*Note references are provided in the full report
effects of human induced climate change however, citizens have a right to voice their opinions on developments such as CCS. Central to this debate is the issue of justice and fairness, and the notion of justice questions whether sacrifices of the few can be justified in terms of benefits to the many in order to avoid a greater injustice (Rawls, 1971; i.e. in this context local risks of storage, for example, in comparison with climate change). Social justice can be seen ‘as having to do with the distribution of benefits and burdens’ (Dobson, 1998), which acts as a useful tool for framing ethical concerns surrounding CCS. Scientific research can aid the decision making process but value judgements need of be made regarding the benefits and burdens, or advantages and disadvantages.

The shift towards public and stakeholder decision making requires new deliberative processes, and decisions related to the development of new low carbon energy technologies have transformed from a purely technical process to a socio-technical one (Flueler and Scholz, 2004; Flueler, 2006) requiring methodologies for an integrative participatory approach (Cotton, 2009). However, impacts of climate change extend beyond local areas potentially affected by development of technologies and there are implications for both current and future generations. Social contracts have also undergone criticism for not being applied equally (Nussbaum, 2006), and for legitimizing the exploitation of the natural resources for development, progress and economic growth (O’Brien, 2009).

Distribution of benefits and risks, or distributive justice, applies on both spatial (intragenerational) and temporal (inter-generational) scales, and is relevant to climate change mitigation and in particular CCS. As CO₂ must be stored ‘indeﬁnitely’ or for very long periods of time to be effective in CCS, its legacy affects future generations who will be responsible for future management of the storage sites. This issue is in addition to those such as continuation of fossil fuel use in electricity production and associated infrastructure, and of course the issues surrounding not acting on climate change now which will also impact future generations; resulting in the question of balancing the fairness of placing burdens on present generations against those placed on future generations (Wolf et al., 2009).

For CCS the situation is further compounded by low levels of public awareness which complicates the involvement of communities in the decision making process. Upham and Roberts (2010) found if people are given limited information about the technology without the opportunity to ask questions, their perspective is likely to be dominated by uncertainty and risk concerns, resulting in unwillingness to support the technology. As CCS is a technology that is relatively unfamiliar to the public (e.g. Reiner et al., 2006), perceptions of CCS have been shown to be heavily influenced by the provision of information, how CCS is framed (e.g. Shakley et al., 2005) and the level of trust in the information provider (Terwel et al., 2009a, b). Information needs as well as opinions have been shown to vary in relation to socio-demographic variables, attitudinal variables, the content of information provided, and local contingencies such as industrialisation of the area (Oltra et al., 2010).

Ethical Assessment - background to methodology

The two most prominent approaches to ethics are utilitarianism, to take actions that provide the greatest utility for the greatest number balancing net cost and benefits (McKay, 2000) and rights based, decisions made on the basis of whether the act itself is right or wrong regardless of the consequences, contrasting with teleology from which utilitarianism originates. Application of such approaches will not provide categorical answers for the ethical dilemmas presented by CCS, but help to clarify questions and discussion. A rights based approach would be less concerned about the end consequences of developing CCS, focussed on the legitimacy of the process itself; compared with, for example, if CCS was demonstrated to assist in significantly reducing CO₂ emissions whilst maintaining jobs and economic growth then from, CCS could be seen in as a positive development from a utilitarian approach.

*Note references are provided in the full report*
Technology assessment is the study and evaluation of new technologies, through a scientific, interactive, and communicative process that aims to contribute to the formation of public and political opinion on societal aspects of science and technology. Technology innovation is of interest to social scientists as technology is seen as influencing social structures through legal, psychological and physical means, and can reinforce those structures (Scolve, 1995; Bereano et al., 1985). The relationship of technology to social, economic and political groupings was considered a challenge for technology assessment well over three decades ago (Wynne, 1973) and remains so today (Hendriks, 2010). Potential economic, social and cultural impacts has been argued to be treated as significant factors in the implementation of technology strategy, which has led to the proposed constructive technology assessment (CTA), concerned with constructively redirecting the process of technical change by actively organising relationships between developers and users (Rip et al., 1995); a method which is still evolving.

Technology assessment literature, including ethical technology assessment favours neutral, descriptive approaches to elucidate understanding of technologies, whilst engineering ethics favours normative prescriptions and guidelines (Grunwald, 1999); both of which are drawn upon to develop the methodology used in this study: the ethical matrix. Literature from radioactive waste management is particularly useful when examining an ethical Technology Assessment (eTA) matrix (Palm and Hansson, 2006). The ethical matrix uses four ethical principles: autonomy, avoiding harm, beneficence, justice, and uses these to structure specific technology concerns within a deliberative process. The matrix places the ethical principles on one dimension, different stakeholder types on the other, and enters specific issues related to each principle as perceived by the stakeholder. This eTA approach has been applied to a number of case studies including bioremediation (Kaiser et al., 2007).

Limitations have been identified for this approach, relating to the use of the ethical matrix in an inclusive deliberative application, including conflict between maintaining practical simplicity and ethical validity of a small number of dimensions to the matrix, the top-down definition of principles may frame discussions, and it is difficult to account for relationships between stakeholder groups (Cotton, 2009a). However, Palm and Hansson (2006) provide some guidelines for its implementation, including continually assessing ethical implications of the technology by early interaction with actors; highlight conflicts and support open consideration, ensuring discussions are not closed to early as issues need time and space to develop. Cotton (2009) developed a matrix approach to mapping actors’ perspectives against ethical principles and Palm and Hansson (2006) developed a checklist of ethical issues that are common for NESTs. The first step of an eTA is to identify and engage all relevant actors, opening the dialogue for two-way communication and allow stakeholders to present their perspective: participative; followed by deliberative to allow actors to interact through on-going dialogue. Actor selection should identify key stakeholders and organise them into universal types such as local communities, developers, etc; and can include non-human actors such as future generations. The selection of principles should be made to provide ‘the most informative exploration of the issues’ (Cotton, 2009a).

Developing the Tyndall Ethical Matrix

The Tyndall methodology adapts the ethical matrix approach to explore the ethical landscape and support the development of a checklist of ethical issues which may emerge as CCS technology develops. As this is a scoping study, the aim is not to facilitate deliberative engagement amongst actors hence the matrix is less restricted in complexity and size, allowing unusual, emergent, disputed and, ‘fringe’ principles to be included as and when they are required to provide an understanding of the issues. The development of such aims to capture the diversity of perspectives as well as broad principles, and with a global outlook though there is an inevitable bias towards the EU and UK at this stage.

*Note references are provided in the full report*
The ethical matrix has been developed on an Excel spreadsheet provided as a printed appendix to this report, and is available on request. The identification of actors and principles begins with a review of the literature on ethical principles and other material specifically related to CCS. The set of principles have been allowed to develop and change with time; however, the number of actors has been limited to around twenty, selected to capture a variety of perspectives, via a top-down process as a participatory approach is not possible at this stage. Once the selectors and actors have been selected, they are used to structure the matrix (rows: actors; columns: ethical principles) and the individual cells used to detail specific concerns raised by actors related to specific principles. Actor’s reasoning may not be valid from scientific or technical perspectives, but the point is to capture the actors’ perspectives on how CCS complies with or deviates from ethical principles. Statements have been identified from the most up to date material which is publicly available and referenceable that can be interpreted from an ethical stance.

The extent to which the actors’ understandings of the technology conform with or deviate from each ethical principle is coded according to five codes (see Table 1), with each matrix cell coloured with the appropriate colour code.

Looking across the two dimensions of the extended ethical matrix, can support:

- Understanding of various ethical frames of different actors and the emergence of coalitions or conflicts.
- A better understanding of the critical features of the ethical landscape in relation to key principles and the level of congruence of views.

For this ethical matrix, an ethical frame is defined as a specific set of responses to the ethical principles. Where two or more actors share an ethical frame they may be grouped to form an ethical coalition (though within coalition’s internal heterogeneousness would exist). Degrees of colour variance in single columns of the matrix reveal degrees of disagreement on actors’ and coalitions’ positions on CCS with regard to a specific principle. Columns with significant colour variance may be describes as ethical faultlines which may indicate the loci of potential or actual contentions.

Table 1. Coding ethical framings of CCS.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;&gt;</td>
<td>CCS conforms strongly/explicitly with the ethical principle</td>
</tr>
<tr>
<td>&gt;</td>
<td>CCS conforms moderately/implicitly with the ethical principle</td>
</tr>
<tr>
<td>#</td>
<td>CCS neither conforms nor deviates from the ethical principle</td>
</tr>
<tr>
<td></td>
<td>No statement is available in relation to the principle</td>
</tr>
<tr>
<td>&lt;</td>
<td>CCS deviates moderately/implicitly from the ethical principle;</td>
</tr>
<tr>
<td>&lt;&lt;</td>
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The thirteen ethical principles presented in the extended matrix has been built up iteratively, starting with a preliminary list, and when populating the matrix these have adapted and

*Note references are provided in the full report*
changed accordingly to provide a variety of views useful when exploring the ethical landscape of CCS; which is not considered to be exhaustive. The matrix must be flexible, and the analyst must constantly evaluate the extent to which the actors and principles allow the ethical landscape to be captured. Not all actors’ ethical framings can be captured, and a targeted scale is necessary with small scale analyses allowing greater depth. The following describes each of these principles which are grounded in the available literature.

Ethical Principles identified

Four principles of justice have been identified. These are: **Intergenerational Justice** - Does CCS conform with the interests of future generations and is it of greater benefit to less advantaged generations?; **Social Justice** - Does CCS conform with the interest of all social groups, and is it of greater benefit to less advantages social groups?; **Environmental Justice** - Does CCS technology conform with the interest of non-human animals, valued environmental qualities such as biodiversity and ecological sustainability; and does the technology conform with the provision of environmental services for all?; **Financial/Economic Justice** - Does CCS conform with an appropriate distribution of rewards, incentives and liabilities? For wellbeing, there are two main principles: **Providing Benefits** - principle of beneficence and asks: does CCS provide some benefits? and **Preventing Harm** - non-malfeasance and asks: does CCS conform with the prevention of harm to self and others?

For principles concerned with distribution of control, influence and power, there is: **Autonomy** - Does CCS affect actor’s capacity for self-determination and freedom to shape their own understandings and decisions? **Honesty** - Is the information disseminated accurate and thorough, and does it come from appropriate balanced sources? **Accountability** - Does CCS conform with actors being responsible and accountable for the consequences of the risks they take? **Technical/Scientific Competence** - Are scientific, technical and engineering practices and knowledge of a sufficient standard to ensure effective, safe, reliable operation of developments? **Managerial/Regulatory Competence** - Are managerial, regulatory, legal practice and knowledge of a sufficient standard to ensure effective, safe, reliable operation of developments?

Finally, social values describes the way people understand themselves and the way humans understand other things such as people, technologies, practices, biota, environments etc, and the two ethical principles associated with such are: **Naturalness** - Does CCS deviate from or transform social understandings or human values regarding nature, natural processes or human relationships with nature? and **Propriety** - Does CCS deviate from or transform social understandings or human values regarding what is right and what is the right way to progress, deal with problems and search for solutions?

The Ethical Matrix

An example of the ethical matrix is provided in Figure 1, showing four actors and Justice ethical principles. An outline of the structure showing the coded ethical framings is provided in the full report as is an appendix of the full matrix. Cells are left blank where no statements relating to a specific principle are available, which is to some an extent an artefact of a desk based approach though there will be inevitable areas for which actors do not hold strong opinions.

Relatively few responses were recorded with reference to intergenerational implications of CCS. NGOs represented in this matrix raised concerns about future generations inheriting responsibility for storage sites and costs of management of any legacy, but in contrast IEA and the EU have stated regulations can manage handover of these costs; hence accordingly it appears this conflict appears to hinge on management and transfer of responsibility. The energy penalty associated with CCS is also seen in relation to this principle with the greater associated production of CCS increasing the burden on future generations, as framed by

*Note references are provided in the full report*
Climate Action Network. CCS was identified to deviate from social justice principle tend to focus on technical and environmental risk concerns to local communities. The broader social benefits, complying with the social justice principle were typically expressed at a less localised scale.

The environmental justice principle has polarised actors, hinging on whether CCS can deliver significant reductions in CO₂ emissions, and is considered a faultline in the ethical landscape; with contrasting proponents arguments such as risks reducing over time and describing CCS as a ‘revolutionary technology’, in comparison with opponents expressing less confidence in levels of understanding on potential associated environmental risks as well as concerns over increased water usage. Concerns of the financial cost of CCS were identified in general, balanced by premises that CCS has lower costs than resulting impact of emitting CO₂ or implementing alternative means. Key factors of compliance with the financial justice principle appears to hinge on confidence over costs, such as whether it is competitive with other technologies and whether government subsidy is seen as desirable or not. Other statements of compliance with financial justice include job creation and export opportunities; comparing to deviation statements of concerns costs of storage could be passed on to future generations and increased abatement costs of new coal power plants built on a capture ready basis.

*Note references are provided in the full report
### Figure 1. A selected subsection of the developed Ethical Matrix showing four actors and the four justice ethical principles

Principles of wellbeing proved difficult to disentangle without participation of the actors. For the providing benefits principle, debate on CCS compliance revolves around whether CCS provides benefits or whether it is antithetical to the provision on benefits because it promotes lock-in to a problematic technology. A high level of compliance was seen for this principle, and deviation generally concerned the term capture ready could be used as an excuse for new coal power plants, that CCS was not necessary for achieving the 2°C target temperature rise, and labelling as a bridging technology would risk losing time. The preventing harm principle is particularly polarised, suggesting another faultline in the ethical landscape. Deviation and compliance appeared to rest on how emissions reductions associated with CCS compare to alternative investment options against a backdrop of the risk of storage failure.

How CCS relates to autonomy is a complicated multi-level issue with links to managerial/regulatory competence principle. No strong patterns emerge to reflect positions on the relationship between CCS and this principle. Statements associated with the honesty principle show concerns about vested interests compared with potential for demonstration to facilitate knowledge sharing, although few responses were captured. A number of actors framed CCS as deviating from accountability principle, with particular reference to legal and

*Note references are provided in the full report*
regulatory accountability, with no framings of CCS in compliance with this principle. This expresses an ethical problem and that the issue of accountability is currently not adequately addressed.

In response to scientific/technical competence, actors were divided over whether they can trust the technology to deliver on its promises and whether the technology knowhow to ensure the long-term success of the technology can be guaranteed: showing a potential ethical faultline with respect to this principle. In parallel to this faultline is another for managerial/regulatory competence; therefore exposing challenges to the management and regulation of CCS.

A variety of framings of how CCS relates to propriety have been identified, including physical, political and financial/economic. Compliance was found in potential as a cost-effective solution and the notion that CCS returns the carbon to the ground; however there were also many concerns including political propriety hinging on political will to transform energy infrastructure and whether CCS will be used to prolong the use of coal, as well as a need to invest in sustainable clean energy as opposed to CCS, showing deviation from financial propriety. Only one response was captured on naturalness, relating to CCS returning the carbon to where it came from, which is also linked to propriety, though a deliberative approach would generate more on this principle.

Ethical framings related to specific actors are also discussed briefly in the report, though it should be noted the actors’ positions have been drawn from material which were not produced with the purpose of establishing an ethical frame and hence viewpoints may not be entirely accurate of representative of these specific actors (see p39-42 of the report).

**Features of the ethical landscape**

None of the principles identified were associated with unanimous compliance, though the least contentious was that of providing benefits. Accountability presents a key challenge with no compliance observed. Faultlines indicating potentially divisive issues were observed for: environmental justice, preventing harm, scientific/technical competence, managerial/regulatory competence. The issue of scale is important and the matrix reveals possible linkages between principles which should be explored further. Two potential ethical coalitions were identified between i) CCS101, CCSA, ScottishPower and Shell and ii) Coal Action, Friends of the Earth and Greenpeace.

Intergenerational justice appears to hinge on the management of transfer of responsibility for future costs and how great a burden this may be. Potential disadvantages of CCS at a local level may be balanced against global or national advantages, with respect to social justice. Perception of environmental implications of CCS can be characterised at three levels: it will reduce the net environmental impact of fossil fuels, that the risks are manageable or minor and the risks are unknown or unevenly distributed, and tensions between such results in a potential faultline. Caution is needed over exaggerated claims of CCS performance in the context of honesty, and while there may be confidence that managerial and regulatory frameworks are adequate in some nations, challenges remain. Who should bear the costs, how great are these costs, and how does CCS compare to alternative options needs consideration, as do issues over physical, political and financial/economic propriety of CCS.

**Expert Review Comments**

This report is currently under review.

**Conclusions and Recommendations**

The study results indicate the approach used in the production of an ethical matrix can support the exposure and exploration of particular ethical issues that relate to CCS. The methodology captures valuable features of the ethical landscape, but is limited by the nature of an initial scoping study which could be corrected and expanded upon with further participatory research.

*Note references are provided in the full report*
A participatory approach would allow actor validation of the results, and the ethical landscape could be analysed at different scales. Hence, IEAGHG should consider a further participatory study to allow a deliberative approach, particularly given the nature of the study which is the first of its kind, providing the first insights into underlying ethical attitudes towards CCS to understand local and broader perception. Should this methodology be applied wider, receiving responses specifically targeted for ethical framing, the ethical frames and landscape in general would provide detailed insight into CCS ethics and issues necessary for effective communication.

In the presented ethical landscape there are several features which indicate areas of contention, including accountability for which there was no compliance by actors, as well as environmental justice, preventing harm, scientific/technical competence, managerial/regulatory competence; all of which should be explored further to ensure adequate engagement in these areas. The study also highlights caution should be followed in terms of potential exaggerated claims of CCS performance when communicating, and costs, including how CCS compares to alternative options should be further considered in engagement. These preliminary conclusions highlight the potential of the approach.

*Note references are provided in the full report
Introduction
The emissions of CO₂ from power plants equipped with carbon dioxide capture systems are reduced by upwards of 85% compared to equivalent plants without capture. However the full environmental impact of a plant fitted with CO₂ capture will depend also on what changes are induced in emissions of other substances in gaseous, liquid and solid form. Furthermore due to the increase in fuel and chemicals consumption typical for a CCS plant emissions due to the “upstream” and “downstream” processes and particularly those associated with increased fuel use, will also increase. Both these effects need to be taken into account if the technology is to be assessed on a life cycle basis. This study focuses on the changes which are to be expected in the direct emissions, discharges and solid wastes of substances other than CO₂ from power plants fitted with CO₂ capture.

Scope
The study conducted by TNO covers the main technologies for CO₂ capture for coal and natural gas fired systems and includes the three main technology routes of post, pre and oxy combustion. TNO adopted two approaches in making their estimations. The first was to base them on the literature references which include both theoretical predictions and actual measurements from pilot, demonstration and commercial units. The emissions reported in the literature are based on plants with different operating parameters and fuels. In order to obtain properly comparable data a harmonisation step was included in the analysis. The second approach was to use modelling to come up with an estimate of emissions and wastes. This used data on the performance of the various unit operations of the capture processes and thus also to some extent relies on information derived from literature. A key difference between the two types of analysis is that modelling is based on best available technologies whilst figures derived from literature represent average performance which is generally poorer.

Baseline and reference data
Baseline data was collected for three types of power plant without capture
- an Ultra Supercritical (USC) Pulverized Coal (PC) fired steam plant,
- a coal fired integrated gasification and combined cycle power plant (IGCC)
- a natural gas fired combined cycle power plant (NGCC).

Data for 4 CCS plants for comparison with these baselines was collected:
- a USC PC plant with post combustion capture using an MEA solvent,
- an oxyfueled USC PC plant using the CO₂ separation and clean up process of Air Products,
- an IGCC plant adapted for CO₂ capture using Selexol to recover the CO₂
- an NGCC plant fitted with post combustion capture again using an MEA solvent.

A total of 37 references were found in the literature and these were used to populate a database of 176 different cases. However complete datasets could not be generated for all of these cases as the amount of information varied quite widely. This data formed the basis for estimation of emissions using the harmonization approach. It is thus expected to yield “average” values based on current experience. The range of values will also give some indication of the best and worst which might be expected and hence also represents the full range of technologies.
In contrast the modelling method of estimation used a design approach to estimating emissions and for this the researchers chose generally to model “Best Available Technology” (BAT). In practice they have chosen what is considered to be state of the art versions of processes which are considered to be economically applicable and thus may have not have explored the extremes of possible performance.

The results of the analysis finally allow comparison of emissions and wastes against baseline for 4 technologies.

- Coal fired USC Post combustion against coal fired USC
- Coal fired oxycombustion against coal fired USC
- Pre-combustion IGCC against conventional IGCC
- Post combustion NGCC against conventional NGCC

The emissions and wastes which are compared include (where data is available)

Gaseous emissions
- Acid gases
  - CO₂
  - SOₓ (Broken down to SO₂ and SO₃)
  - NOₓ (Broken down in to NO and NO₂)
  - HCL
  - HF
  - CO

- Trace elements
  - Mercury (Hg⁰, Hg²⁺, Hg(p))
  - Trace metals (As, Cd, Cr, Co, Pb, Mn, Ni, Se, Zn, Cu and by class 1,2,3)

- Other compounds
  - Ammonia
  - Chemical degradation products (NB subject of separate report)
  - VOC’s

- Particulates
  - PM
  - PM₁₀

Solid and liquid waste categories.
- Gypsum
- Particulates from ESP
- Furnace bottom ash/
- Coarse slag
- Fly ash /
- Fine slag
- Mill rejects
- Sludges from WWT
- Reclaimer waste
- Activated carbon
- Waste water

Assessment results for each type of emission

Acid gas emissions other than CO₂
Both the reference database and the modeling method suggest almost complete elimination of
gaseous sulphur compound emissions as a result of adding either post or oxy combustion CCS
to pulverised coal steam power plant. Both methods show IGCC plants already have a low
level of emissions because of the syngas cleaning process and even lower levels when CCS is
applied. For the case of NGCC sulphur emissions of the base case are already very low
because of the low sulphur content of natural gas. The modeling shows virtually all sulphur
emissions eliminated.

Nitrogen oxides consist mainly of NO with some N\textsubscript{2}O. Both reference data and models suggest
that NO will not be removed by addition of post combustion CCS and thus NO\textsubscript{x} emissions are
expected to increase slightly roughly in proportion to the increased fuel use. Average values
from the literature show an increase somewhat in excess of this. Modelling suggests that some
N\textsubscript{2}O will be removed by the absorption unit but as most of the NO\textsubscript{x} is in the form of NO there
will be an overall increase.

For IGCC emissions are solely due to NO\textsubscript{x} formed in the gas turbine. Fuel efficiency is
reduced which would lead to increased emissions. The modelling caters for some advances in
NO\textsubscript{x} control for hydrogen burning which roughly counterbalance increases due to reduced
efficiency. Expert reviewers are expecting up to 99\% destruction of Nitrogen oxides in the
reactors of the clean up process. However any NO which passes into the cryogenic separation
section will partition into the inert vent stream and thus be emitted.

For oxy combustion modeling currently suggests that NO\textsubscript{x} emissions will be significantly
decreased in the clean up process. The literature shows wide variation and suggests only a
partial reduction. This because the oxy combustion CO\textsubscript{2} clean up process has undergone rapid
development in the last few years. The harmonized reference data is using averages and the
data shows variations from complete to limited reduction.

HCl, HF and CO emissions reductions were considered only through modeling and only for
coal fired USC PC steam systems. The strongly acidic components HCl and HF are predicted
to be reduced by 95\% in the case of post combustion and to be completely eliminated in oxy
combustion CCS systems. CO is not expected to be absorbed in post combustion. The report
gives no evaluation of the CO emissions from oxycombustion.

The study shows CO emissions from IGCC with and without CCS as virtually the same based
on literature references. However given that in CCS nearly all CO is removed by the shift
reaction this conclusion is questionable.

**Trace elements**

Trace elements usually encountered are the metals Hg, As, Cd, Cr, Co, Pb, Mn, Ni, Se, Sb, Zn, Cu.
These are divided into three classes according to the way they partition between gaseous
emission and solid waste. Hg and Se are considered volatile and fall into Class 3. As, Cd, Sb
and Pb are semi-volatile falling into Class 2 and the rest are considered non volatile and fall
into Class 1.

Information on the removal of these components by the CCS processes is limited. For those
CCS systems which pass flue gas through a solvent system a conservative assumption that only
20\% of classes 1 and 2 would be removed has been made. This is roughly equivalent to the
increased fuel usage so that trace metal emissions in these classes would be unchanged.
However given that these materials tend to partition to the solid phase it might be expected that
the additional contacting in absorber columns and direct contact coolers might make bigger
reductions. In order to verify this it will be necessary to make measurements of these components in flue gases from CCS plants.

The effect of MEA scrubbing on mercury depends on the oxidation state. There is evidence that Hg^{2+} is absorbed in MEA and in modeling a removal of 76% has been assumed. Elemental mercury is not chemically absorbed in MEA solutions and a low reduction factor of only 8% has been assumed. Since about ¾ of the mercury is typically present as elemental mercury there is only a small reduction in emission concentration in the absorber which will be offset by the increased flow. Again more accurate measurements of emissions and build up in the solvent are needed to determine the partition effect.

**Particulate Matter**

Particulate matter is reduced by several processes within power plants. The final reductions are mainly achieved in the Electrostatic Precipitator (ESP) and the Flue Gas Desulphurisation unit (FGD), if either are fitted. Without these units reliance is placed on drop out in the boiler at various points and removal by filtration. The literature gives a confusing view of how particulate emissions will be affected suggesting an increase whereas modeling assumes that where an absorption unit or direct contact cooler provides additional liquid gas contacting a reduction of 50% of particulates would occur. Thus even allowing for the increased fuel use there should be a net reduction in particulate emissions. There is a need to better understand why the literature results are an average higher and also for a better measurement of the effect of additional gas liquid contacting equipment on particulate emissions. Oxycombustion should exhibit zero particulate emissions since the only remaining gaseous stream is a small flow of inerts from the CO₂ clean up unit which is unlikely to contain particulates as it will have passed through several gas liquid contacts in the clean up reactors and the cold box. Literature also shows almost but not quite complete elimination of particulate emissions from oxy-combustion plants.

**Other substances**

Ammonia is emitted from plants without capture if SCR is installed and there is any ammonia slippage. The harmonized data shows a small average ammonia emission for pulverised coal plants without capture. The data for NGCC plants without capture suggests very low average levels probably because it is less common to add SCR to such plants. Ammonia is a volatile degradation product of plants using MEA (and also for plants using other amines). The literature thus suggests a substantial increase in Ammonia emissions from Coal fired USC CCS plants. No data is available for NGCC plants with post combustion capture but similar effects could be expected. Ammonia emissions were not estimated by modeling and this and other MEA degradation products is being addressed in a separate IEAGHG study on chemical emissions from post combustion capture plants. Ammonia emission from IGCC plant were not evaluated but expert reviewers suggest that these are absent since they are already removed upstream of the acid gas removal system in the wet scrubbing system of such plants.

**Solid and liquid waste**

For the coal fired cases the amount of solid waste increases more or less in line with the increased fuel usage. Sludge from waste water treatment increases similarly. Gypsum production in the post combustion capture case may increases slightly more than this due to deeper sulphur removal. On the other hand there is no gypsum by-product in oxy-combustion since the SO₂ is removed as Sulphuric acid in solution. NGCC does not produce any ash wastes.
Reclaimer waste and a small amount of spent activated carbon from solvent clean up are two new wastes emanating from post combustion plants fueled either with gas or coal. Oxy-combustion plants remove mercury using mercury guard beds which may use activated carbon or pre-sulphided adsorbent. This material may also be used in base line coal and IGCC plants to reduce mercury emissions. However no data on the quantities is reported in this study.

There is a significant increase in the amount of waste water production from post combustion coal plant due to the condensation of water out of the flue gases. No information was included in the study on the composition of the waste water streams expected from oxy-combustion. Experts pointed out that oxy-combustion process will produce a waste water stream containing sulphuric and nitric acids along with some mercury. Before discharge this stream will need to be treated for example by neutralization with caustic soda and for mercury extraction. Development of the clean up process for this stream is ongoing.

Overview of changes

Full details of the expected emission levels evaluated by the two techniques, (modeling and harmonization of figures published in literature) with and without CCS are included in the main report. Set out below in the form of a pictorial chart is an over view of the changes to emissions and wastes which each of the capture technologies will cause when applied to the baseline power plants. The indication is of the relative magnitude of emissions and wastes and does not indicate the actual size of the emissions. For some categories of emission the baseline plant already has essentially zero emissions and this is indicated by a cross where this is the case. A distinction is made between changes which are certain and those which are not. The arrows indicating the change have a dotted outline/contain a “?” symbol where there is currently uncertainty. Further work is needed to clarify all changes which are shown as uncertain. Most notable is the almost complete elimination of gaseous emission in the oxy-combustion process. Post combustion processes lower most emissions substantially but the exact extent is still subject to uncertainty. However there are small increases in NO and an introduction of a potentially substantial ammonia emission. There are also potentially other chemical emissions which are subject of a separate report. The extent of the ammonia emission is dependent on the additional scrubbing technology which is eventually deployed downstream amine absorbers.

The most notable change in solid/liquid wastes is the appearance of a new liquid waste from post combustion processes in the form of a stream of degraded solvent from the amine reclaimer. For oxy-combustion a new water stream containing sulphates and nitrates possibly containing some mercury is expected to be produced (not shown on the chart). Exactly how benign this stream can be made is not yet known. Ash from all of the coal fired processes increases in line with the increased fuel consumption.

Conclusions

Overall gaseous emissions will in general be reduced when CCS is applied. Of the three main processes oxy-combustion is expected to approach near zero emissions for most substances. All CCS processes produce more solid/liquid wastes and careful attention needs to be given to the onward processing and disposal of these. There do not appear however to be any reasons why completely safe and environmentally benign methods for handling these waste should not be found.
### Changes in emissions and wastes when CCS is applied

<table>
<thead>
<tr>
<th></th>
<th>NGCC Postcombustion</th>
<th>IGCC pre-combustion</th>
<th>Oxycombustion</th>
<th>Post combustion</th>
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<tr>
<td>SOx</td>
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<td>N2O</td>
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<td>Increase</td>
<td>&lt;&lt;Decrease</td>
<td>Increase</td>
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<tr>
<td>HF/HCL</td>
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<td>Increase</td>
<td>&lt;&lt;Decrease</td>
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<tr>
<td>CO</td>
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</tr>
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<td>Increase</td>
<td>&lt;&lt;Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td>Hgp</td>
<td>&lt;&lt;Decrease</td>
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<td>&lt;&lt;Decrease</td>
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<td>&lt;&lt;Decrease</td>
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<tr>
<td>Reclaimer waste</td>
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<td>Increase</td>
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<tr>
<td>WTU sludge</td>
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<tr>
<td>Ash</td>
<td>&lt;&lt;Decrease</td>
<td>Increase</td>
<td>&lt;&lt;Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>&lt;&lt;Decrease</td>
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<td>&lt;&lt;Decrease</td>
<td>Increase</td>
</tr>
</tbody>
</table>
Introduction

Amine based post combustion CO\textsubscript{2} capture technology is widely seen as a promising option for reducing atmospheric emissions of CO\textsubscript{2}. Great efforts have been made to develop and demonstrate this technology. However less attention has been given to the likely emissions of amines and their degradation products, some of which are well known to be harmful to human health and the environment. The components of concern do not currently figure in the emission slate of power plants. Standards and legislation are thus not fully developed for their control, particularly considering the scale on which CCS plants may be deployed. A full understanding of the nature of the likely emissions and the limits which need to be imposed is necessary so that appropriate improvements in the capture process can be made to protect human health and the environment from adverse impacts. A study was thus commissioned with CSIRO, Australia to identify the chemical species likely to be emitted, estimate the levels of emission expected from the present generation of capture plant designs, assess what emission limits might be applied and research the process modifications needed to meet these limits.

Estimating chemical emissions

The report evaluates the emission of amine based inhibitor-free solvents, particularly MEA, ammonia and amino acid salt based solvents, and their degradation products. MEA is chosen for more detailed assessment as this is currently the major constituent of most absorption solvents used in post combustion capture systems. Chemical emissions and wastes from the process fall into three categories.

(1) physical entrainment and evaporative loss of amine and its degradation products into the gas streams,
(2) discharge of organic degradation products, heavy metals and heat stable salts in the liquid waste streams,
(3) fugitive emissions during plant operation and handling of chemicals.

The report only considers the first of these.

Estimates of emissions were made in two ways. Firstly values mentioned in extensive literature on the amine based capture processes were examined enabling some idea of the likely range of emissions to be assessed. Secondly a simulation of the process and the complex degradation reactions which occur has been made in order to provide an alternative assessment. Sampling and analysis of traces of chemicals in flue gas is difficult and most laboratory, pilot and demonstration work on the capture process have tended to concentrate on the technical rather than environmental performance of the process. As a result there is both wide variation and uncertainty in the estimates.

Baseline PCC processes

Two processes based on use of MEA without other additives were chosen as base cases for evaluation of emissions via simulation. These were a coal fired ultrasupercritical steam plant and a gas fired combined cycle plant based on studies carried out previously for IEAGHG. The processes use a single stage of water wash after the absorber and for simulations cooling
was applied so that flue gas exit temperatures were reduced to 45°C. This choice is important because the levels of volatile compounds are greatly affected by temperatures in and after the absorber. Degradation of MEA proceeds via two main pathways, thermal degradation and oxidative degradation both of which have been considered in this study.

**Modeling of Amine degradation and related emissions**

Modeling of the process was undertaken using ASPEN plus and was divided into two elements. The first was to build a steady state simulation of the process and the second was to model the progress of the known chemical degradation reactions with time. It is not possible to use the steady state simulator for the time dependent reactions. Instead these were simulated in two stirred tank reactors in series one for the thermal and one for the oxidative reactions.

As the solvent in an MEA absorption plant degrades some degradation products build up, for example heat stable salts, and these are removed from a slip stream of solvent either continuously or batch wise in a reclaimer. The reclaimer recovers amine and concentrates the degradation products for disposal as waste. If the batchwise operation is chosen the composition of the solvent gradual changes until the reclaimer is re-started. This is generally every few weeks. The simulation was based on batchwise reclamation as follows. The stirred tank reactors were allowed to run for up to 6 weeks and compositions of solvent derived at the end of each week. These compositions were then used in the steady state simulator to calculate emissions at that point in time.

Simulation runs were made in which it was assumed that no droplet carryover was occurring and also with carry over set at the worst prediction for demister performance found in the GPSA handbook namely 0.13M³/million m³. This is a very high figure but enables a worst case scenario and the split between vapour and liquid carryover effects for each component to be estimated.

The reactions modelled were based on the open literature. However not all reactions could be modelled and not all components were available in the ASPEN database. Where this was a limitation the reactions either had to be omitted or in the case of a missing component data a component with similar volatility was chosen for the steady state simulator. There were also some reactions, one notably involving DEA, where there are differences of opinion as to what reactions are occurring.

**Literature data on emissions**

The report contains extensive data and references both on measured and estimated emissions but also on the reactions involved in degradation. The chemical pathway, equilibrium and kinetic data chosen for modelling the degradation reactions is presented. In addition the estimated and measured emissions from a number of laboratory investigations and demonstration plants are reported.

**Estimated emission levels from simulation**

The results from simulation are different but not in conflict with those which have been measured in practice. Even though very pessimistic assumptions have been made about droplet carry over there are some measurements which are higher than simulator predictions. On the other hand the effect of droplet carry over is often not dominating particularly for the more volatile components. The report summarises the expected ranges for both the USC coal and NGCC cases as a table of maximum and minimum expected values for all compounds expected to be detectable. The maximum values calculated in the simulations are shown below.
Maximum emission levels from simulations of coal and gas fired MEA based post combustion capture plants

<table>
<thead>
<tr>
<th>Component</th>
<th>mg/Nm³ dry CO₂ lean flue gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEA</td>
<td>5.5</td>
</tr>
<tr>
<td>NH₃</td>
<td>1.14</td>
</tr>
<tr>
<td>DEA</td>
<td>0.254</td>
</tr>
<tr>
<td>FORMALDEHYDE</td>
<td>0.314</td>
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<tr>
<td>ACETALDEHYDE</td>
<td>0.326</td>
</tr>
<tr>
<td>ACETONE</td>
<td>0.422</td>
</tr>
<tr>
<td>METHYLAMINE</td>
<td>0.26</td>
</tr>
<tr>
<td>ACETAMIDE</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Three principle heavier degradation products Oxazolidone, 1-(2 Hydroxyethyl) imidazolidone-2 (often abbreviated to HEIA) and N-(2-Hydroxyethyl)-ethylenediamine (often abbreviated to HEEDA) which have slight volatility were found to have extremely low emission levels in the simulation. The single stage water wash is very effective in removing heavier components.

Emission levels from literature
The report includes data from a number of references which show that emission levels which have been measured have been both substantially higher and lower than the simulated values. In some cases the exact process conditions are not available and perhaps the best general conclusion that can be drawn is that there is potential for chemical emissions but that with the current typical one stage water wash these will be low but not negligible providing the water wash is conducted close to ambient temperatures.

Of particular interest are references in the literature to the formation of nitrosamines. The formation of these was not included in the simulation as the exact mechanisms are not known. Nitrosamines have been detected in the solvent by some researchers but the exact mechanism of their formation is not agreed. Nitrosamines are known to be a class of compound which can be highly carcinogenic. Their formation is thought to be due to reactions of NOₓ with amines but MEA itself is not thought to be the precursor of a stable nitrosamine. The nitrosamines detected are N-nitrosodiethanolamine (NDELA) and nitrosodimethylamine (NDMA). Diethylamine (DEA) was also detected in the solvent and may be a precursor although the origin of the DEA is uncertain. A small amount of the nitrosamine (NDELA) has been measured in the Trona plant in California at the level of nearly 3 µmol/ml but this level may however only have been reached after a long build up period. To estimate whether this would result in an emission the simulation was run with this amount added to the solvent. However this component is not in the library of ASPEN so the lighter dimethyl nitrosamine was substituted.

The results of the simulation showed between 2 and 6 mg/Nm³ mainly due to its vapour pressure in the exhaust flue gas from the water wash. Thus with a single water wash it is potentially possible for nitrosamines to be emitted until proven otherwise.
Processes to reduce chemical emissions
The processes currently applied are cooling, demisting and water washing. The reason that a single stage water wash is not effective is that the water has to be circulated and the chemicals which are washed out build up. They then exert a vapour pressure and the water with contaminants can be entrained as droplets. The simulations show clearly the value of cooling the outlet stream as far as possible and one good way to do this is to apply intercoolers in the absorber column so that the top temperature is kept low.

Increasing the number of scrubbing stages is an option but references suggest that while this further reduces the emissions levels it is only partially effective. Washing with an acid solution on the other hand appears from literature sources to be rather effective and this is because most of the contaminants react with acid. A range of choices for the acid are available through strong inorganic acids, weak organic acids even to carbonic acid itself. The weaker acids might allow captured MEA to be regenerated.

Other more exotic measures were investigated including exposure to UV radiation, adsorption on solid beds and, cryogenic cooling. UV radiation appears to be an option for dealing with Nitrosamines as it causes their decomposition. Solid beds would need to be regenerated by vacuum rather than pressurised operation or temperature swing because parasitic energy losses would otherwise be unacceptable. A major difficulty would be selecting an active absorbent which was not unduly affected by the water vapour in the effluent fluegas. It would certainly not be practical to dry the entire flue gas stream. Limited cryogenic cooling could improve emissions marginally as lowering temperature is already known to improve the effectiveness of water scrubbing. However it is costly since the whole stream must be cooled although some energy could be recovered in a regenerative heat exchanger. Cooling could not go below the freezing point and, unless reheated, the flue gases would no longer be buoyant.

The report examines the performance of various types of demister available on the market. Demisting is particularly important for complete removal of MEA as this is the component which will have the highest concentration in the wash system liquids. Three mechanisms are employed for demisting. Impingement whereby droplets collide with a surface on which they subsequently coalesce and drain away, inertial devices where gas follows a tortuous pathway which liquid droplets cannot because of their inertia and devices based on Brownian motion where very fine droplets impinge on a surface due to their irregular Brownian motion. The devices are described in some detail in the report which shows several examples of how separation efficiency correlates with droplet size. The most appropriate demisting device is shown to be the Swirl Mist Eliminator (SME). This combines high efficiency, good liquid drainage properties (important during overloading or process upsets) and space requirements which allow for it to fit inside the diameter of absorber and wash columns. Although they have no moving parts they are more complex and likely more expensive than wire mesh and corrugated vane type demisters.

Emission standards and legislation
The report contains a comprehensive overview of the various directives, regulating bodies and emission standards which apply. This reveals that in general emission levels for the new chemical substances which might be emitted have yet to be established. Environmental and health data from industrial uses might help in this process but is in itself not a sufficient basis for defining emissions levels. In the case of compounds which are know or suspected carcinogens regulation is most likely to be to adopt Best Available Techniques (BAT) rather than to set an emission standard. Often no numerical standard is set for carcinogens as it is not possible to define a lower safe limit.
The industry may come up against three main types of emissions limitation. The first is simply the acceptable concentration in the air to safeguard human health. The second is the imposition of upper limits for the total annual emission industry of a substance in a country or region. For example ammonia is regulated in this way in Europe. The report however shows that the potential emissions from post combustion amine plants of all major sources of CO₂ were captured would only contribute around 5% of this allowance. The third is limitations due to cumulative and instantaneous affects on plants and their habitats. For example nitrogen and sulphur emissions may be limited to avoid eutrophication and acidification.

Given that the acid wash process appears to be rather effective and that high efficiency demisting devices are available a conclusion could be that these or similar enhanced measures will become the de facto standard when large scale capture plants are deployed. The addition also of a UV process to ensure complete elimination of nitrosamines is in reserve in the unlikely event that the acid washing and high efficiency demisting processes are insufficient.

New solvent systems and their emissions
The likely emissions from two alternative systems were examined. Amino acid salt solutions have relatively fast rate of CO₂ absorbion, higher CO₂ selectivity, high stability towards oxygen, very low vapour pressure, high biodegradability and favourable binding energy but lower CO₂ absorbion capacity than MEA solution. Due to these favourable properties, the amino acid salts have been deployed for commercial scale acid gas removal processes in the past, such as the Alkazid process. Recently, with the increase in interest in Post combustion capture, Siemens and BASF have developed new processes for CO₂ capture from power stations. As reported in the literature, these processes produce an insignificant amount of degradation products and have lower emissions to atmosphere.

Aqueous ammonia processes have also been claimed, in the literature, as an effective separation with potentially low emissions despite the fact that ammonia is toxic and corrosive. The main attractions are claimed to be ammonia’s estimated 3 times more CO₂ uptake capacity, relatively higher stability, no interference from SO₂ and NO₂ on the ammonia capture efficiency, and less corrosive nature as compared to MEA. It is also reported in the literature that the chemical regeneration energy required by ammonia is about three times less and this is reflected in reduction in capital and operating cost by about 15% and 20% as compared with MEA. Researchers are currently trying to reduce ammonia losses and emissions. It is important that the performance of ammonia process is thoroughly evaluated to ascertain the operating costs, energy consumption and emissions prior to any construction of commercial scale plant is considered.

Both amino acid salt and aqueous ammonia processes seem to have an insignificant extent of solvent degradation and the base case emissions of ammonia is reported to be below 1 and 10 ppmw, respectively. There is no report on the list of any other degradation products (than ammonia) formed in these processes. On application of acid wash the emissions from these processes could be brought down to near-zero. UV methods are probably not required for these processes as there is no report on nitrosamine emissions from them. However the acid treatment process, recirculation or disposal of acid and salt have to be further studied in the laboratory prior to implementation at larger scale.

Conclusions
The main conclusions of the report can be summarized as follows:

- Detectable levels of lighter components will probably be emitted to atmosphere from amine based capture plants employing single water wash technology.
• Emissions to air of heavier degradation products will be at well below detectable levels.
• Application of an additional acid wash is an effective way of eliminating emissions of the lighter components.
• The preferred choice of demister seems to be the Swirl Mist Eliminator (SME).
• Emissions standards are not yet set for many of the substances which are likely to be emitted.
• Stringent emissions standards and regulatory requirements to adopt best available techniques can be expected particularly so if even the presence of trace amounts of known carcinogens are confirmed.
• More research into emissions and their measurement is required.
• Regulatory authorities have much work to do to create appropriate emission standards which can be applied to MEA based capture processes.
• Some alternative solvents have lower emissions but may still need to apply similar additional clean up steps.
This study was approved by members at the 38th ExCo meeting and follows on from a similar study looking at the application of CCS in the cement industry. The study is undertaken with M EFOS of Sweden. A draft report of the study was received in June 2011 and the final report is currently being prepared.

An overview will be prepared for member’s reference once the final report is complete. A presentation giving an update on the outcomes of the study will be given at the 40th ExCo meeting.
INTRODUCTION

A shorter format summary report of each of the storage networks is being tried this year, and this paper presents the summary of these reports for the Modelling, Wellbore Integrity, Monitoring and Risk Assessment meetings.

A key theme arising from all the networks is the improvement in application and understanding of various techniques, arising from more real experience and results from real projects. We are also seeing good examples of risk assessments which integrate all the network disciplines, with specific examples being shown by Shell from two of their current projects. These also reinforce that the design of monitoring programmes should be based upon the risk assessments.

Each of the networks also considered the relevant issues from the UNFCCC Decision at Cancun on CCS in the Clean Development Mechanism, which fed into the UNFCCC workshop in September.

COMBINED MEETING OF THE IEAGHG MODELLING AND WELLBORE INTEGRITY NETWORKS

This combined meeting of the IEAGHG Modelling and Wellbore Integrity networks was held from the 27th to the 29th of April 2011, in Perth, Australia, hosted by Curtin University and the University of Western Australia and sponsored by Shell, Chevron, Curtin University, the University of Western Australia and the Government of Western Australia Department of Mines and Petroleum. Seventy five delegates attended the meeting, representing 9 different countries.

The three day event looked at the complexity of models, real projects (local and international), geomechanics and wellbore integrity, followed by a field visit to the site of the planned Collie Southwest CO2 Hub. The agenda and presentations from the meeting are available in the network members’ area of the IEAGHG website (www.ieaghg.org).

A key point recognised during the meeting was that modelling is site-specific and should be done on a project-to-project basis. Simplified models can be useful as they allow exploration of a wide range of scenarios on a short time-scale - but this may not improve the overall understanding of the reservoir. The assessment of caprock systems is highly site-specific and has many knowledge gaps in which further research is needed. There is also a noticeable lack of data on reservoir stress paths – again, an important issue when looking at injection and geomechanics, and there is a need for further 1D and 2D pressure, temperature and flow control experiments when modelling leakage rates.

There is a trust issue between regulators, operators and the public – more needs to be done in bridging the gaps between all stakeholders, public or otherwise. Modelling should be put into a better context to perhaps help with this communication issue - modelling doesn’t necessarily represent reality but is crucial to guide monitoring and risk management strategies. Mitigation is a crucial component of risk management strategies that requires early consideration in project planning.

Research into wellbore integrity issues continues to improve our understanding of the performance of cements and other well materials in the presence of CO2, and highlights the
importance of field data from projects such as Weyburn-Midale to calibrate theoretical and laboratory studies.

A crucial point that was raised at many points throughout the meeting is the ongoing need for further, large scale storage demonstration projects to calibrate modelling science and further inform wellbore integrity issues.

**Monitoring Network**

The 7th IEAGHG monitoring network meeting was held in Potsdam, Germany and hosted by the GFZ (German Centre for Geosciences). Sponsors were GASSNOVA and Vattenfall.

The theme for this year's meeting centred on the 3 criteria for transfer of responsibility in the EU directive:

- Actual behaviour of the injected CO₂ conforms with the modelled behaviour
- No detectable leakage
- Storage site is evolving towards a situation of long-term stability

Throughout the meeting the first two criteria from the EU directive were considered and discussed, and the conclusions and summary are:

**Actual behaviour of the injected CO₂ conforms with modelled behaviour:**

Seismic detection limits have been discussed for Otway, Ketzin and Nagaoka and it is clear that repeatability is key to be able to compare results over time and with modelling data. At Ketzin, monitoring results show that the plume migrated to a lesser extent than expected from the initial modelling due to the heterogeneity in the subsurface. This is within expected limits, however, history matching has been carried out since to improve the model. It will always be the case that the models improve with more information, but a range of models may show the expected plume limits. Breakthrough was also later than detected, which was unexpected, but not negative. This all shows how important it is to define monitoring and performance indicators.

**No detectable leakage**

This was mostly considered in the session on monitoring of the outer envelope. Traditional techniques include soil-gas and atmospheric monitoring as well as monitoring of shallow water sources. It is very important to capture the full natural variation of CO₂ and associated compounds in the baseline. There are issues with sampling and what points to measure. There are also areal methods to detect possible leakage, but these may not be able to quantify the CO₂, necessitating a 2 step approach to first locate the leak, then quantify it. A new process based approach to soil monitoring was also presented, for which a baseline is not needed as the amount of exogeneous CO₂ is derived from the ratios of CO₂ to other gases.
The excellent work and results from monitoring at the Ketzin project were highlighted throughout the meeting, and the Network visited the Ketzin project site.

Overall, there was much progress being made, with the increasing amount of monitoring results becoming available and providing good learnings and experiences from real projects. The use of risk assessments to define monitoring programmes was also demonstrated for real projects.

**Risk Assessment Network**

In June the IEAGHG Risk Assessment Network held its 6th network meeting, hosted by BRGM in Pau, France, sponsored by BRGM and IPAC-CO₂.

The benefits of including biosphere risk assessment and community asset values was discussed and demonstrated by URS. Induced seismicity was covered by ETH-Zurich, highlighting lessons learnt from cases of induced seismicity connected to the exploitation on deep geothermal energy, with discussions on expectations for large-scale CO₂ storage.

The session on Understanding Potential Groundwater Impacts, with presentations from Los Alamos National Laboratory, BRGM, GCCSI and BGS, highlighted the geochemical and hydrogeological heterogeneity present in the subsurface which is difficult to characterise and highly site specific. Greater observations are needed as is data integration from natural analogue, controlled release and laboratory experimental studies. In-situ CO₂-water-rock interactions may not be as important for groundwater impacts as reactions elsewhere, for example as a result of migrated brine interactions;. Buffering and scavenging processes may control trace element mobility, and microbial activity can have both physical (e.g. porosity) and chemical impacts (e.g. catalysis of mineral reactions) hence should be considered in CCS operations. BP highlighted the BP quantitative risk through time concept and tool, integrating changes in the CO₂ storage system relative to risk mechanisms through time and space. Shell presented an update of the QUEST project’s risk assessment techniques and their use to develop the monitoring programme.

The Network visited the TOTAL Lacq-Rousse project, including the oxycombustion capture site and the storage site.

Key recommendations from the meeting included the reinforcement that monitoring programmes should be risk-based, the need for translation of risk assessment outputs to a common easily understandable language; the need for benchmarking of outputs of methodologies; community asset values being included in risk assessment, further investigation into microbial influences, consideration of induced seismicity for larger projects, the importance of baseline data, and further work is needed on the evolution of risk through time.

Presentations from the Workshop and the detailed agenda are available on the IEAGHG Risk Assessment Network member’s website, see [www.ieaghg.org](http://www.ieaghg.org).
Introduction
The third meeting of the IEAGHG high temperature solid looping network was held from 29th August to 1st September at the Technical University of Vienna. It was held in parallel with a meeting of the IEA Fluidised Bed Combustion implementing agreement and the International Conference on Polygeneration. This gave the 108 + delegates who attended the network meeting the opportunity to meet with those engaged in these other related areas. For this meeting a considerable effort was made to attract members of the Chemical Looping Combustion (CLC) research community which has been less represented at past meetings where calcium oxide looping (CaL) cycles for CO₂ capture have tended to dominate. This should be a useful change as both processes use similar dual fluidised bed hardware and there is also emergence of hybrid schemes employing both types of reaction. Also several of the larger test facilities are now set up to test both CLC and CaL processes using the same equipment.

This year the meeting was extended to 3 days with inclusion of a site visit to two fluidised bed combustion biomass facilities south of Vienna. One facility also had extensive experimental facilities testing Fischer Tropsch synthesis and mixed alcohol synthesis from the gas leaving the biomass gasifier.

Highlights of progress
This year saw the first results presented from larger MW scale demonstration plants. Further units will start up shortly and thus more results are expected in the coming year. At the present time the operating campaigns are quite short and all recognised the need to build up experience with longer periods of stable operation.

Development of both sorbents and oxygen carriers is ongoing. For sorbents the emphasis has now shifted from proving that activity can be maintained for sufficient cycles to be economic to optimising the preparation and re-activation processes to extend sorbent life. It was also encouraging to see work presented on using the technology in the iron and steel industry. In particular it seems very likely that spent sorbent can be used as feedstock for cement.

It was also evident that designs for CaL systems are now entering the third generation of process refinements now that the basic system is better understood. Also as mentioned in the introduction more new schemes in which CLC, CaL and sorbent enhanced reforming in both fluidised and fixed bed arrangements are being developed.

CLC is also entering a new phase of larger scale extended testing now that around 16 demonstrations of various sizes have been built accumulating so far some 5000 hours of collective operation. Most notably this has been done with no failures. A key development in CLC is the use of so called CLOU materials for combustion of solid materials such as coal. Chemical Looping with Oxygen Uncoupling implies that at the temperature conditions of the fuel reactor the oxygen carrier exerts a significant partial pressure of oxygen so that combustion does not have to rely solely on gas/solid and solid/solid reactions between the gases/char and the carrier. Copper oxides are the best example of this type of carrier and one presentation showed how complete burn out of coal is now demonstrated.
The meeting identified a number of important emerging areas for research and development. High on the list is measurement of emissions. There is some concern particularly with CLC that trace metals may be emitted. A key to progress remain enhancing the performance of naturally occurring materials, mainly the limestone but also engineered sorbents and oxygen carriers. In order to support industrial application there is a need for reliable testing and characterisation methods for these materials. Work is already ongoing on this issue at a few institutions. More work needs to be done on the retrofit and integration of the process into power plant and also cement and steel plants. To date much of what has been done has been optimisation of the basic circulating loop. In particular a large amount of heat contained in the hot CO₂ and depleted flue gas stream has to raise steam or be otherwise used in the power plant. Whilst the general principle of how to do this is established the detailed layout of heat recovery coils and steam and water flows needs further work.

CO₂ quality is an issue which needs further study. The extent to which further clean up can be avoided is uncertain. The quality of raw CO₂ may be improved by process improvements in the main circulating loop. Alternatively processes to further concentrate CO₂ could be employed. The trade off between enhancing the capture process and applying further clean up needs to be better understood.

The time has also come for a better understanding of the economics and cost of the process as well as checking and fully understanding the waste disposal and life cycle impacts. The costs are needed to assess viability of commercial scale units. Confidence that costs are competitive with other capture technologies is essential in the process of getting funding committed to larger scale significantly more expensive demonstrations.

For the first time the meeting covered issues of funding and commercialisation for larger scale demonstration. The EU commission outlined future funding arrangements which were in the pipeline applicable to the technology. Researchers from New Zealand showed how they had concluded work on a hydration process for reactivation of deactivated sorbent and were offering this for commercial development. An opportunity first identified last year in the Alberta oilsands for using CLC to generate steam from gas for Steam Assisted Gravity Drainage SAGD was confirmed as having considerable potential at a number of sites and has a real competitive advantage over other processes. Significant research funding may become available to develop this application.

Organisational matters.
This year saw a further increase in numbers of submitted presentations and posters as well as delegates. For this reason two of the sessions were held in parallel. The need for a format change was discussed but consensus was that a two day meeting should remain the format and that limited parallel sessions could be used. As the number of posters rises so more time should be made available for the poster session. The site visit proved very popular and in principle will be retained if a suitable relevant facility worth visiting can be identified. This year the organisers were again able to attract some sponsorship which has enabled the basic fee for the event to be kept low.

Tsinghua University confirmed their earlier offer to host the 2012 meeting at about the same time of year. The following year a tentative proposal to hold the meeting in Alberta was tabled.
1ST POST COMBUSTION CAPTURE CONFERENCE (PCCC1)

This was the first time the Post Combustion Capture Network had been held in conference style as a result of the growing attendance and interest in presenting at the network meetings.

Held in Abu Dhabi 17th-19th May, and attended by some 115 delegates from 20 counties. The conference hosted 47 presentations in two parallel sessions and a well attended poster session with 20 contributions over 3 days.

The conference was hosted by Masdar with sponsorship from Doosan Power Systems, Gassnova, EnBW and Mitsubushi Heavy Industries.

A presentation on the key outcomes will be given during the ExCo
Following the success of OCC1 Cottbus, Germany 7th-9th September 2009, the 2nd Oxyfuel Combustion Conference (OCC2) was held in Yeppoon, Queensland, Australia 12th-16th September.

Despite the remote location 203 delegates attended from 23 countries. The conference saw 6 keynote talk, 3 plenary sessions and 103 presentations delivered in 18 technical sessions (3 parallel sessions were required to accommodate the presentations). The poster session was well attended with 30 posters presented.

The conference was organised by IEAGHG, Callide Oxyfuel Project and the University of Newcastle. Xstrata Coal were partners for the conference, sponsorship came from Air Liquide, Vattenfall and Hitachi. Anlec R&D, CIUDEN and Alstom also supported the event.

A presentation on the key outcomes will be given during the ExCo
Prioritisation of new studies
18 proposals for new studies were sent to members and sponsors for voting. These consisted of:

- 1 proposal re-submitted from the previous round of voting
- 17 new proposals, 10 from the Programme Team and 7 from members.

Members were asked to vote for up to five of the proposals and indicate their first choice.

Votes were received from 35 of the 46 members and sponsors, representing an 76% return of votes.

The table shows the number of single votes received, the number of ‘first choices’, and the weighted number of votes, in which the first choice vote is assumed to be equivalent to 2 votes.

<table>
<thead>
<tr>
<th>Proposal number</th>
<th>Title</th>
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<th>First choices</th>
<th>Weighted votes</th>
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<td>Methodologies and Technologies for Intervention During CO₂ Leakage Events</td>
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<td>12</td>
<td>41</td>
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<td>The process of developing a CO₂ test injection: Experience to date and best practice</td>
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<td>7</td>
<td>24</td>
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<td>GHG Footprint and Other Issues on Shale Gas Production</td>
<td>13</td>
<td>3</td>
<td>19</td>
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<td>40-01</td>
<td>Dehydration of captured CO₂</td>
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<td>Biomass CCS – guidance for the accounting of negative emissions</td>
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Other proposals

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<td>Tools for the optimization of CCS systems and CO₂ pipeline infrastructure</td>
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<td>40-02</td>
<td>Bio-X t L with CCS</td>
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<td>Mineralisation – carbonation and enhanced weathering</td>
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<td>Environmental Impact Statements – Review of Gaps</td>
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<td>Global Atlas of Natural Releases of CO₂</td>
<td>6</td>
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<td>40-07</td>
<td>The Effects of Microbial Activity on CO₂ Storage</td>
<td>8</td>
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<td>Local compensation for CO₂ storage – an overview</td>
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<td>40-17</td>
<td>Communication messages from natural releases of CO₂</td>
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<td>40-12</td>
<td>CO₂ Emissions Database</td>
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<td>40-03</td>
<td>Techno-Economic Evaluation of the Potential CO₂ Capture Application in Pulp</td>
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After reviewing the outstanding studies waiting tendering and our current study commitments we will be able to take on up to 5 new studies. The outline proposals for the 5 studies which received the most votes (over 15 weighted votes) have been included here for members to consider.

Following the presentations of the outline study specifications, the Committee will be asked to decide:

i) Should the Programme proceed with these studies?

ii) Do the outline specifications of the studies properly describe the work required?

iii) Which of the proposals not selected in this round of voting should be re-submitted in the next round?
IEA GREENHOUSE GAS R&D PROGRAMME
40th EXECUTIVE COMMITTEE MEETING

METHODOLOGIES AND TECHNOLOGIES FOR INTERVENTION DURING CO₂ LEAKAGE EVENTS

The proposal submitted to the members for this study as part of the voting round is attached for reference. A presentation on the scope of the proposed study will be given at the ExCo meeting. After the presentation members will be invited to consider whether they wish to proceed with this study.

Proposal

It is proposed that a study should be carried out.

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<tr>
<th>RESOURCES REQUIRED</th>
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<tr>
<td>Financial</td>
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The committee is requested to
i) Approve proceeding with this study.
ii) Suggest possible contractors
iii) Suggest possible expert reviewers for the completed study
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<td>Meeting</td>
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<tr>
<td>Title</td>
<td>Methodologies and Technologies for Intervention During CO₂ Leakage Events</td>
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<td>Subject area</td>
<td>Storage</td>
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<tr>
<td>Originator</td>
<td>Chevron</td>
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**Description**

Site characterisation for each potential storage site is carried out to opt for sites where it is extremely unlikely to be any CO₂ leakage. However, it is important to have a mitigation and remediation plan in place in the unlikely event that migration of CO₂ out of the storage formation occurs. Mechanisms that could lead to migration out of the storage formation and potentially leakage to the atmosphere or potable aquifers could include equipment failure e.g. wells, fault activation due to over-pressurisation or geochemical reactions between the CO₂ and the caprock.

If leakage were to occur to any degree, the project operator must first be able to have indications and ways to characterize the pathways and magnitude of any leakage. If it continues to a significant extent, the mitigation potential of CCS as a technology will have been negated and public acceptance may be adversely affected. However, if it can be demonstrated that any leakage, which may result in significant leakage, can have simple and cost-effective interventions, then if the leakage continues there are also ways to remediate, then this will be very important information for policy makers. Mitigation strategies or plans could also be a regulatory requirement as part of the risk management process. There is therefore, a need to determine what can be done in the event of leakage from a CO₂ storage formation being detected.

The aim of this study is to build on the work carried out on the previous IEAGHG report on leakage mitigation (2007/11). Since then there has been more work on drilling and venting modeling which would be reviewed in this study. While prevention of leakage is always important, this study will focus on remediation methods in the event of CO₂ leakage or migration out of the storage formation and what the operator can do.

The study will review literature and determine the state of knowledge about:
- Mechanisms and pathways of potential leakage of CO₂
- Methodologies for detecting and characterizing the mechanisms and pathways of potential leakage of CO₂
- Technologies and methodologies to address such leakage, including intervention (to stop the leakage) and remediation (to address the already leaked out CO₂); such as CO₂ venting, pressure relief, plume redirection, plugging of wells and increased monitoring.

**Resources required**

- Financial: Average
- Management: Average

**Links with other on-going or proposed studies**

- Building on and updating the Remediation of Leakage report IEAGHG 2007/11
- Potential Impacts of CO₂ Storage on groundwater (CO₂GeoNet, in progress)
IEA GREENHOUSE GAS R&D PROGRAMME
40th EXECUTIVE COMMITTEE MEETING

THE PROCESS OF DEVELOPING A CO₂ TEST INJECTION:
EXPERIENCE TO DATE AND BEST PRACTICE

The proposal submitted to the members for this study as part of the voting round is attached for reference. A presentation on the scope of the proposed study will be given at the ExCo meeting. After the presentation members will be invited to consider whether they wish to proceed with this study.

Proposal

It is proposed that a study should be carried out.

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<th>RESOURCES REQUIRED</th>
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<td>Financial Average</td>
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The committee is requested to
i) Approve proceeding with this study.
ii) Suggest possible contractors
iii) Suggest possible expert reviewers for the completed study
For countries looking to embark on their first CO₂ test injection, it would be valuable to be able to refer to the experience and lessons learned through the development and operation of CO₂ test injection projects elsewhere in the world. The purpose of this study is to document experience of the development of CO₂ test injection projects.

The study will be carried out in 4 parts; the first part will be the identification of projects. To date there has been a significant number of CO₂ 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 CO₂ test injections and pilot projects in the order of 10,000 t CO₂ 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, 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 CO₂ test injection development manual could be produced.

<table>
<thead>
<tr>
<th>References required</th>
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<td>Management: Average</td>
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Links with other on-going or proposed studies
- Injection Strategies for CO₂ Storage Sites (2010/04)
- CCS Site Selection and Characterisation Criteria (2009/10)
IEA GREENHOUSE GAS R&D PROGRAMME
40th EXECUTIVE COMMITTEE MEETING

GHG FOOTPRINT AND OTHER ISSUES ON SHALE GAS PRODUCTION

The proposal submitted to the members for this study as part of the voting round is attached for reference. A presentation on the scope of the proposed study will be given at the ExCo meeting. After the presentation members will be invited to consider whether they wish to proceed with this study.

Proposal

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<tr>
<td>Project management</td>
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The committee is requested to
i) Approve proceeding with this study.
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iii) Suggest possible expert reviewers for the completed study
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<td>Meeting</td>
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<tr>
<td>Title</td>
<td>GHG Footprint and Other Issues on Shale Gas Production</td>
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<td>Subject area</td>
<td>Overall CCS</td>
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<td>Originator</td>
<td>Chevron/IEAGHG</td>
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<td>Description</td>
<td>In a soon to be published WEO report 2011 on the future for gas, IEA indicate that unconventional gas resources now rival those of conventional gas and are predicting that gas use for power generation and industry will rise significantly as a result. The report indicates that the GHG footprint is only slightly increased if “best practice” in gas production is followed. However it is not clear what the best practise is. Recently published literature give differing opinions on the overall GHG footprint of shale gas production. One by Howarth et al, who openly admits he is not an advocate of shale production indicates that the GHG production of shale gas extraction is much worse than both gas and coal fired power generation. In addition, the French Government has recently banned shale gas extraction because of concern relating to the environmental damage to water courses and potable aquifers. The Dutch Government has suspended shale gas drilling pending an enquiry re potential environmental issues resulting from shale gas production in the USA. Also, in the UK a recent exploratory drilling programme for shale gas was stopped because of a seismic event in the proximity to the drilling rig. All these issues require some form of independent analysis to be undertaken to qualify whether the issues warrant concern. It has been suggested that IEAGHG could use its independent status to review and comment on the GHG footprint and environmental consequences of shale gas production. Such information would feed as technical perspective into the policy debate and provide some qualified assessment of these aspects and will help inform the IEA on its gas analyses. If the GHG footprint is higher than the conservative estimates used by IEA this needs to be identified early. It would emphasise the need for CCS on gas fired plant to offset the higher GHG footprint even more strongly.</td>
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<tr>
<td>Links with other on-going or proposed studies</td>
<td>Shale and Coal Gas extraction and implications for CO₂ storage.</td>
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</table>
IEA GREENHOUSE GAS R&D PROGRAMME
40th EXECUTIVE COMMITTEE MEETING

DEHYDRATION OF CAPTURED CO₂

The proposal submitted to the members for this study as part of the voting round is attached for reference. A presentation on the scope of the proposed study will be given at the ExCo meeting. After the presentation members will be invited to consider whether they wish to proceed with this study.

Proposal

It is proposed that a study should be carried out.

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The committee is requested to
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ii) Suggest possible contractors
iii) Suggest possible expert reviewers for the completed study
### Description

Studies on impurity specifications for captured CO$_2$ and rotating equipment for compression of captured CO$_2$ have highlighted the importance of the water specification in the design of capture plant. The dehydration step is a relatively minor part of the capture process and most studies have in the past treated it as a black box process element paying little attention to the details of its design. Over stringent specification has knock on implications for the compression system since if fixed bed dryers have to be specified the standard designs require about 10% gas recycle and use of process heat for bed regeneration. Standard TEG drying systems are applicable but may struggle to reach tighter specifications. However there are special variants which can be employed such as application of dry stripping gas or adoption of proprietary arrangements such as the DRIZO process which can reach much tighter water specifications. Recently also considerable advances have been made in the use of so called “Heat of Compression” (HOC) driers in which heat of compression is used for regeneration of a solid desiccant. A further issue is the effect of impurities on drying systems in particular the presence of oxygen in CO$_2$ captured from oxy-combustion is considered to preclude use of glycol based drying because of degradation of the glycol solution.

For continuous operation in the supercritical state a much less stringent water specification could be applied as water is significantly more soluble in SCCO$_2$. Strategies to manage the pressurization/depressurization operation could eliminate the need for any drying beyond that afforded by cooling and knock out of water in the compression system. These might be application of temporary measures such as methanol injection, line pigging or startup drying beds.

This study would examine in detail the characteristics of the various drying processes which are available for Captured CO$_2$ and the way in which they can best be integrated into the CO$_2$ capture and purification system. It would at the same time review the methods available for monitoring and control of water content and practices which might be adopted to handle process upsets and water drop out during start up and shut down.

### Resources required

| Financial | Average |
| Management | Average |

### Links with other on-going or proposed studies

This study would follow up on issues raised by studies already undertaken on water usage, CO$_2$ impurity levels and CO$_2$ compression.
The proposal submitted to the members for this study as part of the voting round is attached for reference. A presentation on the scope of the proposed study will be given at the ExCo meeting. After the presentation members will be invited to consider whether they wish to proceed with this study.

Proposal

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ii) Suggest possible contractors
iii) Suggest possible expert reviewers for the completed study
Title: Biomass CCS – guidance for the accounting of negative emissions  

Subject area: Overall CCS

Originator: Alstom

Description:

In recent years biomass combustion and co-firing as well as all kinds of biofuels were regarded CO₂ neutral and therefore proposed to reduce CO₂ emissions from fossil fuels. Due to the lower heat value and power density of biomass compared to coal even a small power capacity of 50 MW might, depending on the kind of biomass, require a large catchment area (~100 km) hence, pure biomass combustion takes place in small boilers (10-50 MW) at significantly lower conversion efficiencies making the generated electricity more expensive. Therefore, biomass co-firing is mostly considered the more economically feasible way, as up to 20% biomass can be easily added to big coal boilers of 800 - 1000 MW generating electricity at higher conversion efficiencies and lower costs.

Biomass CCS would make pure biomass combustion even more expensive as the costs of CCS facilities follow the economies of scale. However, whether biomass is purely combusted or co-fired its CO₂ neutrality (without capture) or its “negative emissions” could make biomass firing economically more feasible in a carbon constrained markets like the EU emissions trading scheme (ETS) where allowances have to be bought for all fossil emissions.

Unfortunately, there is yet no consistent, logical method to account for emissions avoided by biomass combustion, neither for CO₂ neutrality nor for “negative emissions”. Today all biomass in general is considered CO₂ neutral. However, whether biomass burnt within seconds in a power plant is considered CO₂ neutral depends on the kind of biomass and its growing frequency, e.g. is it the annual waste of any crop yield or annual rest wood in forests or a whole tree trunk grown over 30 years. As biomass could be a real incentive for compensation of fossil emissions with (negative emissions) or without CCS (CO₂ neutral) it could be an economical driver for smaller pure biomass CCS at higher CO₂ prices in the future. In case of co-firing CCS it could at a certain percentage neutralize the fossil emissions.

Therefore, a study to develop recommendations on a consistent system to account for “negative emissions” in transparent and sustainable way is crucial to have biomass CCS included in the EU ETS. Such recommendations would be relevant to any cap-and-trade based ETS.

The study will build on the analysis by Groenenberg and Dixon ‘Using carbon markets to advance negative emissions biomass and CCS’ (Energy Procedia 2010), which assessed in detail the EU ETS and Joint Implementation mechanism, but was restricted on specific recommendations on solutions for the EU ETS.

Resources required:
- Financial: Below average
- Management: Average

Links with other on-going or proposed studies:
- Groenenberg and Dixon ‘Using carbon markets to advance negative emissions biomass and CCS’ (Energy Procedia 2010)
- IEAGHG Biomass CCS Global Potential Study (2011/draft).
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STUDIES TO BE RESUBMITTED FOR VOTING

Members are invited to suggest which studies should be considered again in future voting rounds.

NOTES
As part of the contract with GCCSI, IEAGHG is required to supply GCCSI with a status report and financial statement twice a year. The fourth status report was supplied in September 2011.

Most activities are making good progress. Many have achieved notable outcomes and success already. The largest events have taken place, GHGT-10, the 2010 Summer School, and the Mentored Student programme at GHGT-10. The two student activities were considered a great success, with excellent feedback. The two GCCSI-funded studies have progressed well, on Effects of Impurities and on the Global Storage Gap Analysis, one published and one nearing being published. The Global Storage Gap Analysis is proving to be of strategic value and interest, being input into the CCUS Action Group’s work. The Social Research Network has now held its first two meetings, and both fed directly into two GCCSI workshops on public communications for industry (in Paris and Tokyo).

The What Have We Learnt from Large-scale Operational Projects was delayed but still proceeding and very near completion. Two activities were requested to be put on hold (updates to Projects Database and to Emissions Database) by the Institute, although IEAGHG is funding lower level activity in these areas due to pressing need for them. The Institute also requested that Activity on Key messages for stakeholders be cancelled. At IEAGHG members request this will now proceed funded by IEAGHG.

In addition to these activities Tim Dixon was seconded to GCCSI part time to assist them in building up their Regulatory Team. This is a separate contract with GGCSI. This contract has been extended twice to include the UNFCCC CoP meetings, the second time for a further 12 months to include the COP-17 meeting at Durban, at a reduced part-time rate (12:5%).

Also under a separate contract, the General Manager is a member of GCCSI’s Technical Advisory Committee.
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WHAT HAVE WE LEARNT PHASE 1b

In 2009, IEAGHG carried out an assessment of learning that is being provided by operational, large-scale, pilot, demonstration and commercial CCS projects around the world. This was undertaken by questionnaires and analysis of the responses and a report was published, presenting the results. Phase 1b was intended to be an addendum to the original report, gaining further information from projects on more specific topics within the subjects of well injectivity, regulation and public communication. In Phase 1b, twelve projects responded out of the twenty nine that were contacted. IEAGHG received 7 responses on well injectivity, 10 on regulation and 8 on public communication.

The well injectivity document asked for information on topics including injection conditions, predicting injectivity, injectivity in practice and improving injectivity. The projects were also questioned on features of injectivity, such as reservoir parameters and operating parameters. The projects questioned covered a wide range of injection depths, reservoir thicknesses and brine salinities. Many of the projects reported that it is difficult to predict injectivity solely on the basis of reservoir models and properties - therefore injection tests are invaluable for calibration. There was some evidence that injecting CO₂ could enhance injectivity over time. Collectively the projects had tried a range of techniques to improve or maintain inflows.

The results from the regulation questionnaire showed that many projects had no specific aspects of interaction with regulations or regulators that caused them concern during the project. There were, however some minor issues at a couple of the projects with permitting and applying for certificates, but these were easily overcome and interaction with regulations was generally positive. Most of the projects found that regulations and standards were adequate for the pilots and regulators were often flexible. There were no gaps identified in the regulatory framework, but a couple of projects found that there were several overlaps between different jurisdictions, which may lead to new legislations being more self-contained.

Regarding public communication, the projects were questioned on the general approach taken, methods employed, any novel communication methods that may have been used, lessons learned and any suggestions for public communication strategies for future projects. Many projects emphasised the effectiveness of an informal approach and the importance of listening to concerns of various stakeholders. Careful planning of public outreach strategies was considered essential by all of the successful projects. A key lesson discovered in Phase 1b of the What Have We Learnt study is that objections to a CCS project are unlikely if there are identifiable local benefits.

IEAGHG would like to acknowledge the support and funding from the Global CCS Institute for this work.
1. **Introduction**

An assessment of the learning that is being provided by operational, large-scale CCS (carbon dioxide capture and storage) projects around the world was undertaken by the IEA Greenhouse Gas R&D...
Programme (IEAGHG, 2009). This second consultation round (phase 1b) intends to add additional information to the original report on:
- Well injectivity
- Regulation and permitting
- Public communication.

By compiling and assessing this information we hope to continue to increase awareness of current projects and associated learning, along with assisting wider CCS development and deployment. We also hope to use the information to identify gaps within the global CCS portfolio to help direct future funding, research and ultimately further projects.

We contacted the 29 projects that were recognised in the initial phase (1a) of the What Have We Learnt study, of which 12 projects (see table 1) came back with responses.

As mentioned above, the three topics chosen for further investigation were Well Injectivity, Regulation, and Public Communication. Questionnaires were drawn up by IEAGHG and additional expert advice was sought on the questions - on the well injectivity section in particular. The questionnaires were then sent to applicable projects (for example some received all three sections/questionnaires; others just received one or two where appropriate). The majority of the responses referred to in table 1 responded by completing and returning the questionnaires, while others were telephoned where possible.

<table>
<thead>
<tr>
<th>Capture Projects</th>
<th>Storage Projects</th>
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</thead>
<tbody>
<tr>
<td>Chemical Co. ‘A’ CO2 Recovery Plant</td>
<td>CO2SINK (Ketzin Project)</td>
</tr>
<tr>
<td>IFFCO CO2 Recovery Plant – Aonla</td>
<td>Nagaoka</td>
</tr>
<tr>
<td>IFFCO CO2 Recovery Plant – Phulpur</td>
<td>Otway Basin Project</td>
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<td>Petronas Fertiliser Plant</td>
<td>Pembina Cardium Project</td>
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<td>Schwarze Pumpe</td>
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<td>SECARB – Tuscaloosa Cranfield II</td>
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<td>MRCSP Phase II</td>
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<td>Zama EOR Project</td>
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Table 1 – Projects which responded in Phase 1b of the ‘What Have We Learnt’ study

2. **Well injectivity**

Additional information about well injectivity was obtained from a total of 7 injection projects:

**Injection conditions**

The projects cover a wide range of injection depths and reservoir thicknesses as shown in Figure 1. Injection pressures, as expected, vary with depth and are very much in line with the hydrostatic
gradient. (Figure 2). Where reported (3 returns) the fracture pressure gradient was similar 16.8-20.1 kPa/m and all projects reported a substantial margin of fracture pressures over initial downhole injection pressures ranging from 65-90%. The projects covered a wide range of brine salinities as shown in Figure 3, an important concept when it comes to injection, due to the effects that the viscosity contrast between brine and CO2 has on mobility.

**Predicting injectivity**

Five of the projects included an injection test in their development programme and two relied on previous experience with the formation. The injection tests were generally preceded by estimations of injectivity derived from core flood tests and well logs. Several projects reported that it is difficult to predict injectivity solely on the basis of reservoir models and properties and as such injection tests are invaluable for calibration.

**Injectivity in practice**

Three of the projects experienced somewhat higher injection rates than predicted - one project expected an average of 38 tonnes per day for vertical injection wells and achieved an average of over 100 tonnes per day and a second project predicted 20 ton/day and experienced 40 ton/day. For some, injectivity was not a limitation because the formation had a very high permeability. One mentioned a problem well which even after acid treatment had difficulty maintaining planned rates. Another had problems of well blockage caused by sulphate reducing bacteria (SRB) but was able to back flush this and restore sufficient injectivity.

There was some evidence that injecting CO2 might tend to enhance injectivity over time but this is difficult to distinguish from other effects particularly changes in reservoir pressure which influence inflow rates.

The average injection rates achieved by the various projects as well as the reported normal minimum and maximum rates are shown in Figure 4.

**Actions to improve injectivity**

Despite the generally favourable injectivity found in practice compared to design predictions, operators had collectively tried a range of techniques to improve or maintain inflows. These have included acid injection (employed by two projects in Japan and Canada), re-perforation, horizontal drilling (which was employed successfully at the Pembina Cardium site, increasing well productivity) as well as pre-injection fracking and pre-injection back flushing (both employed at projects in Canada).

**Conclusions**

CO2 injection has now been demonstrated successfully in a wide range of settings. The methods used to predict and enhance injectivity are based on commonly used industry techniques and are reliable.
Figure 1 - Depth and thickness of the CO₂ storage reservoirs
Figure 2 - Pressure-depth relationships

Figure 3 - Formation water salinity
3. **Regulation**

Information from ten CO₂ injection projects on regulation was received in phase 1b of the What Have We Learnt Study. The information gained demonstrated the differing aspects of regulatory issues in each individual project.

**Interaction with regulations and regulators**
Many of the projects had no specific aspects of interaction with the regulations or regulators that caused them concern during the project. There were some issues with the Mining Safety Laws and Regulations when projects were located in an active hydrocarbon field. Some difficulty was encountered at one project when trying to apply for various authorisation certificates. Some issues arose on how to permit the observation wells for a particular project – these issues were overcome by permitting them as producer wells. Interaction with regulations was generally positive, although there was some difficulty with projects in areas where there were no regulations for CCS in place (and it was not allowed under the existing regulations – so a site-specific regime was created).

Many projects found that regulations and standards in conjunction with pro-active community policies have resulted in a satisfactory relationship with the community.

**Areas where assurance was important but regulations were poorly placed?**
Most of the projects found that the regulations and standards were adequate for the pilots and regulators were often flexible to allow a dynamic monitoring regime. Issues occasionally arose with the regulations that were in place when looking into potential failures of the CO₂ pipeline and with caprock integrity (for example the Nagaoka project (Japan) found issues with regulations dealing with CO₂ leakage, seepage to groundwater etc.).

Some projects found it challenging where governments had not yet ratified various guidelines or directives on implementing CCS legislation. It has caused some concern and created risks in some work at the Schwarze Pumpe site in Germany (although not direct problems), as the project then does not know all the demands on them (for example when it comes to what information is needed, etc.).

**Gaps in the regulatory framework**
Most projects had no specific issues when it came to possible gaps in the framework. A couple of projects found that there were several overlaps between different jurisdictions which sometimes proved problematic - but they are hopeful that the new legislation will be more self contained.

Underground CO₂ inventory
In terms of learning from the management of the underground CO₂ inventory (in the context of emissions accounting), one project measured the tonnage of CO₂ injected along with all emitted out of the reservoir (including all flare) but has not tried to test the accuracy by applying for credits. Most of the projects have not attempted to register any CO₂ credits at this stage. A key learning was the better understanding of the range of characterisation activities and supporting MVA documentation that may be required in the presence of a carbon credit market - knowledge that will be applied to ongoing efforts to inject large tonnage of CO₂ into the subsurface in an effort to mitigate the current practice of venting to the atmosphere.

One project in particular gained valuable experience in making subsurface measurements, in precision and estimates of uncertainty. It is difficult to predict mixing in a reservoir where natural gas is already contained - the density decrease affects the flow pattern. The temperature changes are presumably due to equilibration with the rock and/or in situ fluids, but perhaps also related to the heat content of the introduced CO₂ - also affecting flow patterns. Above-zone pressure monitoring was used to document the inventory - where the monitoring is carried out in the zone above the storage formation, which can indicate any anomalies (i.e. leakages) from below. It is important that the injection reservoir is completely isolated from the intervals above where pressure is being monitored.

Conclusions
For the most part, there was little concern caused when it came to interaction with regulations and regulators - the minority did come up against some issues in certain situations. It was found that regulations and standards, coupled with proactive community policies led to a positive relationship with the community. Most projects found that regulations and standards were adequate, with regulators displaying flexibility in most cases. We found that all projects which responded to the regulation questionnaire have not yet attempted to register CO₂ credits.

We have seen that the first demonstration projects are too small to come across many significant issues in terms of regulations - and any problems have been relatively easy to address. At best, some authorities have been alerted to the fact that at full scale there may be some potential issues.

4. Public communication

Additional information about public outreach and information dissemination was received from 8 CO₂ injection projects - all of which have been successful. All projects had recognised that public acceptance was important and had deployed considerable efforts in this direction. The lessons learned are perhaps rather obvious but are nevertheless worth describing.

General approach and setting
Several projects emphasised the effectiveness of an informal approach, whereby staff directly engaged at the grass roots level in the development are given an opportunity to discuss the project and their part in it with local residents and other local stakeholders. A key subject seems to be the establishment of situations where conversations can be held as equals. In one project much of the dialogue was left to “landmen” working on the ground to establish and sign up residents to mineral right and land access leases. Many of the landmen were in fact local residents and presumably such negotiations help to establish a dialogue between parties on an equal footing. Others had smallish gatherings to impart information or mark key milestones in the project at which there were good opportunities for staff involved with the project to mingle and explain the technology.

Several projects mentioned that underground operations formed a part of the local economy so that local residents to some extent already understood and were interested in the type of underground operations being proposed.

**Communication methods employed**

Most projects had at some stages encouraged visitors to the site of operations. Most had organised meetings generally of an informal kind to which local residents and interested parties were invited. Turnout does not seem to have been large, typically a few tens of persons might come. All projects setup websites with information. The information provided was both about CCS in general and also the project plans in particular. Different projects placed different amounts of emphasis on the two aspects but most at some stage appear to have concentrated on the project plans.

One project emphasised the importance of listening to the concerns of the various stakeholders. No mention was made of the extent to which concerns were acted upon, only that there appeared to be no particular adverse reactions to carrying out the projects. The only major concerns raised were related to the correct use of government funding and out of region expertise rather than impacts of the project.

**Novel communication methods**

The projects were asked about any particularly effective ways of communicating about CCS. One project described a hands-on display involving porous and non-porous rock samples. Simply using a water spray, visitors could observe the difference in sample properties. A more sophisticated display involved submerged core samples with a hole drilled in connected by tubing to a bicycle pump. Visitors could experience firsthand how effective non-porous rocks were as only porous rocks allowed air to bubble through. Another project had constructed a device to show, in a high pressure steel chamber with a sight glass on either side, how CO₂ transitions from the gas/liquid phase to the dense phase and back.

**Lessons learned**

As expected, careful planning of public outreach was considered essential by all of the successful projects. Creating conditions for informal discussions between interested stakeholders and those working on the project at an early stage should be a key aim. Why such an informal approach seems to be effective is not revealed but may be due to the fact that this creates a good setting for listening to any concerns.

The existence of identifiable benefits of some sort, either direct in the form of royalties or indirect through enhanced employment opportunities seems to have been present at most of the sites. Some of the individual responses would suggest that a perception of some sort of benefit is important and that risks are not considered to be a significant reason for objection. Many of the sites have a history of
successful and safe underground operations and it is possible that this underlies this apparent lack of concern.

The key lesson is thus that objections to a CCS project are unlikely if there are identifiable local benefits. For sites where there is no previous history or experience with underground operations, safety and risk may be seen as reasons for objection and if coupled with a lack of benefits, serious objections might be expected. Future projects will have to adapt to positively address these issues.

**Suggestions for future projects**

Large projects will require proportionately larger efforts and organisation to interface effectively with all of the stakeholders. Projects should aim to be the first to provide information on all of the key project activities. More work needs to be done to establish clearly identifiable benefits for local communities in the vicinity of possible storage sites. This could be particularly important in jurisdictions where land rights are not vested in the local community.

5. **Conclusions**

This additional consultation round provided IEAGHG with further information on some of the 29 originally identified operational large-scale projects.

The depths of the storage reservoirs at these particular sites vary from 600 to 3300 metres, with the reservoir thicknesses ranging from 5 to 90 metres. Most projects experienced higher injection rates than anticipated, with the average rate ranging from approximately 30 to 500 metric tonnes per day. Injection pressures vary with depth and hydrostatic gradient (as expected) and all agreed that injection tests were invaluable for model calibration. Injection of CO₂ has been successfully demonstrated at all projects.

Regulations and standards were found to be adequate, although many agreed that most demonstration projects are too small to come up against many significant issues with regulators. In order to maintain a good relationship with the community, regulations and standards should be coupled with practical community policies.

The careful planning of public outreach policies is crucial and the effectiveness of an informal approach with the public was emphasised. It was found that objections (from the local community) to a CCS project were unlikely if there are identifiable local benefits. Projects should aim to be the first to provide information to the community and establish clearly identifiable benefits to the local community early on.

6. **References**

IEAGHG, “What Have We Learned from CCS Demonstrations?” 2009-TR6, November 2009
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FEEDBACK IEA ACTIVITIES

NOTES
The next scheduled meeting will be the 41st ExCo meeting, hosted by Norway, 7th-10th May 2012. There will also be an opportunity for the ExCo to visit the Test Centre Mongstad.

The 42nd ExCo meeting will be held in Kyoto, 15th-16th November 2012, Japan prior to GHGT-11 which is being held between the 18th to 22nd November 2012.

We have received an offer from Canada to host the 43rd ExCo, spring 2012.