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Final Report from the Task Force for Identifying Gaps in Monitoring and Verification of Geologic CO_2 Storage

Background

At the meeting of the Technical Group in Melbourne, Australia on September 15, 2004, a Task Force was created to identify gaps in monitoring and verification of geologic CO_2 storage. This Task Force consists of the Canada (lead), the European Commission, France, Norway, and the United Kingdom. It was instructed to produce a discussion paper that would then undergo review and be presented at a Technical Group meeting. A first version of this discussion paper was presented at the meeting of the Technical Group in Oviedo, Spain, on April 30, 2005 and a revised version was presented at the meeting of the Technical Group in Berlin, Germany, on September 28, 2005. However, at the meeting of the Technical Group in Delhi, India, on April 3, 2006, it was reported that the International Energy Agency's Greenhouse Gas Programme (IEA GHG) was also preparing a paper on this topic. Rather than engage in a duplication of effort, there was concurrence that the Task Force would instead coordinate with the IEA GHG and, with the approval of the IEA GHG, use the IEA GHG's paper on this topic as its final report. This final report represents the conclusion of the Task Force's activities.

REVIEW OF IPCC SRCCS GAPS IN KNOWLEDGE

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INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. The IEA fosters co-operation amongst its 26 member countries and the European Commission, and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 40 Implementing Agreements. These agreements cover more than 200 individual items of research, development and demonstration. The IEA Greenhouse Gas R&D Programme is one of these Implementing Agreements.

DISCLAIMER

REVIEW OF GAPS IN KNOWLEDGE FROM THE IPCC SPECIAL REPORT ON CO_2 CAPTURE AND STORAGE (SRCCS)

Background

The IEA Greenhouse Gas R&D Programme (IEA GHG) was actively involved in the development of the IPCC[1] Special Report on Capture and Storage (SRCCS). Three of its then Programme team were directly involved in 5 out of the 9 chapters. The chapters concerned were: 1 (Introduction), 2 (Sources of CO_2), 3 (Capture), 4 (Transport) and 5 (Geological Storage). In addition, IEA GHG's technical study reports were drawn upon by many of the chapters as reference material for their chapters, as were the proceedings and peer reviewed journals from the GHGT conference series that IEA GHG organizes. Because of its active involvement in the construction of the report IEA GHG was considered to be well placed to comment on the findings of this report.

IEA GHG has, therefore, undertaken a review of the gaps in knowledge that were listed in the IPCC SRCCS. It must be noted early on that that the IPCC SRCCS did not undertake an extensive gap analysis on CCS, this is discussed further later. The aim of the review was twofold:

1. To assess the significance of the gaps in knowledge identified within the IPCC SRCCS. The gaps have been considered against a broad objective of their significance in terms of bringing CO_2 capture and storage (CCS) technology closer to wide scale implementation

2. To assess key research needs that are identified in the IPCC SRCCS

IPCC Report Methodology and Development of Gaps in Knowledge

Before considering the gaps in knowledge identified in the IPCC SRCCS, it is first considered necessary to understand the process by which the report was developed and how the gaps in knowledge were identified. The report itself consists of two parts. The first part is the Summary for Policy Makers and Technical Summary, whilst the second is the main report itself. Work on the drafting of the report began in at the first Lead Authors (LA's) meeting held in Oslo in September 2003. Some 115 Lead Authors[2] took part in the drafting exercise. Each LA was then drafted into a chapter team and the whole report was developed as 9 separate chapters. A Coordinating Lead Author (CLA) was then appointed to oversee the production, technical integrity and quality of each chapter.

The report itself is a review of the published literature, presented in: technical reports, conference proceedings and peer reviewed journal until December 2004[3]. With the publication times taken

[1] Intergovernmental Panel on Climate Change
[2] A Lead Author is considered to be an expert of a topic within the report. The Experts or lead authors were nominated by Governments to participate in the drafting of the report because of their technical specialism.
[3] A few pieces of literature from 2005 were allowed into the report providing the need for these references had been highlighted in the Expert and Government review on the Final draft of the report.

into consideration, the underlying works that lead to these publications is probably a year old, which means the technical literature is probably approaching eighteen months to two years old by the time the report was issued in late 2005.

Four drafts were developed over the period between initial workshop held in Oslo in June 2003 and the final draft which was completed in July 2005, almost two years after the process started. The final draft was then reviewed by the Technical Support Unit of IPCC Working Group III and was edited by professional copy editors to produce a coherent report. The Technical Summary (TS) and Summary for Policy Makers (SPM) followed the same drafting process and schedule. Contributions to the TS were provided by the individual chapters but the report was overseen by a separate CLA, again to produce a coherent report. The SPM was written by the Technical Support Unit of IPCC Working Group III. Both the TS and SPM were approved by the CLA's of each Chapter prior to presentation of the SPM and approval at the IPCC Plenary held in Montreal in September 2005. The main report was reviewed four times as it developed; first by the drafting teams, then twice by independent government appointed experts and finally by governments.

The gaps in knowledge were introduced into the main report and the TS at the second draft stage. Each chapter drafted its own gaps section in isolation. As the chapters developed the gaps section developed as well. However, it must be noted that many chapters were still under going large scale revisions, based on the comments received from the government review, at the final draft stage and it is fair to state that in all cases the gaps were not as well considered as could have been possible. The gaps in knowledge in the final draft of the TS were limited to headline gaps only. No information on gaps in knowledge was put into the SPM, but after the IPCC plenary a short sentence was added (at Austria's request) to say there were gaps but this was not expanded upon. At no time was an overview of the gaps in knowledge for CCS developed as part of this process. For the purposes of this exercise the gaps of knowledge listed in the main report were those that were reviewed.

Review of SRCCS Gaps in Knowledge

For each of the chapters[4] the gaps in knowledge were listed out in the attached Appendix. For each gap identified IEA GHG has, based on its own judgment, commented on their relevance. Next, IEA GHG had added a further set of comments on work that it is aware of that is underway or planned to address each gap. Finally, each gap was rated on a scale of 1 to 5 where:

1. Very important and needs to be urgently addressed to move the technology towards full scale implementation
2. Important and needs to be addressed with some urgency
3. Less important but needs to undertaken
4. Not important – CCS can be implemented without this gap being addressed or gap will be addressed through natural development
5. Unimportant – gap does not need to be addressed

Results of SRCCS Gaps in Knowledge Analysis

One general comment that can be made on the Gaps in Knowledge listed in the SRCCS is that they are very focused on the technical issues relevant to each chapter and do not look at the "big picture" for CCS implementation. Such a result is not surprising when the drafting teams were split into groups focusing on the issues relevant to each chapter and no attempt was made in the SPM to draw together a more composite review of the gaps in knowledge relating to the technology as a whole. Once again it must be emphasized that the report was a review of the existing literature, if there was no published literature on a particular topic, this may have been glossed over in the main report. Furthermore, it is considered that the gaps listed will not have been comprehensively identified through a structured gap analysis process. In hindsight, a more structured approach might have been warranted in the IPCC SRCCS.

In general, IEA GHG considers that most of the gaps identified are technical in nature, as could be expected. In addition, it is felt that many of the gaps are now being addressed by research work that has started since the drafting process for the report began.

Two gaps that are considered to be high priorities (rated 1) that were identified in the SRCCS were:

- The need for full scale commercial demonstration of a post combustion capture plant,
- The need for a demonstration of a fully integrated system.

A proposal to develop a post combustion demonstration plant under the auspices of the IEA has been tabled. It was also noted that several member countries (Canada, Australia, and the Netherlands) were considering the development of such a plant. For IGCC, the Future Gen initiative in the USA has now been launched and the EC supported DYNAMIS[5] project will also

[4] The exception was the introduction, Chapter 1, where no gaps were listed

[5] The DYNAMIS project will undertake a feasibility study to build an integrated electricity and hydrogen production plant incorporating CO_2 storage in Europe.

be launched in early 2006. Fully integrated demonstration projects based are also being developed in Australia by Stanwell and Monash Energy and in China as part of a UK/EU initiative to develop zero emission coal fired technology in China. A number of industry led initiatives (E.ON, RWE and Vattenfall) in Europe are also assessing the feasibility of developing integrated demonstrations. All the projects are aimed at demonstration projects between 2012 and 2015. Several initiatives are therefore already underway to address the need for a demonstration of fully integrated operation.

One key action is that the need for concerted global initiatives was identified; in particular, the need for improved data to define the storage capacity in sedimentary basins worldwide. To date there have been a number of regional studies (North America, Europe, Australia, APEC[6] Region) but there are still large areas of the world where detailed analyses have not yet been taken. In addition there is a need for the development of consistent methodologies and data set requirements. As indicated some work has already been undertaken and IEA GHG is aware of new initiatives in India[7], China[8] and the Middle East[9]. In addition, the CIAB[10] has launched an initiative to develop a global data base for storage capacity data. IEA GHG believes that initiatives such as that of the CIAB need to be encouraged and support needs to be provided to effectively map the global storage potential in sedimentary basins. The CSLF[11] has also produced a standard methodology for storage capacity assessment that will help the integration of these activities and allow presentation of the results in a common framework.

The review highlighted a small number of studies/reviews that IEA GHG could undertake to help address some of the gaps identified. The studies are set out on the Table 1 overleaf:

[6] Asia Pacific Economic Consortium
[7] IEA GHG approved regional study
[8] EU/UK ZETS study and CSLF supported activity
[9] Initiative being led by Saudi Aramco.
[10] The Coal Industries Advisory Board is a group of high level executives from coal-related industrial enterprises, established by the International Energy Agency (IEA) in July 1979 to provide advice to the IEA on a wide range of issues relating to co
[11] Carbon Sequestration Leadership Forum

Table 1 Future studies that IEA GHG could undertake to address gaps in knowledge identified in IPCC SCRCCS

Activity to Address Gap	Action type	Status
Review the available literature to assess likely future scale of biomass plants for CCS	Technical Review	Completed
Assess to potential to odorize CO_2 to highlight low level leakage from pipeline systems	Technical Review or part of larger Technical Study	Study now underway
Building public acceptance of CCS	Technical Study	Communication activities to commence shortly
Assess international implications of transboundary transmission in pipelines or shipping of CO_2 both with and without impurities	Technical Study	Study proposed
Assess CCS cost variability between specific sites	Technical study	Study proposed
Global assessment of biomass CCS potential	Technical study	Study proposed

A small number of studies could be added at a later date pending the outcome of current activities. These studies include:

- A new study to consider the potential for large scale synthetic fuels plants incorporating CCS as large scale future emissions sources of CO_2.
- A new study to consider the potential for large scale synthetic fuels plants incorporating CCS as large scale future emissions sources of CO_2 following completion of current[12] study on co-production of hydrogen and electricity.
- A new study on incorporation of CCS under the Kyoto Mechanisms could be considered after publication of the IPCC 2006 Guidelines on National Inventories and Reporting. Note: the need for such a study might be overtaken by activities underway to develop methodologies for including CCS in ETS and CDM schemes.

APPENDIX

Review of Gaps in Knowledge from the IPCC Special Report on Carbon Dioxide Capture and Storage

The 'Gaps in Knowledge' column refers to gaps identified within the IPCC report SRCCS report. Note where no specific gaps were identified within a chapter IEA GHG has attempted to identify the key gaps discussed in the main report. Also, no gaps were listed from the introduction because it was felt that the other chapters identified all the issues of concern. Under comments, IEA GHG has added its thoughts to the gaps identified and their relevance. Developments that IEA GHG is aware of are described in 'Work Underway to Address the Gap'. The column, 'Priority', sets out IEA GHGs thoughts on the need to address the identified gaps. The gaps are prioritsed on a scale of 1-5 where:

6. Very important and needs to be urgently addressed to move the technology towards full scale implementation
7. Important and needs to be addressed with some urgency
8. Less important but needs to undertaken
9. Not important – CCS can be implemented without this gap being addressed or gap will be addressed through natural development
10. Unimportant – gap does not need to be addressed

The final column suggests what action IEA GHG could take top address these gaps for member's reference.

Note: There were no gaps in knowledge listed in Chapter 1 – Introduction of the IPCC SRCCS

Chapter 2 – Sources of CO_2

Gap in Knowledge	Comments	Work Underway to Address the Gap	Priority (scale 1-5)	IEA GHG Action
Emission Source Data				
1. Determine the likely potential for biomass energy as a source of CO_2 emissions in the future	Will be necessary to review literature to compare available data on future scale of bioenergy plant and put results in context	IEA GHG is not aware of any work in this field	3	Because of high attention biomass energy is getting IEA GHG should consider a study to independently assess literature data
2. Determine the likely potential for large scale synthetic fuel plants as sources of CO_2 emissions in the future	Need to address feasibility of poly generation schemes proposed and their future scale	IEA GHG is not aware of any work in this field. Currently planned work by IEA GHG does not address this issue	3	Could consider new study after existing work is complete
3. Determine the likely potential for large scale hydrogen plants as sources of CO_2 emissions in the future	Need to address feasibility of large scale hydrogen schemes based on fossil fuels and co-fired with biomass, their likely size and distribution.	Work underway will look at feasibility of hydrogen-electricity co-production plants but not biomass	2	Consider study after feasibility is confirmed
4. Detailed mapping of ocean storage opportunities and large point sources are required	Work could be considered but need for this is dependant on whether ocean storage will be accepted as a mitigation option.	IEA GHG is not aware of any work in this field	4	None
Sedimentary Basins				
5. Need an improved data set to define the storage capacity of sedimentary basins	Further detailed regional analyses of potential storage opportunities in sedimentary basins are definitely required	Yes, now being looked at in several regions but not necessarily in as much depth as required. IEA GHG proposed study on India will only look at matching source/storage potentials	2	None -. Needs concerted action by many countries. Out of capability of IEA GHG.

Chapter 3 – Capture of CO_2

Gap in Knowledge	Comments	Work Underway to Address the Gap	Priority (scale 1-5)	IEA GHG Action
Individual Components				
6. Technical details required to assess performance and costs	Sensitivities of costs to local parameters needed More detailed design studies and plant construction should increase confidence in costs	IEA GHG will propose a study on regional variations of costs	2	Nothing more than planned at present
7. Develop systems to capture CO_2 from steel and cement production	Need to engage relevant industries	Significant work starting on steel, e.g. ULCOS and IEA GHG study. Some work so far on cement, e.g. in Norway. IEA GHG has proposed studies on these topics, steel study accepted.	2	Nothing more than planned at present
8. Development of membranes, sorbents and post-combustion materials needed	Membranes may be a niche application	Practical work by various universities etc, on improved solvents and membranes is progressing.	3	None – but to maintain awareness of any developments
9. Post-combustion capture and oxy-fuel combustion must be expanded to a larger scale	Full commercial scale demonstration plants urgently required to help build confidence in technology	Work in Canada and possibly Australia. IEA GHG to attempt to organize a demo plant through the IEA	1	Nothing more than planned at present, but maintain awareness of any developments
Integrated System				
10. No demonstration of a fully integrated system at present. Need this to fully evaluate the costs, environmental impact and reliability	Full commercial scale demonstration plants urgently required.	IGCC projects in the US (FutureGen) and Europe (Hypogen) but less firm proposals for post-combustion capture although IEA GHG aware of an initiatives planned in Canada an trying to organize demo through IEA	1	Nothing more than planned at present, but maintain awareness of any developments

Enabling Technologies				
11. Need for improved processes for the effective removal of S,N Cl, Hg and other pollutants needed for effective unit operations for CO_2 separation in post and precombustion capture systems	Necessary clean-up technologies largely available but some further demonstration would be helpful and the number of vendors should be increased.	Need integrated demonstration projects to demonstrate components	3	None, but maintain awareness of developments
12. Need for improved gasification reactors for coal and biomass	Gasification technology is available from a number of vendors but this could be developed to operate more effectively and efficiently	If a market for gasification technology develops then more effective systems will need to be developed by the current vendors	3	None, but maintain awareness of developments
13. Need for hydrogen burning gas turbines to be developed	Hydrogen burning turbines from a variety of manufacturers need to be demonstrated. Such turbines will be developed by manufacturers when there is a perceived market.	GE is understood to be developing H_2 GT technology	3	None, but maintain awareness of developments
14. Need for hydrogen burning fuel cells	Fuel cells are a longer term objective. Integration with CCS needs to become a priority	Fuel cell technology being developed by a number of manufacturers, hydrogen market not yet established	4	None, but maintain awareness of developments
15. Need to develop new high temperature system components for oxy fuel systems or new class of CO_2 turbines and compressors	Pilot plant demonstration of clean-up from oxy-combustion is needed.	Several equipment suppliers looking to develop oxy fuel systems. Vattenfall pilot plant may demonstrate oxyfuel clean-up.	4	None, but maintain awareness of developments
Pollutants				
16. Investigate emissions and the effect of fuel impurities and temperature	Tests with a wide range of fuels are needed. More information needed on solvent and other waste production and treatment	Pilot plants e.g. CASTOR will provide practical information. IEA GHG doing a study on environmental impacts of solvent scrubbing	2	Nothing more than planned at present. Assess results of work underway when available

Chapter 4 – Transport of CO_2

Gap in Knowledge	Comments	Work Underway to Address the Gap	Priority (scale 1-5)	IEA GHG Action
Pipeline Systems				
17. Define an acceptable composition of gas	Conventional design Work needed to define standards for pipeline systems but depends on storage methods used	None required	4	None
18. Determine whether it is possible and economical to dry the CO_2	Yes, it is. CO_2 dried at Weyburn, therefore not considered to be a problem	None required	5	None
19. Determine the most cost effective pipeline system – larger backbone with feeders or a network of smaller pipes?	More work needed to assess scenarios and to study how networks could be developed in the market. More work needed to assess possible collection from smaller scale sources.	Planned IEA GHG study will address small/medium scale sources. Some work completed in cost curve studies for NA and EU.	3	Nothing more than planned at present. Assess results of work underway when available
20. Assess the ecological impact of a marine pipeline failure	Environmental impact of sub sea leakage is becoming an important issue.	Research underway in Norway, USA and UK to assess impact of low level leakage on sub sea ecosystems. IEA GHG has study underway to assess state of knowledge on this topic	2	Nothing more than planned at present. Assess results of work underway when available
21. Find a suitable odorant	There is a need to discuss the merits, or not of odorizing CO_2	IEA GHG is not aware of any work in this field	3	Consider new study for work on this topic for members to consider
22. Generate public acceptance and support	There is a general need to build public confidence in CO_2 transport as part of overall acceptance of CCS.	Work underway in many countries to build on overall acceptance of CCS. Further work on modeling of impacts of pipeline failure needed to answer public questions to help support this activity.	1	Consider new study for work on this topic for members to consider

Ships				
23. Only small scale at present, need to design larger CO_2 ships and associated liquefaction and intermediate storage facilities	Ship design is conventional, but if large scale ship transport is required a 'demonstration ship' may help to increase confidence amongst project developers. Possible impacts of impurities on liquefaction plant design should be assessed.	None, but more detailed design work on ships and liquefaction plants would be done in response to a perceived market.	4	None, but maintain awareness of developments
24. Set construction and operation standards	Conventional design and operational standards could be used.	None required	5	None
25. Assess the impact of a CO_2 leak on the ocean's surface	Would need to be done as part of EIA for any CO_2 transport terminal. Unsure about situation on high seas. Dependent on development of CO_2 sea borne shipping system, pipelines currently favored.	IEA GHG is not aware of any work in this field	4	None, but maintain awareness of developments
Legal Issues				
26. Transport for pure CO_2 across international boundaries is unlikely to be an issue. The impact of presence of impurities may be an issue.	The presence of impurities in the CO_2 may cause the CO_2 to be defined as a hazardous waste which could restrict transportation under the Basel Convention	IEA GHG has proposed a study to the Weyburn Project to review transboundary issues	2	Await outcome of Weyburn project or initiate new IEA GHG study

Chapter 5 –Geological storage of CO_2.

Gap in Knowledge	Comments	Work Underway to Address the Gap	Priority (scale 1-5)	IEA GHG Action
Storage Capacity				
27. Need to get universal agreement on a storage capacity assessment method, particularly for aquifers	This is a very important requirement, which the IPCC report was unable to address. This knowledge is needed to determine effective capacity for CO_2 storage in geological formations to drive policy and research initiatives	IEA GHG is a developing its own methodology and work underway through CSLF to develop a consistent approaches to be used.	2	Nothing more than planned at present. Assess results of work underway when available
28. Need a full global data set – presently most data is from Australia, Japan, N America and W Europe	Will develop in time	EC supported GeoCapacity looking at Eastern Europe, several initiatives are looking at China, IEA GHG proposed study on India. The Global Atlas proposed by Geoscience Australia should pull all the threads together and identify gaps	2	Nothing more than planned at present. Assess results of work underway when available
Storage Mechanisms				
29. Determine the kinetics of geochemical trapping and the long term effects of CO_2 on reservoir fluids and rocks	Developing our state of knowledge on the geochemical interactions that occur within a reservoir is important, in particular any adverse geochemical effects that might occur to reduce the integrity of the cap rock. Knowledge on such a topic will build up as the number of injection projects with associated research programmes develops	Initial geochemical studies from projects like Sleipner and Weyburn indicate limited potential for geochemical trapping and no adverse effects on cap rock integrity. It is expected that many of the R&D activities currently underway or planned worldwide will expand our knowledge on this topic	3	None, but maintain awareness of developments
30. Greater understanding of CO_2 adsorption and CH_4 desorption on coal during storage needed	This is a key research item for CO_2 storage in coal beds that is needed to develop an understanding of the reactions occurring within a coal seam during CO_2 injection	Work underway by COAL SEQ III consortium in USA	4	None, but maintain awareness of developments

Improved Confidence				
31. Risks of leakage from abandoned wells and methods of leakage need to be determined.	Wells have been identified by early RA studies as major areas of concern re future leakage from storage sites	IEA GHG with BP/CCP II has developed an international Well bore integrity network to develop our knowledge base of what is known on this topic. CCP II are undertaking a project to sample an existing well to assist in developing knowledge on the mechanisms occurring that will allow leakage from well bores to be modeled	2.	None, but maintain awareness of developments
32. Assess the temporal and spatial variability of leaks arising from inadequate storage sites.	Efforts should be concentrated on ensuring sites are selected that are not inadequate stores to minimize the risk of leakage.	Such information may arise from monitored storage projects but it is not considered a research priority to engineer leakage to measure such variations because the results could be misleading because of the variability of the subsurface.	4	None, but maintain awareness of developments
33. Determine microbial impacts in the deep subsurface	Such topics concern environmental NGO's. It will certainly be necessary to determine of these communities exist and if they will be destroyed by CO_2 injection into the sub surface.	IEA GHG is unaware of any research underway in this area, but do not consider this to be a major barrier to the development of the technology.	4/5	None, but maintain awareness of developments
34. Assess the environmental impact of CO_2 seepage on the marine seafloor	IEA GHGs RA network identified this as a gap topic – see 16 earlier.	Research work underway to develop our understanding in this area in Japan and EU (CO2GEONET) IEA GHG undertaking study to assess state of knowledge and identify further research needs	2	None, but maintain awareness of developments

35. Quantitative assessment of risks to human health required	Qualitative data largely only available at present. RA for CCS is currently in its infancy but will develop as the number of projects studied increases	RA studies are now underway in a number of research projects worldwide. IEA GHG and BP have developed an international RA network to assess the results generated from such activities to allow the results gained to be fully understood and help assist in RA tool development and assessment of impacts on humans and ecosystems	2	None, but maintain awareness of developments
36. More leakage rate data from more projects.	Data currently available is sparse and more is definitely needed. However this is driven by the number of injection projects underway that will monitor CO_2 injection	As more and more projects are now being planned this knowledge will develop. IEA GHG and BP have established an international monitoring network which can act as a forum to bring together and discuss the data as it becomes available.	2	None, but maintain awareness of results generated by demonstration projects
37. Develop reliable coupled hydrogeological-geolchemical-geomechanical simulation models to use as prediction tools	Currently much of the simulations of CO_2 injection undertaken are based on oil field simulators which may not b sufficiently developed for the purpose. Better simulation tools are	Such a gap is clearly understood by many of the industrial stakeholders, projects like In-Salah, Weyburn are planning to develop such tools as part of their research plans	2	None, but maintain awareness of developments
38. Develop probabilistic RA tools for predicting leakage rates	Concerns have been raised about the confidence levels that can be assigned to the probabilities of events occurring that lead to leakage in geologic formations. If the probabilities are inadequately addressed then the accuracy of results obtained can be considered dubious and misleading	IEA GHG considers that the development of our knowledge base on leakage needs to build first and our confidence in both qualitative and quantitative assessments of risk before we consider moving to probabilistic	3/4	None, but maintain awareness of developments

39. Further knowledge needed on history of natural accumulations of CO_2	Several pieces of research work have already been undertaken further work would take considerable effort	Not sure any new work is underway in this field. Research money might be better directed on monitoring injection projects	4	None, but maintain awareness of any developments
40. Develop effective protocols to achieve desirable storage duration and safety	Unsure of exact intent of this statement	Development of regulatory processes to ensure effective storage of CO_2 is now underway	3	None, but maintain awareness of developments
Monitoring Techniques				
41. Need improved quantification and resolution of CO_2 in the subsurface	Agreed	Technique development in underway in many current R&D projects to achieve this goal. IEA GHG and BP have established a monitoring network to maintain awareness of new developments	3	None, but maintain awareness of developments through network
42. Improved detection and monitoring of sub-aquatic CO_2 seepage needed	Acoustic and sonar methods are currently used by industry in this area	Need to assess suitability of currently available techniques and address development needs	3	None, but maintain awareness of developments through network
43. Remote-sensing and cost-effective surface methods for temporally variable leak detection and quantification must be developed	Important	Development of techniques is underway in a number of R&D projects e.g. Otway, Australia	3	None, but maintain awareness of developments
44. Improve fracture detection and characterization of leakage potential	Important	Need to assess literature/seek expert opinion to see what further development requirements there are	2	Could consider a technical review in this area
45. Development of long-term monitoring strategies required	Agreed, first need to agree definition of timescales required for monitoring	Fits into both tool development and regulatory process development – views are now beginning to develop in many countries. IEA GHG and BP have established a monitoring network to maintain awareness of new developments	3	None, but maintain awareness of developments through network

Leakage Remediation				
46. No present examples of remediation for leaked CO_2, it might be valuable to have an engineered, controlled, leakage event that can be used as a learning experience	Study by IEA GHG has identified an example of a remediated CO_2 well failure	An engineered leakage experiment could be useful providing we understand how appropriate an individual test is to the geology of all formations that we plan to inject into. Such a test could also attract adverse public opinion if not handled well	3	Nothing more than planned at present. Assess results of work underway when available
Cost				
47. Only a few experience-based cost data from non- CO_2-EOR storage sites, more would be useful	Agreed	Need more demonstration projects. Several new projects planned in many countries	2	None, not in IEA GHG scope to develop new demonstration projects. Maintain awareness of developments
48. Little knowledge of regulatory compliance costs	Agreed, need to develop regulatory process needs to determine costs	IEA GHG Monitoring network addressing regulatory needs and implications on monitoring costs. Information developing as regulatory needs are firmed up	3	Nothing more than planned at present. Maintain awareness of developments through network
49. Inadequate information on monitoring strategies and requirements and how much these will cost	Disagree with gap	IEA GHG has completed a study that has looked at monitoring strategies and costs. Cost data also coming from monitoring projects	4	Nothing more than planned at present. Maintain awareness of developments through network

Regulation and Liability				
50. Framework yet to be established, it should consider.: the role of pilot projects, Verification of CO_2 storage for accounting purposes, approaches for selecting, operating and monitoring CO_2 storage sites in the short and long term, approaches to long-term stewardship and requirements for decommissioning a storage project	Agreed	Knowledge will develop as regulatory process for CCS becomes developed. Regulatory frameworks now being developed in many countries. Monitoring and RA networks working with regulators to address framework requirements.	2	Nothing more than planned at present. Maintain awareness of developments through network

Chapter 6 – Ocean storage

Gap in Knowledge	Comments	Work Underway to Address the Gap	Priority (scale 1-5)	IEA GHG Action
Biology and Ecology				
51. Lack of studies about the response of biological systems in the deep sea to long duration, large scale additions of CO_2	Also relevant to concerns about ocean acidification	IEA GHG uncertain if such work underway. Need for research is dependent on whether ocean storage is to be implemented. Current political climate indicates that is unlikely	4	None, but maintain awareness of any developments
Research Facilities				
52. Need in-situ research facilities allowing small-scale, continuous assessment	Would also be relevant to sub-sea geological storage	As 51	4	As 51
Engineering				
53. Development of deep sea technology needed	Work being done for oil and gas exploration is relevant	As 51	4	As 51
Monitoring				
54. Development of techniques and sensors to detect CO_2 plumes and their biological and geochemical consequences required	Would also be relevant to sub-sea geological storage	As 51	4	As 51

Chapter 7 – Mineral carbonation and industrial uses

Gap in Knowledge	Comments	Work Underway to Address the Gap	Priority (scale 1-5)	IEA GHG Action
Mineral Carbonation (MC)				
55. MC still an immature technology without the literature base necessary to assess the technological potential, costs or environmental impacts	Recent IEA GHG review concluded that MC is in its infancy and that considerable further development work was needed to make the technology economically viable	Limited research underway at various universities	5	None, but maintain awareness of any new developments
56. Need to assess the volume of natural silicates that can be exploited	See 51	Limited research underway at various universities	5	None, but maintain awareness of any new developments
57. Need to identify a method for depositing the product, taking leaching and water system contamination into consideration	See 51	Limited research underway at various universities	5	None, but maintain awareness of any new developments
58. Must identify the most economic, effective and environmental way to extract metal oxides from their ore ensuring complete recovery of the chemical species and elimination of interference between contaminant metal oxide dissolution and carbonate precipitation	See 51	Limited research underway at various universities	5	None, but maintain awareness of any new developments
Life Cycle Analysis				
59. Mining costs are well constrained but the energy requirements and cost of carbonation are poorly known	See 51	Limited research underway at various universities	5	None, but maintain awareness of any new developments

60. No demonstration plant at present	See 51	Nothing planned more fundamental work is required before this can be considered	5	None
Carbon Dioxide Utilization				
61. Using CO_2 in an industrial process is small scale, based on short time scales and has an unfavorable energy balance	Agreed comment not a gap	None required	5	None

Chapter 8 – Costs and economical potential

Gap in Knowledge	Comments	Work Underway to Address the Gap	Priority (scale 1-5)	IEA GHG Action
Cost Development				
62. Little literature about variability between specific sites	Agreed	IEA GHG unaware of any work in this area.	2	Consider new study for work on this topic for members to consider
63. Little literature regarding CO_2 Capture and Storage (CCS) in biomass systems	Important because of high profile of biomass/CC and negative emissions in the IPCC report	Definitive study on this topic is needed; IEA GHG would be well placed to undertake such work. IEA GHG has proposed a study but was not selected by Members at last voting round but may be in future	2	Bring back biomass study for members to consider
64. Little empirical evidence regarding cost decrease due to “learning by doing”	Will only become evident when we start “doing”, i.e. building plants	Need more demonstration plants	4	None, but maintain awareness of any new developments
Future of Technology				
65. As with all research projects the impact of research, development and deployment (RD&D) are unknown	Comment rather than gap but no action required	None required	5	None
66. Unknown life cycle costs, including costs of storage of non-pure CO_2	Agreed	IEA GHG undertaking a study on impurities in capture systems and their impacts on storage this could feed into this gap	2	No action at present but maintain awareness of developments
67. Unclear monitoring and regulatory framework costs	See 44 &45	See 44 & 45	See 44 & 45	See 44 & 45
68. Unclear environmental damage and liability costs	Potential for, and consequences of environmental damage needs to be assessed and resultant liability	IEA GHG unsure how to address this cost issue. Further work on likely leakage rates and impacts needed. Will be followed through risk assessment network.	2	No action at present but maintain awareness of developments

Policy Changes				
69. Need to analyze the robustness and sensitivity of CCS to changing energy prices and policy regimes	Agreed	Energy modelers should work on this. IEA GHG and others also need to keep updating their studies	3	IEA GHG to continue discussions with energy modellers

Chapter 9 – Implications of carbon dioxide capture and storage for greenhouse gas inventories and accounting

Gap in Knowledge	Comments	Work Underway to Address the Gap	Priority (scale of 1-5)	IEA GHG Action
70. Lack of methodology to estimate physical leakage as well as estimations of emissions from capture systems, transportation and injection processes	Estimates of leakage from surface facilities unnecessary – fugitive emissions will be reported under national inventories. Unable to estimate at present physical leakage from a storage reservoir. No methodology is required if zero emissions proposal and tier 3 methodology implementation as proposed in IPCC 2006 guidelines	Refer to IPCC 2006 Guidelines for details when published	4	None, reappraise after publication of 2006 Guidelines
71. No methods for estimating and dealing with potential emissions resulting from system failures	Failures of surface facilities, wells pipelines etc., should be covered under existing fugitive emission guidelines. Underground system failure is uncertain. Tier 3 methodology proposed in IPCC 2006 guidelines.	Refer to IPCC 2006 Guidelines for details when published	4	None, reappraise after publication of 2006 Guidelines
Political Processes				
72. No existing methodologies for reporting and verifying reduced emission under the Kyoto Mechanisms	Under development in IPCC guidelines	Refer to IPCC 2006 Guidelines for details when published	4	None, reappraise after publication of 2006 Guidelines
73. Need for CCS accounting rules	Process to include CCS in Kyoto mechanisms need to be established. This could take several years then existing accounting rules can be modified for CCS.	IEA GHG has completed study on inclusion of CCS under CDM schemes. EU initiative to include CCS under EU ETS.	4	None, maintain awareness of developments