June 11–14, 2012

CSLF Technical Group Meeting
&
CO_2 Interactive Workshop

Bergen, Norway

Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF Technical Group Meeting
and
CO_2 Capture Interactive Workshop

Bergen, Norway
11-14 June 2012

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Carbon Sequestration Leadership Forum
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CSLF-T-2012-01
Draft: 23 May 2012
Prepared by CSLF Secretariat

DRAFT AGENDA
CSLF Technical Group Meeting
Radisson Blu Royal Hotel
Bergen, Norway
11-14 June 2012

Tuesday, June 12

08:30-09:00 Registration

09:00-10:45 Technical Group Meeting
Kongesal 4

1. **Opening Remarks**
   Trygve Riis, Technical Group Chair, Norway
2. **Welcome from Norway**
   Norway
3. **Introduction of Delegates**
   Delegates
4. **Adoption of Agenda**
   Trygve Riis, Technical Group Chair, Norway
5. **Review and Approval of Minutes from Beijing Meeting** CSLF-T-2011-08
   Trygve Riis, Technical Group Chair, Norway
   John Panek, CSLF Secretariat
6. **Review of Beijing Meeting Action Items**
   Trygve Riis, Technical Group Chair, Norway
   John Panek, CSLF Secretariat
7. **Report from Secretariat**
   - Global CCS Institute/CSLF Integration Workshop
     – *special report from CSLF Secretariat*
   - CSLF Financing Roundtable
     – *special report from CSLF Secretariat*
   - CSLF Capacity Building Activities
     – *special report from Tony Surridge, South Africa*
     – *special report from CSLF Secretariat*

   John Panek, CSLF Secretariat
8. **CCS in Norway**
   Bjørn-Erik Haugan, CEO, Gassnova, Norway

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9. Update from CO_2 Field Lab Project
Menno Dillen, Research Director, Geophysics and Reservoir Technology Department, SINTEF, Norway

10:45-11:00 Refreshment Break

11:00-12:30 Continuation of Meeting

10. Report from Projects Interaction and Review Team
Clinton Foster, Australia

11. Approval of Projects Nominated for CSLF Recognition

- Illinois Basin – Decatur Project
  presented by Robert Finley, Director, Advanced Energy Technology Initiative, Illinois State Geological Survey, University of Illinois
- Illinois Industrial Carbon Capture and Storage Project
  presented by Scott McDonald, Biofuels Development Director, Archer Daniels Midland Company
- Air Products CO_2 Capture from Hydrogen Facility Project
  presented by Vince White, Research Associate, Energy Technology, Air Products and Chemicals Inc.

12:30-14:00 Lunch

14:00-15:30 Continuation of Meeting

12. Update on 2012 and 2013 CSLF Technology Roadmaps
John Panek, CSLF Secretariat
Clinton Foster, Australia
Trygve Riis, Technical Group Chair, Norway

13. Report from Assessing Progress in Technical Issues Affecting CCS Task Force CSLF-T-2012-02
Clinton Foster, Australia

14. Report from Risk Assessment Task Force CSLF-T-2012-03
Grant Bromhal, United States

15. Overview of Technical Group Action Plan CSLF-T-2012-04

- New Task Forces
- Deferred Actions
- Proposed New Actions
- Related Activities

John Panek, CSLF Secretariat

16. Report from Technical Challenges for Conversion of CO_2 EOR to CCS Task Force CSLF-T-2012-05
Stefan Bachu, Canada

17. Report from CO_2 Utilization Task Force CSLF-T-2012-06
Joseph Giove, United States

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18. Report from Storage and Monitoring for Commercial Projects Task Force CSLF-T-2012-07
Trygve Riis, Norway

19. Report from Technical Gaps Closure Task Force CSLF-T-2012-08
Richard Aldous, Australia

15:30-15:45 Refreshment Break

15:45-16:30 Continuation of Meeting

20. Presentation on CCS Activities of University Centre in Svalbard
Gunnar Sand, Program Manager, SINTEF and UNIS, Norway

21. Discussion of Ideas for Future Technical Workshops
Meeting Attendees

22. Date and Location of Next Technical Group Meeting
John Panek, CSLF Secretariat

23. New Business
Delegates

24. Action Items and Next Steps
John Panek, CSLF Secretariat

25. Closing Remarks/Adjourn
Trygve Riis, Technical Group Chair, Norway

18:00 Meet in Hotel Lobby for Cultural Event and Reception / Dinner

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Wednesday, 13 June

10:00-21:00 **Visit to CSLF-recognized CO_2 Technology Centre Mongstad (TCM) Project**
Transportation via TBD
(casual dress, walking shoes, and all-weather jacket recommended)

10:00 Bus departs Radisson Blu Royal Hotel
11:15 Arrive Mongstad
11:30 Short Presentations on Selected Activities in R&D in Norway
- Project Experience Overview (*Lars Ingolf Eide*)
- CCS R&D Program in Norway (*Åse Slagtern*)

12:30 Lunch
13:30 Tour of the TCM facility
16:30 Depart Mongstad
21:00 Arrive Bergen after Evening Event

Thursday, 14 June

09:00-15:30 **CSLF CO_2 Capture Interactive Workshop**
(see separate Agenda)

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CSLF CO_2 Capture Interactive Workshop

Bergen, Norway
14 June 2012

09:00-09:30
Plenary Session

Workshop Introduction and Background

John Panek, Deputy Director, CSLF Secretariat

Welcoming and Keynote Address

Trygve Riis, Special Adviser, Research Council of Norway

09:30-11:45
Session 1: Scaling Up Carbon Capture for Commercial Deployment

Session Co-Chairs:
Jürgen-Friedrich Hake, Head, Systems Analysis and Technology Evaluation, Forschungszentrum Jülich GmbH, Germany
Ping Zhong, Programme Officer, The Administrative Centre for China's Agenda 21, China
Raconteur: *CSLF Secretariat*

This session will identify and describe possible issues and other considerations for CO_2 capture in commercial-scale projects, such as identifying and understanding the scale-up risks of CO_2 capture processes. Project sponsors will detail their real-world experience utilizing carbon capture at commercial scale.

- **CO_2 Technology Centre Mongstad Project**
  Tore Amundsen, Managing Director, CO_2 Technology Centre Mongstad, Norway
- **Rotterdam Opslag en Afvang Demonstratieproject (ROAD)**
  Hans Schoenmakers, Director of Stakeholder Management, ROAD, Netherlands
- **CO_2 Capture Project – Phase 3**
  Mark Crombie, CCP3 Program Manager, BP Alternative Energy, United Kingdom
- **EERC Partnership for CO_2 Capture (including Fort Nelson and Zama Projects)**
  Mike Holmes, Deputy Associate Director for Research, Energy & Environmental Research Center, United States

11:45-13:00
Lunch

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13:00-16:00

Session 2: Strategies and Technologies for Carbon Capture Cost Reduction

Session Co-Chairs:
Lars Ingolf Eide, Consultant, CLIMIT Programme, Research Council of Norway
Ed Steadman, Senior Research Advisor, Energy & Environmental Research Center, United States
Raconteur: *CSLF Secretariat*

This session will explore possible strategies and other considerations that can reduce the cost for CO_2 capture at commercial scale. These could include regeneration of plant heat and cooling; maximizing efficiency in integrating environmental control systems (i.e., SOx, NOx); achieving the right balance between plant operation and integration; front-end investment as a means of mitigating risk (and thereby costs); identifying and assessing critical equipment; and developing and validating modeling tools.

- **Quest CCS Project**
  Len Heckel, Quest Business Opportunity Manager, Shell in Canada
- **Lacq CO_2 Capture and Storage Project**
  Jacques Monne, CCS R&D Project Manager, Total, France
- **SaskPower Integrated CCS Demonstration Project at Boundary Dam Unit 3**
  Michael Monea, President, CCS Initiatives, Saskatchewan Power Corporation, Canada
- **CO2CRC Otway Project**
  Richard Aldous, CEO, CO2CRC, Australia
- **CO_2 Removal at Sleipner**
  Eivind Johannessen, Principal Researcher, Gas Treating Technologies, Statoil, Norway

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Workshop Concept

- Each project representative will give a presentation emphasizing CO_2 capture aspects and technologies.
- Following the presentations, there will be a discussion among the panelists facilitated by the session co-chairs.
- Following the panelist discussion, there will be an Audience Interaction Q&A session.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF Technical Group Meeting
Bergen, Norway
11-14 June 2012

	Monday **11 June** **Radisson Blu Royal Hotel**	**Tuesday** **12 June** **Radisson Blu Royal Hotel**	**Wednesday** **13 June** **CO_2 Technology Center Mongstad**	**Thursday** **14 June** **Radisson Blu Royal Hotel**
Morning	Meeting Registration *09:00-16:00* CSLF Risk Assessment Task Force *Vågen 1* *10:00-11:00* Storage and Monitoring for Commercial Projects Task Force *Vågen 1* *11:00-12:00*	Meeting Registration *08:30-09:00* CSLF Technical Group *Kongesal 4* *09:00-12:30*	*10:00 Depart Hotel via Bus* Site Visit to CSLF-recognized CO_2 Technology Centre Mongstad Project	**CO_2 CAPTURE WORKSHOP** Plenary Session *Kongesal 4* *09:00-09:30* Session 1: Scaling Up Carbon Capture for Commercial Deployment *Kongesal 4* *09:30-11:45*
	Lunch *12:00-13:00*	Lunch *12:30-14:00*	Lunch	Lunch *11:45-13:00*
Afternoon	CSLF Projects Interaction and Review Team (PIRT) *Vågen 1* *13:00-16:00* CO_2 Utilization Options Task Force *Vågen 1* *16:00-17:00* Technology Gaps Closure Task Force *Vågen 1* *17:00-18:00*	CSLF Technical Group *Kongesal 4* *14:00-16:30*	Site Visit to CSLF-recognized CO_2 Technology Centre Mongstad Project	**CO_2 CAPTURE WORKSHOP** Session 2: Strategies and Technologies for Carbon Capture Cost Reduction *Kongesal 4* *13:00-16:00*
Evening		Cultural Event and Reception/Dinner *18:00-22:00*	Evening Event *21:00 Return to Hotel*	

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2011-08
Revised Draft: 25 November 2011

TECHNICAL GROUP

Revised Draft
Minutes of the CSLF Technical Group Meeting

Beijing, China
20-21 September 2011

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Carbon Sequestration Leadership Forum

www.cslforum.org

CSLF-T-2011-08
Revised Draft: 25 November 2011

MINUTES OF THE CSLF TECHNICAL GROUP MEETING
BEIJING, CHINA
20-21 SEPTEMBER 2011

Note by the Secretariat

Background

The Technical Group of the Carbon Sequestration Leadership Forum held a business meeting on 20-21 September 2011, in Beijing, China. Initial draft minutes of this meeting were compiled by the CSLF Secretariat and were circulated to the Technical Group delegates for comments. Comments received were incorporated into this revised draft. Presentations mentioned in these minutes are now online at the CSLF website.

Action Requested

Technical Group delegates are requested to approve these revised draft minutes.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2011-08
Revised Draft: 25 November 2011
Prepared by CSLF Secretariat

REVISED DRAFT
Minutes of the Technical Group Meeting
Beijing, China
Tuesday & Wednesday, 20-21 September 2011

LIST OF ATTENDEES
Technical Group Delegates

Australia: Niki Jackson
Brazil: Beatriz Espinosa, Viviana Coelho
Canada: Stefan Bachu, Eddy Chui
China: Sizhen Peng, Jiutian Zhang
European Commission: Jeroen Schuppers
France: Didier Bonijoly
Germany: Jürgen-Friedrich Hake
Italy: Giuseppe Girardi, Sergio Persoglia
Japan: Ryo Kubo, Shingo Kazama
Korea: Chang-Keun Yi
Netherlands: Harry Schreurs
Norway: Trygve Riis (Chair), Jostein Karlsen
Poland: Janusz Michalski
Saudi Arabia: Khalid Abuleif, Ali Al-Meshari
South Africa: Tony Surridge (Vice Chair)
United Kingdom: Philip Sharman
United States: Joseph Giove, George Guthrie

CSLF Secretariat

John Panek, Adam Wong, Matt Gerbert

Observer Participants

Gary Kirby, Principal Geologist, British Geological Survey, United Kingdom
Li Zheng, Professor, Tsinghua University, China
Mike Miyagawa, Projects Advisor, Global CCS Institute
Tim Dixon, Manager for CCS and Regulatory Affairs, IEA Greenhouse Gas R&D Programme

Tuesday, 20 September

1. Technical Group Chairman’s Opening Statement

The Chairman of the Technical Group, Trygve Riis of Norway, called the meeting to order and welcomed the delegates and observers to Beijing. Mr. Riis introduced Vice Chair Tony Surridge of South Africa and noted that Vice Chair Clinton Foster of Australia was unable to attend. He expressed his appreciation to the Ministry of Science and Technology, and the National Development and Reform Commission of the People's

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Public of China for hosting this meeting. Mr. Riis provided context for the meeting with a brief summary of the previous CSLF Technical Group Meeting in May 2011 in Edmonton, Alberta, Canada. Four new projects have been nominated and will be reviewed for CSLF recognition. Two other projects were already nominated and reviewed for CSLF recognition at the meeting in Edmonton, and will be brought to the Policy Group later today. Mr. Riis will go to the Policy Group to present all six projects for CSLF recognition. Another topic that will be discussed today is the Technical Group's Five-Year Action Plan, in which 12 proposed Action Plan Components will be ranked by priority for the future.

2. Introduction of Delegates and Observers

Technical Group delegates and observers present for the session introduced themselves. 17 of the 25 CSLF members were present at this meeting, including representatives from Australia, Brazil, Canada, China, the European Commission, France, Germany, Italy, Japan, Korea, the Netherlands, Norway, Poland, Saudi Arabia, South Africa, the United Kingdom, and the United States. Observers representing Brazil, Canada, China, Hong Kong, Japan, the Netherlands, the United Kingdom, and the United States were also present, along with representatives from the Global CCS Institute, IEA GHG, and UNIDO.

3. Adoption of Agenda

The Agenda was adopted with one minor addition. Item 16 on the agenda was amended to include two presentations: one by the Global CCS Institute and one by the IEA GHG.

4. Review and Approval of Minutes from Edmonton Meeting

The Technical Group minutes from the May 2011 meeting in Edmonton, Alberta, Canada, were approved as final with no changes.

5. Review of Edmonton Meeting Action Items

John Panek of the CSLF Secretariat reported that all action items from the Edmonton meeting had been completed or were in progress.

6. Report from CSLF Secretariat

Mr. Panek gave a presentation that provided an update on CSLF Secretariat activities. The 2011 CSLF Technology Roadmap has been developed and was distributed during registration for this meeting. The document can also be found on the CSLF website. Another document is the September 2011 CSLF Strategic Plan Implementation Report (SPIR), found in the conference book. The document includes updates and reports from CSLF recognized projects, task forces, and a variety of other activities.

Based on recommendations from the Technical Group at the Edmonton meeting in May 2011, the In Salah CO_2 Storage Project, Algeria; the Sleipner CO_2 Project, North Sea; and the Weyburn-Midale CO_2 Project, Canada; will each receive a CSLF Global Achievement Award during the 2011 CSLF Ministerial Meeting Opening Ceremony. The CSLF has also received project submission forms from four projects for CSLF recognition. This is in addition to the two projects that were received prior to the Edmonton meeting and approved by the Technical Group at that meeting. That brings the total number of projects up for CSLF recognition to six.

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Attendees were also encouraged to go to the CSLF website to sign up for daily updates from the CSLF on carbon capture, utilization and storage (CCUS) activities. Mr. Panek then noted that in the September 2011 CSLF Strategic Plan Implementation Report (SPIR), there are several photographs from the recent CSLF Storage and Monitoring Projects Interactive Workshop help in March 2011 in Saudi Arabia. Ten CSLF recognized projects participated, and their presentations can also be found on the CSLF website. Mr. Panek thanked Saudi Arabia for hosting such a wonderful event.

7. Approval of Projects Nominated for CSLF Recognition

Rotterdam Opslag en Afvang Demonstratieproject (ROAD) Project
Harry Schreurs of the Netherlands gave a presentation about the Rotterdam Opslag en Afvang Demonstratieproject (ROAD), nominated by the Netherlands and the European Commission. The goal of ROAD is to demonstrate that an industrial-scale, integrated carbon capture and storage (CCS) chain (i.e., capture on a coal-fired power plant and offshore storage) can be applied in a reliable and efficient way within a 10-year timeframe (by 2020) and can make a substantial contribution to climate change objectives. The project will share knowledge and experiences with other industries, countries, general public, NGOs and other stakeholders. ROAD is one of the six large-scale CCS demonstration projects within the European Energy Programme for Recovery (EEPR). Captured CO_2 will be transported via pipeline and injected into depleted gas reservoirs under the North Sea. After brief discussion, there was consensus by the Technical Group to recommend CSLF recognition for this project.

CGS Europe Project
Gary Kirby, Principal Geologist, British Geological Survey, United Kingdom, gave a presentation about the CO_2 Geological Storage (CGS) Europe Project, nominated by France, Italy, Norway, and the European Commission. CGS Europe is a collaborative project involving extensive structured networking, knowledge transfer and information exchange, and is designed to facilitate the large-scale demonstration and deployment of CCUS, and to support implementation of the Directive on geological storage of carbon dioxide in all relevant EU Member States and associated countries. Building on the sound basis of the CO_2 GeoNet Association, the CGS Europe Project will create a pan-European network of experts in the geological storage of CO_2 and a centralized knowledge base which will provide an independent source of information, research and advice for national, European, and international stakeholders. It will enable access to the most up-to-date results of CO_2 storage studies, the sharing of experiences and best practices, support of implementation of regulations, the formulation of relevant new research and the development of appropriate new projects. After brief discussion, there was consensus by the Technical Group to recommend CSLF recognition for this project.

SaskPower Integrated CCS Demonstration Project at Boundary Dam Unit 3 Project
Stefan Bachu of Canada gave a presentation about the SaskPower Integrated CCS Demonstration Project at Boundary Dam Unit 3 Project, nominated by the Canada and the United States. The goal of this project is commercial co-production of electricity and CO_2 for sale using indigenous coal resources. The Boundary Dam ICCS Demonstration Project is expected to be the first application of full stream flue gas treatment for a pulverized coal unit. Operations of the highly integrated system will demonstrate not only CO_2 capture technology, but its interaction and optimal thermodynamic integration with the heat power cycle and with power production at full commercial scale. The

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captured CO_2 will be used for Enhanced Oil Recovery. After brief discussion, there was consensus by the Technical Group to recommend CSLF recognition for this project.

CO_2 Capture Project – Phase 3

Philip Sharman of the United Kingdom gave a presentation about the CO_2 Capture Project – Phase 3, nominated by the United Kingdom and the United States. The CO_2 Capture Project (CCP) is a partnership of several major energy companies working together to advance the technologies and to improve operational approaches in order to reduce costs and accelerate the deployment of CCUS. The CCP is currently in its third phase of activity – CCP3 (2009-2013). During the course of CCP3, the program will culminate in at least two field demonstrations of capture technologies and a series of monitoring field trials which will provide a clearer understanding of how to better monitor CO_2 in the subsurface. After brief discussion, there was consensus by the Technical Group to recommend CSLF recognition for this project.

8. Report from Projects Interaction and Review Team (PIRT)

The Acting PIRT Chair, Stefan Bachu, gave a presentation that summarized the PIRT's recent accomplishments. At the Edmonton meeting, the PIRT reached an agreement that the Task Force on Assessing Progress on Technical Issues Affecting CCS should be separated from the PIRT, and report directly to the Technical Group. Also at the Edmonton meeting, the PIRT approved two projects for CSLF recognition: the Jänschwalde Project and the Zero Emission Porto Tolle (ZEPT) Project. The PIRT also discussed the need to simplify the CSLF Project Submission Form and Gaps Analysis Checklist.

At the previous day's PIRT meeting, the four projects that were just approved by the Technical Group were initially reviewed and approved by the PIRT. After approval by the Technical Group, the projects then go for review by the Policy Group. A discussion regarding the level of detail on the CSLF Project Submission Form also occurred. While some argued that the forum should be simpler, there were other arguments to keep it as detailed as possible, particularly if there is a need to uncover what the projects will do and what gaps in knowledge will be address. There was no resolution to the issue, and thus it will be brought up again during the next PIRT meeting.

Dr. Bachu stated that there are now four categories of CSLF recognized projects:

1. Completed Projects
2. Active Projects
3. Inactive Projects
4. Projects that were Withdrawn by Sponsor

Dr. Bachu also briefly mentioned the PIRT's discussion on the Technical Group's Five-Year Action Plan. A decision was made at the PIRT meeting to divide the 12 proposed activities into two categories. One category would be for items taken up by other organizations. The other category would be for items identified by only the CSLF. The PIRT would like to establish a priority list for urgency and importance of these activities within two months. Afterwards, volunteer delegates would be needed within a month after to jumpstart these activities in preparation for the next Technical Group meeting in the first part of 2012.

The PIRT also made recommendations for the 2011 CSLF Technology Roadmap. The PIRT recommends updating the Technology Roadmap every three years. The main content should include an introduction over the current status of CO_2 capture and storage technologies. The module on ongoing activities should be removed and become a web-based document that can be updated annually by delegates and member countries by request of the CSLF Secretariat.

The PIRT was pleased with the recent CSLF Technology Workshop held in Saudi Arabia. Regarding future technology workshops, the PIRT recommends that workshops should be held opportunistically in conjunction with other events, preferably, CSLF meetings. For example, if the next CSLF Technical Group meeting is going to be in Bergen with a visit to the Mongstad Test Center, then that is an opportunity to have a workshop on CO_2 capture.

At the conclusion of the presentation, Mr. Riis opened the floor for questions or comments. Philip Sharman added his thoughts on the CSLF Project Submission Forum. Mr. Sharman stated that while a more simplified list may help at the project approval stage, a longer and more in-depth list is needed at the project evaluation stage and would be useful to refer to. He believed that a full list is more useful to have at the beginning, and that it is more useful to have the project proponent's view of what their project is aiming to assess, even if the CSLF must simplify the list during the approval process.

Chairman Riis announced that during a recent Technical Group Executive Committee teleconference, it was decided that the next CSLF workshop would be organized, in co-sponsorship with the Global CCS Institute, on November 3, 2011 in London, United Kingdom. This workshop is being organized in conjunction with an IEA GHG Executive Committee meeting. Invitations to participate in the workshop will be sent out to relevant large-scale CCS projects which involve integration, as this will be the topic of discussion.

Mr. Panek added that a list of CSLF recognized projects with a strong integration component had been sent to the Global CCS Institute and that invitations would be sent out within the next two weeks. In anticipation of the projects receiving recognition at this meeting, those projects proposed for recognition were included on the list.

Chairman Riis mentioned that the goal is to have about one workshop each year. At the next Technical Group meeting in Bergen, Norway in June 2012, the plan is to have a CSLF workshop on capture in conjunction with the meeting. The third topic to eventually have a workshop on is CO_2 transportation.

Vice Chair Tony Surridge noted that South Africa plans to have a workshop on transportation towards the end of 2012, in October or November. He suggested that it would be another opportunity to hold a CSLF workshop on CO_2 transportation in conjunction with this meeting.

9. Report from Risk Assessment Task Force

The Task Force Chair, George Guthrie of the United States, gave a brief update on the Risk Assessment Task Force (RATF). The RATF meeting earlier in the day discussed three main topics. The first was on interactions with the IEA GHG risk assessment network. The RATF also reviewed the status of their Phase 2 activities, and then discussed the Joint Policy Group and Technical Group Task Force on Risk and Liability.

Dr. Guthrie provided a background to the RATF. The Task Force was initiated in 2006 to examine the risk assessments, standards, procedures, and research activities. A Phase 1 report was completed in 2009 and is available on the CSLF website. Phase 2 activities were initiated in the fall of 2010. With Phase 1, there were several recommendations that the RATF took action on, and some of these led to Phase 2 activities. Dr. Guthrie then reviewed the status of the recommendations. The first recommendation was the notion that risk assessment should be considered in the context of outreach with stakeholders. This recommendation was passed to the Policy Group. The RATF also approved five outreach documents from the Policy Group, which were then approved by the Technical Group at the Pau, France meeting in March 2010. Those documents are available at the CSLF website. During the RATF meeting, a discussion focused on a need for additional outreach activities or outreach documents. The second recommendation out of Phase 1 was that the link between risk and liability should be recognized and considered because of the liability tie on this. RATF felt that this was a Policy Group activity, and thus recommended it to the Policy Group. This led to the formation of the new joint Policy and Technical Group Task Force on Risk and Liability. The RATF is also on the action plan number five of the list of 12 actions from the PIRT. The final recommendation out of Phase 1 was the notion of storage integrity goals, and whether or not there was any possible path forward on developing acceptable risk levels for sites. A paper was developed, which Dr. Guthrie promised to discuss later.

With Phase 2, there were three main tasks. The first task was on the gap assessment relative to CCS tools. Various approaches were used. One of those was leveraging the IEA GHG risk assessment network activities. This has been a good link for the CSLF, as the RATF has received good information back from the workshops, and has had the opportunity to talk at their workshops about the CSLF and its interest in risk assessment. Two short overviews were developed in response to the gap assessment. One of them looked at gaps that were specific to risk assessment in the context of enhanced oil recovery. The second one is a short overview on risk issues related to various phases of CCS projects. The first one will be completed by the end of this year for review by the RATF and will be a room document at the Bergen, Norway meeting in June 2012. The second one on CCS project phases is to prepare for the liability piece coming from the Policy Group in recognition that there could be different phases of liability for a project. The RATF wanted to identify the different risk issues that feed into that liability. The second task for Phase 2 is a feasibility assessment of looking at general technical guidelines for risk assessment that could be applied to specific sites. A document on performance based standards for CO_2 site performance, safety, and integrity was prepared by colleagues in France. This document has had an extensive number of reviews, and comments, and is now ready to also be included in the Phase 2 report. The final task in Phase 2 was to gather further information on what various organizations are doing in the area of technical risk. The RATF decided that this issue should be set aside right now, as this issue would go beyond the scope of what the RATF had for Phase 2, and it was not clear what contribution the CSLF could make to this. This is being considered as a possible activity for Phase 3. However, it has not been resolved whether or not there is a need or for a Phase 3 for the RATF, as this should not be forced as a way of continuing the Task Force.

Dr. Guthrie then showed the status and timelines for Phase 2 documents. The final report should be ready by the spring of 2012. A similar time path is being used for the overview of projects and phases. The paper on performance based standards will be sent out at the same time. The RATF also discussed a proposed path forward for the Joint Policy Group and Technical Group Task Force on Risk and Liability. The proposal was submitted to the Secretariat. Dr. Guthrie showed the five proposed steps that are in the proposal, which will be recommended during the Joint Policy and Technical Group Meeting later in the week. The proposal includes five activities. The first one to establish the Joint Task Force has been completed. The group would have an individual that would then be

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carrying out a lot of the work for the Task Force. This includes a background activity of looking at analysis and critical review of prior work on liability, and comparison of liability frameworks that have been established to date. That would then lead into a more detailed interview of key experts from various disciplines to try to get a better understanding of perspectives on risks, damages, and liabilities. The results of the interviews would then need to be assessed. These would all be used to feed into a set of facilitated workshops that would bring experts together to identify gaps, and methods to address those gaps. The three activities would be combined to propose a path forward for a Phase 2 version of this Joint Task Force, the goal being to have a report in a Phase 2 path forward proposed at the Joint Policy and Technical Group Meeting in 2012.

Didier Bonijoly of France suggested releasing the document from France on performance based standards for CO_2 site performance, safety, and integrity earlier, as it would become less relevant later. After a brief discussion, it was decided that the report will go out immediately to all Technical Group members with a 14-day cycle and, if hearing no objections, will be considered adopted by the Technical Group.

10. Report from Task Force to Assess Progress on Technical Issues Affecting CCS

Stefan Bachu, as Acting Chair of the Task Force to Assess Progress on Technical Issues Affecting CCS, gave a presentation that summarized the Task Force's recent meeting. The main topic discussed was the working groups on covering gaps in knowledge. There was agreement by the Task Force that it will no longer cover scientific gaps, but instead, focus on technical and deployment issues.

The Leader of the Working Group on CO_2 Transportation (Harry Schreurs of the Netherlands) reported that he has contacted the three CSLF-recognized projects that have transportation components and the replies indicated that the projects have information on:

- Selection of the transportation corridor;
- Obtaining rights of way; and
- Handling public concerns.

Mr. Schreurs also suggested that CO_2 Transportation should be the subject of a future CSLF Technical Workshop.

Discussion ensued about CO_2 compression should be considered part of the capture process or part of transportation. It was agreed that CO_2 compression is actually part of both since it occurs first at the capture facility ("behind the plant gate") but it may occur also along the transportation pipeline (booster stations) and in some cases it may occur at the storage site before injection.

Dr. Bachu, as Leader of the Working Group on CO_2 Storage and Monitoring, gave a progress report on the Working Group's activities. A questionnaire has been sent to all 25 CSLF-recognized projects that have a storage component and responses have been received from 17 projects. Based on responses, it appears that there are no show-stopper gaps in knowledge, with only technical issues to be addressed/resolved. The major emerging issue from the responses is that CO_2 capture and storage would be a major cost that would put the respective operators at a significant disadvantage compared to those in the same industry that would continue to vent the CO_2 into the atmosphere. A preliminary conclusion from the survey is that the Project Submission Form should be simplified and should reflect more technical and deployment aspects of CCUS and less scientific aspects.

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11. Schedule and Plan for 2012 CSLF Technology Roadmap Update

A discussion occurred on the plans for the next CSLF Technology Roadmap (TRM). Acting PIRT Chair Stefan Bachu stated that the PIRT recommends that the roadmap be updated every three years, making the next major update in 2013 instead of 2012 (the last major update was in 2010; the 2011 update was minor and concerned only Module 2 of the TRM). The PIRT also believed that the update regarding projects and country activities should be taken out and produced separately as a standalone web-based document to be updated annually at the request and reminder of the Secretariat. This would remove the need for annual TRM updates and will allow the TRM to focus on CCS achievements, challenges and the road ahead. Dr. Bachu also suggested that the table of contents be revised by the Secretariat and be reviewed by a small group of delegates. During ensuing discussion, suggestions were made to release the TRM with each Ministerial meeting. However, some delegates objected to this suggestion, pointing out that time intervals between Ministerial-level meetings are irregular and dictated by other considerations and, therefore, it is unsure when each Ministerial meeting would occur. For example, Ministerial-level meetings were held in 2003 (CSLF founding), in 2004, in 2009, and now in 2011. Ultimately, Chairman Riis announced that a smaller group would be formed to consider this subject and make a decision before the next Technical Group meeting.

12. Technical Group Five-Year Action Plan

Chairman Riis opened the floor for a discussion regarding the Technical Group Five-Year Action Plan, in which 12 Actions were listed. Phillip Sharman believed that a number of the 12 Actions have been addressed by other organizations. Thus, maybe the CSLF can consider the work of other organizations that are already making good inroads into these topics and are producing reports. Therefore the CSLF can focus on looking at the lessons learned and perhaps sharing some of the issues in workshops.

Joseph Giove of the United States wanted to seek a point of clarification on the language in two of the actions: #6 and #7. Action #6 states that the Technical Group will “recommend standards” and Action #7 states that the Technical Group will provide “identification and recommendation of requirements.” Mr. Giove pointed out that “recommends” fell outside of the purview of the group. John Panek stated that the Secretariat would adjust the language. Mr. Panek also noted that for Action #2, the Global CCS Institute has agreed to have the CSLF projects on their mapping website so that the CSLF will have a section of projects which they can maintain. Dr. Bachu again emphasized that the PIRT would like to divide the 12 proposed actions into two categories. One category would be for items taken up by other organizations. The other category would be for items identified by only the CSLF.

Chairman Riis then summarized the discussion. The Secretariat, together with the Technical Group Executive Committee, will review the text and make improvements, such as removing words like ‘recommends’ and ‘standards’. Afterwards, the edited Technical Group Five-Year Action Plan will be sent to delegates for final comments. The delegates are to rank each of the Actions based on level of importance (with 1 as highest priority and 12 as lowest), with one ranking list per CSLF Member. Mr. Riis also requested for volunteers to lead each of the Actions. To that end, Dr. Bachu stated that Canada would like to lead the Action on “Technical Challenges for Conversion of CO_2 EOR to CCS” and Mr. Giove stated that the United States would like to lead the Action on “CO_2 Utilization Options”. Dr. Bonijoly stated that France would like to lead the

Action on “Competition of CCS with Other Resources” (subject to confirmation from the home office). It was understood that, after ranking, any Actions that did not have volunteers to lead would most likely not be acted on.

Wednesday, 21 September

13. Summary of Previous Day’s Session

Chairmen Riis felt that in order to save time, no summary of the previous day’s session was necessary.

14. Guidelines for Safe and Effective CCS in China

Li Zheng, Professor at Tsinghua University, China, gave a presentation on China’s technology and implementation of CCS. Dr. Zheng provided a context of CCS in China, discussing the various challenges and issues faced. He provided information, including pictures, on various CCS demonstration projects in China. Led by a joint partnership between Tsinghua University and WRI, China has successfully conducted a practice for CCS knowledge transfer in a systematic way. The group believes that CCS is not purely a technical issue, and understanding its multi-dimensional characters is essential to ensure its final application. Dr. Zheng stated that CO_2 capture projects should start from the easy ones and proceed to the difficult ones, and that utilization, such as enhanced oil recovery, should be prioritized to ease early CCS development. A book will soon be released that includes seven chapters on knowledge points across CCS technical chain and chronological project chain, and 19 sets of guidelines giving recommendations for important issues in conducting a safe and effective CCS project.

15. Work Plan to Support CCUS Action Group Recommendations

Chairman Riis stated that at the Edmonton meeting, the Technical Group discussed how to proceed and proposed to have an informal meeting with representatives from IEA, IEA GHG, and Global CCS Institute. The organizations were contacted, but no meeting has occurred. The action is currently being monitored, but at this time, there is no clear plan for further action from the Technical Group.

16. CSLF Collaborative Activities

Mike Miyagawa of Global CCS Institute stated that in September, the Global CCS Institute opened a regional office in Tokyo, Japan. This is in addition to their regional offices in Paris, France and North America. The new Japanese office will not only cover Japan, but also neighboring countries like Korea and China.

Tim Dixon of IEA GHG gave a presentation of IEA GHG and its activities. The IEA GHG is a collaborative research programme founded in 1991 as an IEA Implementing Agreement financed by its members. The goal of the organization is to provide its members with definitive information on the role that technology can play in reducing greenhouse gas emissions. IEA GHG activities include publication of more than 120 studies and reports, sponsorship of ten research networks, and co-sponsoring the biennial Greenhouse Gas Technologies (GHGT) conferences, and an annual summer school on CCS for graduate students. Mr. Dixon then discussed various work the IEA GHG has done with the CSLF. The first study idea, originated by the CSLF Technical Group and undertaken by the IEA GHG, was on storage capacity coefficients. The CSLF also provided two additional study ideas in 2010. The first was on CO_2 storage in basalts, and the second was on the effect of shale gas and shale oil production on CO_2 storage. The suggested studies were approved by IEA GHG Executive Committee in 2011, with the second one being expanded to cover the interaction between CO_2 storage and other resources. Mr. Dixon invited the CSLF to submit additional new study ideas by December 2011. Mr. Dixon then briefly showed the IEA GHG's current studies and networks.

17. Next CSLF Technical Group Meeting

Chairman Riis stated that the next Technical Group Meeting would be in Bergen, Norway. The meeting will include a visit to the Technology Center in Mongstad, which has been CSLF recognized and will officially open at the end of 2011. Mongstad is a one hour drive from Bergen. In addition, the plan is to also hold a CSLF workshop on capture. The original plan was to hold this meeting during the first week of June 2012. However, there was a request to move it to the second week of June. The final dates for the meeting will be determined and announced within the next month.

18. New Business

Tony Surridge of South Africa announced that South Africa will be hosting a CCS week from the 24th to the 28th of October. The week will include, on Monday, a CCS project workshop. On Tuesday and Wednesday there will be a conference to disseminate local work being done in South Africa. On Thursday there will be a policy regulatory workshop sponsored by of the Department of Energy. And on Friday there are two workshops: one on risk and the other on public outreach. Details and registration are available online at the South African Center for Carbon Capture and Storage (http://www.sacccs.org.za/). The CCS week is being supported by the CSLF Capacity Building program as well as the South African Center for Carbon Capture and Storage.

19. Current Meeting Action Items and Next Steps

John Panek gave a presentation on the action items from the meeting. Four projects were approved for CSLF recognition and sent to the Policy Group, where they were also approved. Other action items from the meeting are as follows:

Item	Lead	Action
1	Secretariat	Add category for withdrawn projects – "Withdrawn by Sponsor"
2	PIRT	Decision to keep current project submission form
3	Delegates	Proposal to endorse proposed activity "Risk and Liability Assessment for Geologic Storage of Carbon Dioxide – A Proposed Work Plan for CSLF"
4	Technical Group Executive Committee	Consensus for Technical Group Executive Committee to appoint a group to develop a Technology Roadmap Schedule (3 year cycle) • Module 2 to be web based and removed from Roadmap

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Item	Lead	Action
5	Secretariat	Secretariat will adjust language of Action Plan to remove "recommendation" • Technical Group Executive Committee will ask Technical Group for additions and priorities • Request volunteers to take lead on individual Actions (Canada - #7, France - #8, & United States - #12 already volunteered)
6	Secretariat	Risk Assessment report will be provided to the Secretariat. Report will go out to all Technical Group members with a 14-day cycle and, hearing no objections, will be adopted by the Technical Group.

20. Closing Remarks / Adjourn

Chairman Riis thanked the delegates, observers, and Secretariat for their hard work. Mr. Riis expressed his appreciation to the Ministry of Science and Technology, and the National Development and Reform Commission of the People's Public of China for hosting this meeting. Mr. Riis gave a special thanks to Harry Schreurs of the Netherlands for his years of active work in the CCS community. Mr. Schreurs will be retiring in March 2012. Chairman Riis then adjourned the meeting.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2012-02
07 May 2012

TECHNICAL GROUP

Draft Report from Task Force to Assess Progress on Technical Issues Affecting CCS

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2012-02
07 May 2012

DRAFT REPORT FROM
TASK FORCE TO ASSESS PROGRESS ON
TECHNICAL ISSUES AFFECTING CCS

Note by the Secretariat

Background

The CSLF Task Force to Assess Progress on Issues Affecting CCS was formed at the March 2010 Technical Group Meeting in Pau, France and consists of four Working Groups:

- Working Group on Capture (chaired by the United States)
- Working Group on Transport and Infrastructure (chaired by the Netherlands)
- Working Group on Storage (chaired by Canada)
- Working Group on Integration (chaired by the Global CCS Institute)

The original objective of the Task Force was to complement the Project Interaction and Review Team's (PIRT's) assessment of the CCS readiness of the 30 CSLF-recognized projects. Subsequently, at the March 2011 PIRT meeting in Al Khobar, Saudi Arabia, there was agreement that this new Task Force should abandon the CCS readiness assessment and instead concentrate on assessing technology-related issues that affect CCS.

This Draft Report is a summary of the Task Force's activities and outcomes.

Action Requested

The Technical Group is requested to review and approve this Draft Report.

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Carbon Sequestration Leadership Forum

A Draft Report to the Technical Group:
Task Force to Assess Progress on Technical Issues Affecting CCS.

Contributors

Draft Report – Clinton Foster, Chris Consoli

Working Groups

Capture – George Guthrie

Transport and Infrastructure – Chris Consoli

Storage and Monitoring – Stefan Bachu and Lars Ingolf Eide

Integration – Klaas van Alphen

BACKGROUND

The Task Force to *Assess the progress on closing technology-related gaps that affect the deployment of CCS* was established by the CSLF Technical Group (TG) on recommendation by the CSLF Projects Interaction and Review Team (PIRT) at the PIRT meetings in Canberra (1-3 February 2010) and Pau (15 March 2010). The objective of the Task Force was to complement the PIRT's assessment of the CCS readiness of the 30 CSLF-recognized projects. An outcome of the PIRT meeting in Al Khobar (3 March 2011) was the decision to abandon the CCS readiness assessment, but continue with the assessment on closing technology-related gaps. It was also agreed by the Technical Group (TG) that the word 'gaps' be replaced by the term 'issues'.

The Task Force was renamed to *Assess Progress on Technical Issues Affecting CCS.*

The Task Force elicited an initial response from 42 members from 14 countries, including stakeholders, IEAGHG and GCCSI (Figure 1). Following the TG meeting in Edmonton (18 May 2011), membership was later revised by the Working Group Chairs to focus on technical expertise, with the full knowledge and intent that the findings of the Working Groups would be made publicly available.

The Task Force, chaired by Clinton Foster, Australia, comprises four Working Groups:

- Capture Technologies: chaired by George Guthrie, USA
- Transport and Infrastructure: chaired by Chris Consoli, Australia
- Storage and Monitoring: chaired by Stefan Bachu, Canada
- Integration, from project proposal to implementation: developed in cooperation with, and reported by the Global CCS Institute.

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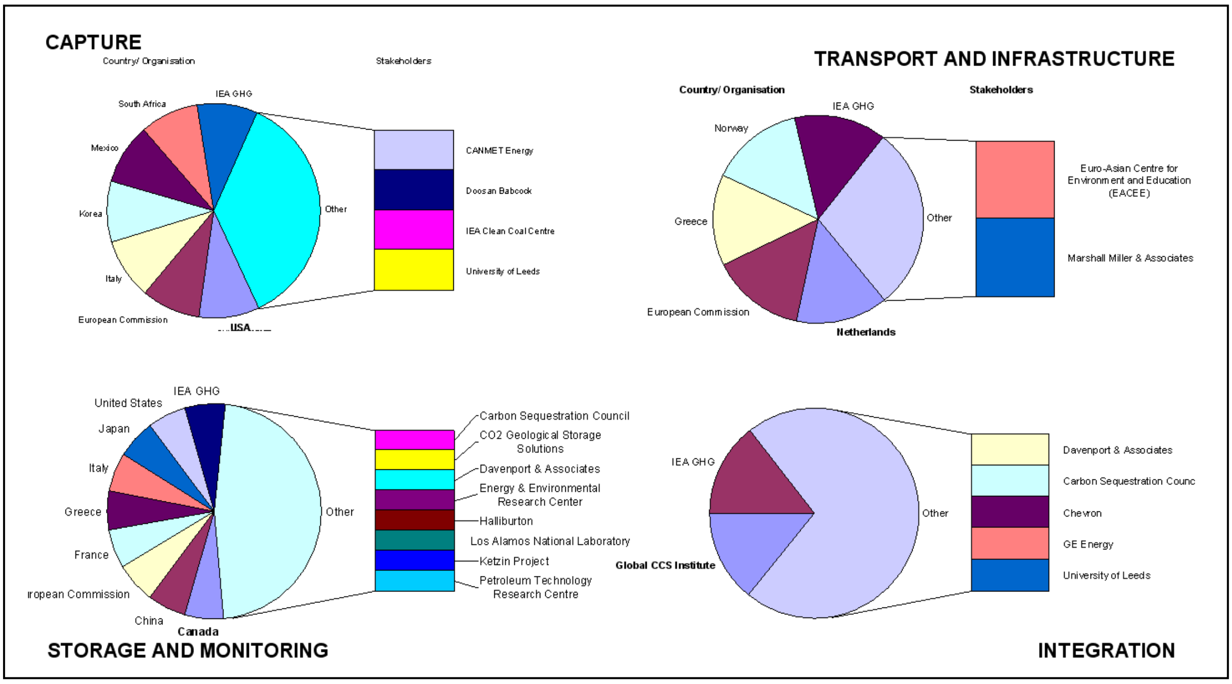

Figure 1. Task Force and Working Group Members (C. Foster. 2010. CSLF Meeting, Warsaw, Poland)

Through consultation between specialists within the Working Groups, technical issues affecting the value chain of CCS have been assessed. This was achieved through initially analysing the major technical issues in CCS technologies, from capture through to storage, both in the R&D and commercial realms. Following this initial study, the focus of further assessments by the Task Force centred on the CSLF-recognised projects. The aim was to identify which projects were, or were not, addressing the issues originally identified. The results have drawn attention to the progress which has been made on the existing technical issues in CCS as well as identifying new technological issues which have emerged (see below). Five major recommendations of the Task Force include:

1. That future CSLF Task Forces within the TG should focus on technical issues affecting large-scale deployment rather than R&D issues.

2. The CSLF should focus on large-scale (>1mtpa) integrated projects as a primary standard, although pilot projects championing new technologies of the CCS chain should also be incorporated and sought by the TG for CSLF recognition.

3. CCS for emissions-intensive industries should be a key focus (eg. cement and steel production), because CCS is the only viable method for reducing emissions at scale.

4. The CSLF TG should focus on, and support the, distribution of knowledge, guideline and best practices to CSLF Projects. This should be seen as a key objective of the CSLF and through a Task Force utilise the expertise/findings of other organisations (e.g., GCCSI and IEAGHG).

5. In addition to technical issues, the Policy Group needs to focus on public acceptance and international regulation/ agreements of CO_2 transport and storage as these are viewed as major hurdles to the rapid deployment of CCS.

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The findings will inform updates of the Technical Roadmap (TRM, CSLF 2011), Strategic Implementation Report, and Project submission forms. Recommendations are summarised below and contained within the individual completed Working Group reports (attached as Appendices A-D).

At the time of submission of this Report, the Capture WG had not yet completed a full report, but a technical analysis checklist was completed (Appendix A). Some recent findings from other, non-CSLF studies, are included for CO_2 capture summary.

SUMMARY OF CHALLENGES AND RECOMMENDATIONS FROM THE WORKING GROUPS

CAPTURE

Challenges

- CO_2 capture and compression is currently the most costly component of CCS (Figure 2). Feron and Paterson (2011) identified the costs of capture within the full CCS chain and identified that capture with compression will cost between \$70 -90 tonne CO_2, transport and storage will cost an additional \$10-50 tonne CO_2, with an overall range of \$80 – 140 tonne CO_2 (although originally given in Australian \$, A\$1~ USD 1). Note: Evidence from advanced storage projects show that the geological storage costs are much greater than detailed below when considering the entire injection program (e.g., when including well remediation).

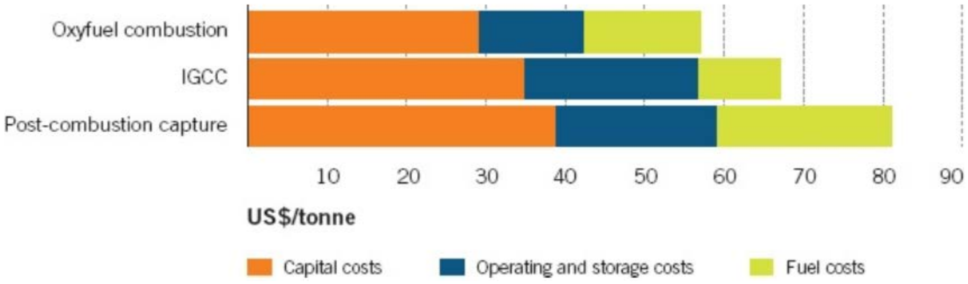

Figure 2. Cost of CO_2 avoided for three major capture technologies (GCCSI, 2011) for coal-fired power generation.

- Although CO_2 capture is common-practice in the natural gas industry, to separate CO_2 (and other impurities) for sales gas, many CCS capture projects are at pilot R&D or lab scale, therefore there is a need for large scale (>1mtpa) capture projects from power plants and other industries, mainly steel and cement manufacturing.

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- The upscaling, energy penalty, environmental impact, and improving the purity of the CO_2 stream are the major technological challenges. Specifically in upscaling, the areas include:
    - Design, cost, and space requirements, operation and integration of CCS with plant facilities.

WG Analysis Findings (with TRM data)

- The majority of CSLF-recognised projects are focussed on, or have a significant component of, capture technologies. However, the CO_2 capture industry is rapidly evolving and new projects should be regularly evaluated to ensure up-to-date technological advancement of capture within the CSLF.
- The rapid evolution of the CO_2 capture industry has resulted in a large number of issues being identified. Many of these are not being, or are poorly, addressed (i.e, only by 1-2 projects). The majority of the issues relates to pre-combustion capture, oxyfuel combustion, novel technologies (e.g., enzyme, cryogenic, or hydrate-based technologies), and interestingly CO_2 compression. In these areas of capture, only one or two projects are addressing the issues related to capture technologies. This probably reflects the embryonic stage of the commercialisation of these technologies to capture CO_2.
- Capture from non-power industrial processes is the focus of four CSLF projects, but they are mostly confined to LNG/EOR/ petroleum production, where capture is part of the operation. It does not reflect ongoing progress of capture in industrial processes such as cement and steel manufacturing.
- The general issues related to advancement of CCS in the capture technology include:
    - Prove technologies at full scale for power plants;
    - Reduce energy penalty through optimized process design and research into improved and novel capture technologies;
    - Generate knowledge that is necessary to validate CCS for bio-power, including exploration of use of existing and new capture technologies and evaluate process efficiencies, economics and HSE aspects; and
    - Build understanding of new capture systems by acquiring pilot scale data (2-4 MW).

***Findings** (from GCCSI-Global Status of CCS, 2011*

The GCCSI report mirrors that of the WG and TRM, with three principal findings:

- A need to construct and operate commercial-scale facilities with carbon capture to demonstrate the host power generation technology integrated with capture.
- CO_2 specifications and the impact of impurities.
- R&D focused on improvement of component performance.

There are also a series of more detailed challenges:

- Increase efficiency of the basic technologies of PCC and combustion (gas) turbines.
- Pre-combustion capture - improve the CO-shift and CO_2-capture with new adsorption media, new catalysts and by optimising process integration.

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- Post-combustion capture - improve solvents through catalysts and chemical modifications to improve loading efficiency, solvent loss and environmental impacts.
- Oxyfuel combustion - more efficient cycles and reduction in the energy penalty for oxygen production.

WG Recommendations

- No recommendations were submitted from the working group.

TRANSPORT AND INFRASTRUCTURE

Challenges

- Although, the technology and infrastructure required for transportation of CO_2 is common practice worldwide and the transportation of CO_2, either via pipeline or tanker (ship, road, and rail) is a mature technology; the challenges for CCS are:
    - Hub and spoke network (multiple-sources, compositions, rates of flow, etc); and
    - Up-scaling of the infrastructure and transport technology required for large-scale, commercial projects.
- Policy and legislative developments (not considered further).

WG Analysis Findings

- 8 CSLF Projects have a component which focuses on transport and/or infrastructure as part of study which also included non-CSLF projects. However, all integrated projects, as well as projects with a storage focus have, in their nature, a transport component and hence will be also addressing key issues of transport; information which could become available to the CSLF, if required.
- All projects addressed infrastructure technical issues; however, for the scope of this analysis, only pilot to large-scale projects were evaluated for infrastructure technology issues.
- The broad issues, detailed below, follow the general nature of the CO_2 transport and infrastructure industry:
    - Effect of impurities in the CO_2 stream on all components of the transport infrastructure;
    - Effect of supercritical CO_2 as a solvent on all components of the transport infrastructure, in particular sealing material; and
    - Research into pipeline incidents (leaks, fractures, effects and impacts) and CO2 dispersion modelling in case of leakage.

WG Recommendations

- The WG recommends that the effect of impurities in the CO_2 stream on transport infrastructure should be the focus of future Task Forces and Project candidates.
- Safety practices and an understanding of risks, including pipeline incidents, associated with the transport of compressed gas should also be the focus of future Task Forces and Project candidates.

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  - Several non-CSLF Projects are currently addressing these two technology-related issues and should be approached (see Appendix C).
- It is important that knowledge and learnings are shared with the CSLF Membership and this should form an integral part of the Technical WG and a future Task Force.
- The Policy Group should examine relevant litigation hurdles yet to be overcome, such as the London Protocol (Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter), allowing the trans-boundary transportation for CO_2 storage purposes.

STORAGE AND MONITORING

Challenges

- Large scale storage is taking place and larger projects are under construction;
  - Generally site specific challenges are the major technical issues faced.
- There are non-technical issues related to the storage technology, which are viewed as major hurdles to any project; both of which have previously stopped the progress of entire CCS projects, including:
  - Public acceptance of storage, especially onshore; and
  - Lack of international regulation and agreements of CO_2 storage in marine environments.

WG Analysis Findings

- The WG identified 25 CSLF projects, which had a storage and monitoring component to their project.
- Through several detailed analyses and concerted effort by the WG, currently, the following issues are either poorly addressed or not being addressed at all:
  - Storage in unconventional media (coals, shales, basalts);
  - Enhanced in-situ mineral trapping and mineralization;
  - Storage engineering for pressure and CO_2 plume control;
  - Monitoring technologies and leakage detection;
  - Effects, risks and remediation of leakage;
  - Site management;
  - Consolidation of various guidelines and “best practices” manuals; and
  - Outreach, addressing public concerns, and educating the public and decision makers (political, regulatory, industry).

WG Recommendations

- Two major issues are not being addressed and the WG recommends that they should be focus for future Storage and Monitoring Task Forces and Project candidates:
  - Development of guidelines; and
  - Storage media other than deep saline aquifers.
- The majority of projects are addressing technical and deployment issues, not scientific issues and this should be reflected in the Project Recognition Questionnaire. Thus it is recommended that the Questionnaire be modified to

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focus on technical and deployment issues rather than the existing largely scientifically-based issues.

- The CSLF Technical Group should refocus its attention and activities in the next 5-10 years on implementation and deployment issues.

INTEGRATION (lead by GCCSI)

Challenges

- The GCCSI (including Institute Member and CSLF Projects), which focuses on facilitating collaboration and knowledge sharing, has already undertaken several studies regarding integration, and achievements include:
    - The development of a generic CCS project development framework, including all activities/task to be undertaken in each stage of a CCS project for each CCS component;
    - Publication, together with American Electric Power (AEP), of 'an Integration report' on AEP's Mountaineer project; and
    - Ongoing work with advanced projects, such as ROAD (Netherlands), Trailblazer (US), GETICA (Romania) and Pioneer (Canada) to make available the learnings from their FEED/Feasibility processes.
- The GCCSI/CSLF WG has identified that the major technical challenge with the CCS chain is the integration of each of the components at a large, commercial scale, and few projects are properly addressing this issue.
- In the early stages of the CSLF, Projects were largely single component based, either capture or storage. However, recently integrated projects, from pilot to commercial scale are receiving CSLF recognition and addressing the issues of integration, which lie largely in three principal areas:
    - A balance between plant operation (outflows, peak production, etc) and integration;
    - Various sectors and industries coming together and working together despite different design and operation philosophies; and
    - Identifying adequate storage at the start of a project.

WG Analysis Findings

- The WG has undertaken a rigorous study incorporating both CSLF and non-CSLF projects (Institute Members) and a workshop of commercial scale project operators was held to identify key integration issues. In summary it was identified that more work is required in the areas of:
    - Integration/regeneration of plant heat (and cooling) in the CO_2 capture process;
    - Integration of environmental control systems (SOx, NOx, and CO_2 removal);
    - Improvement of options for operational flexibility, while ensuring CCS system reliability;
    - Impacts of CO_2 stream composition and impurities for CCS operations (in particular for transportation systems); and
    - Understanding the scale-up risks of CO_2 capture processes.

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WG Recommendations

- The focus of the CSLF TG and Project candidates should be on the first large scale CCS demonstration plants in the power sector and thus:
    - Making CCS work at scale; and
    - To strike the right balance between plant operation and integration.
- The CSLF should facilitate intensive collaboration and communication between the various entities involved in the project.
- Development of a practical, generic CCS project management handbook to highlight key integration issues and associated risks and provide guidance on how they could be addressed.
- For Project candidates, the CSLF should focus on the following two aspects of integration:
    - First steps to any project should be to secure a CO_2 sink (i.e. storage adequately defined (identified, characterised and possibly permitted) before commencing on a capture FEED study.
    - Invest more heavily on the front end of the project (front end loading [FEL]) in order to mitigate risks and cost escalations at a later stage in the project.

CSLF GOVERNANCE RECOMMENDATIONS

1. Nomenclature

1.1 The Task Force reaffirms the importance of using the term *issues*, instead of *gaps*, affecting CCS. Equally important is the term progress – which denotes activity seeking solutions.

1.2 CSLF Project Submission Form and CSLF Gaps Analysis Checklist (GAC):

i. Project Recognition Questionnaire should be simplified.

ii. Gap Analysis Checklist (GAC) should be simplified and synchronized with the checklist of the Technical Roadmap (TRM).

iii. A more granular, detailed Gap Analysis Checklists, as defined by two of the Working Groups, should be utilised. But given that there are limited resources, identified issues are time bound, and that other agencies (such as the Global CCS Institute) undertake annual reviews of progress; the most effective use of these data is to provide them to those relevant bodies undertaking analyses of progress.

ACKNOWLEDGEMENTS

I would like to thank the WG Chairs and their Members for their active participation in this Task Force. In particular, I acknowledge the work of the GCCSI working with the CSLF on their Integration Theme and providing results to this Task Force; also thanks to Research Council of Norway for making available the expertise of Mr Lars Ingolf Eide; and finally thanks to Dr Consoli who compiled the draft of this report.

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Clinton Foster

Task Force Chair

12 April, 2012

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3. Global Status of CCS. 2011. Global CCS Institute Publication (See Figure 3.1) http://www.globalccsinstitute.com/publications/global-status-ccs-2011/online/26886

APPENDIX A. CAPTURE REPORT-

CSLF Technical Issues Analysis Checklist

Capture Technologies

As of 30 March 2012, the Capture WG had completed the following technical analysis checklist, based on responses from 15 of the 35 CSLF identified projects, 6 of which did not address any capture gaps.

A complete report from the Capture WG was not available but some findings based on the references listed at the end of the main report were included.

Technical Issue #	General	# of Projects addressing this issue
1	Development and application of power plant concepts to integrate CO_2 capture	2
2	Development and application of power plant with CO_2 capture (flexibility, operability, control)	3
3	Power plant and CO_2 capture integration and heat recovery	2
4	Development and application of new capture process engineering concepts (flash units, high/low pressure regeneration, vapor compression, split flow, etc.)	2
5	Creation of a full scale capture plant risk analysis (technical, financial, emissions, etc.)	2
6	Advance integration and optimization of components for power station applications	1
7	Capture from non-power industrial processes	4
8	Development of capture systems for NGCC power plants	3
9	CO_2 purity standards for transport and injection (most applicable to oxy-combustion)	3
	Air Separation	
10	Cryogenic air separation	1
11	Ion transport membrane technologies for air separation	
12	Oxygen transport membrane technologies for air separation	

	Post-Combustion Capture	
13	Improved solvent systems	3
14	Advanced chemical solvents that have lower regeneration heat duties	2
15	Improvement in chemical sorbent characteristics	1
16	Advance organic / inorganic non-precipitation absorption systems	1
17	Identify advantages and limitations of precipitating systems (e.g., carbonates)	1
18	Improved process contactors (membranes, packing materials)	2
19	Advanced solid sorbent systems	2
20	Development of highly selective and permeable membrane systems designed for low partial pressure, post-combustion flue gas streams	
21	CO_2 capture pilot plant	3
22	Fully integrated demonstration plant	3
23	Optimize capture process systems to reduce power stations energy loss	2
24	Optimize capture process systems to reduce power stations environmental impact	2
25	Develop better understanding of the assessment of environmental impacts of capture technologies	2
	Pre-Combustion Capture	
26	Develop high efficiency and low emission H_2 gas turbines	1
27	Water-gas shift membrane reactor	1
28	Absorption-enhanced water-gas shift reactor	
29	Improve physical solvent separation process at higher pressure	
30	Improve physical solvent selectivity to improve H_2 losses	

31	Improve physical solvent CO_2 loading at higher temperature	
32	Research into a chemical solvents that utilizes a combination of thermal and pressure swing regeneration too efficiently separate CO_2 from syngas while maintaining pressure	
33	Advance solid sorbent systems	
34	Improvement in membrane selectivity and permeability	
35	Improve membrane stability and durability (hydrothermal, thermal, chemical, physical)	1
36	Optimize membrane process design and integration within the IGCC power cycle	
37	Enhance fuel flexibility - Coal and liquid petroleum gasification, natural gas reformer, syngas cooler	
38	CO_2 capture pilot plant	1
39	Fully integrated demonstration plant	1
40	Optimize capture process systems to reduce power stations energy loss	1
41	Optimize capture process systems to reduce power stations environmental impact	
42	Develop better understanding of the assessment of environmental impacts of capture technologies	
	Oxyfuel Combustion	
43	Development and application of advanced boiler design	1
44	Development and application of oxy-fuel gas turbines	
45	Improved knowledge of oxy-combustion science	2
46	Development and application of high temperature turbines	
47	Development and application of CO_2/N_2 separation technology for industrial processes	

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48	Research into advanced material selections	
49	Development and application of CO_2 purification process (final product conditioning process)	
50	Improve applications to address other emissions (NO_X, SO_X, metals)	
51	CO_2 capture pilot plant	1
52	Fully integrated demonstration plant	
53	Optimize capture process systems to reduce power stations energy loss	
54	Optimize capture process systems to reduce power stations environmental impact	1
55	Develop better understanding of the assessment of environmental impacts of capture technologies	
	Emerging and New Concepts for CO_2 Capture	
56	Research into post-combustion carbonate looping cycles	1
57	Research into chemical looping combustion	2
58	Research into chemical looping gasification	
59	Research into ionic liquids (IL)	1
60	Research into enzyme technology	
61	Research into cryogenic based technologies	
62	Research into hydrate based technologies	
	Initial CO_2 Compression	
63	CO_2 compression utilizing intra-stage cooling	1
64	Refrigeration to liquefy CO_2 and pressure increase using cryogenic pump	
65	Supersonic shock wave compression technology	

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APPENDIX B.

TRANSPORT AND INFRASTRUCTURE REPORT

2011 Report of Transport and Infrastructure WG

Members

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Background

Transport and Infrastructure Working Group (herein Transport WG) formed to review the technical issues (gaps) of the Technical Road Map (TRM). The WG also updated the Project Submission form for CSLF recognition, which is currently ongoing.

Introduction

The long-distance transport of large quantities of substances (i.e. LNG, oil, CO_2, water) over a wide range of environments is common practice worldwide. Moreover, the transportation of CO_2, either via pipeline or tanker (ship, road, and rail) is a mature technology for the EOR and Food/Beverage industries, which generally consists of a single source and composition of CO_2 with direct source to user transport (see Doctor et al. 2005). However, special design considerations will be required for the CCS industry, especially given the potential complexity of the hub and spoke network (multiple-sources, compositions, rates of flow, etc). A second major challenge is seen in the upscaling of the infrastructure and transport technology

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required for large-scale, commercial projects, as well as the associated policy and legislative developments.

Addressing Issues of Transport and Infrastructure

Overall, the Transport WG is well advanced in the identification of issues and addressing them through CSLF-Projects due to the maturity of the transport industry and limited need for new technology. Hence, the expertise, best practices and standards are routine and novel issues that have arisen in the capture and storage technologies are not apparent at this point for the CCS transport component. CSLF-Projects which address issues within Transport are either in the advanced, active or completed categories:

1. CCS Rotterdam (ROAD) (Active)
2. Lacq CO_2 Capture and Storage Project (Active)
3. Geologic CO_2 Storage Assurance at In Salah, Algeria (Active)
4. Regional Carbon Sequestration Partnerships (Active)
5. CANMET Energy Technology Center R&D Oxyfuel Combustion for CO_2 Capture (Active)
6. Dynamis (Completed)
7. CO_2STORE (Completed)
8. IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project (Active)

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Progress on Addressing Issues of Transport and Infrastructure

Technical Roadmap 2011		**CSLF-PROJECT**	**Example Non-CSLF Project**
▪ Conduct cost-benefit analysis and modeling of CO_2 pipeline networks and transport systems for tankers and trucks		All	Chiyoda Corporation Study, 2011
▪ Issues related to the composition of the gas transported in pipelines:	Develop detailed specification with respect to the impurities present from various processes (power station, refineries, industry), which are not present in current CO_2 production units	1, 5, 6	
	Acquire experimental thermodynamic data for CO_2 with impurities (H_2, SOx, NOx, H_2S, O_2, methane, other hydrocarbons etc), develop improved equations of state and establish phase diagram database for the most likely compositions of the CO_2 stream to be transported		
	Understand the effects impurities may have on CO_2 compression and transport, including evaluation of corrosion potentials	1	CO2Europipe
	Gain experience and develop flow models for dense CO_2 streams in pipelines, including depressurization	1, 3	CO2Pipetrains
	Understand the effects of supercritical CO_2 as a solvent on sealing material (e.g., elastomers in valves, gaskets, coatings and O-rings)		
▪ Conduct further research into leaks and running ductile fractures to improve understanding of the effects and impacts of a burst in the pipeline, including experiments and model development			CO2Pipetrains
▪ Improve dispersion modeling and safety analysis for incidental release of larger quantities of CO_2 from the transport system, including the marine setting (e.g., CO_2 pipeline, CO_2 ship, other land transport or intermediate storage tank at harbor)			Kingsnorth E.ON
▪ Develop proper mitigation measures and design, to ensure safe establishment and operation of CO_2 pipelines through densely populated areas		1	CO2Europipe
▪ Identify and define proper safety protocols for CO_2 pipelines, including response and remediation		1, 6	
▪ Update technical standards for CO2 transport as new knowledge become available		n/a	n/a

CSLF Recognised Gaps 2010 Study	**CSLF-PROJECT**
Cost benefit analysis and modeling of CO_2 pipeline and transport systems	1, 2, 6, 7
Tanker transport of liquid CO_2	1, 6
Specifications for impurities from various processes	1, 5, 6
Dispersion modeling and safety analysis for incidental release of large quantities of CO_2	1
Safety and mitigation of pipelines through urban areas	1, 4, 6
Safety protocols to protect CO_2 pipelines, including response and remediation	1
Identify regulations and standards for CO2 transport	1, 6

Advances in Transport and Infrastructure in 2011

1. Policy and Standards

Major legislative arrangements and standards have been addressed for the transport of CO_2. However, only Norway has ratified the amendment to Article 8 of the London Protocol (Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter), allowing for the export of CO_2 streams. Thus the trans-boundary transportation for storage purposes remains proscribed under the Protocol. However, under the OSPAR Convention (Convention for the Protection of the Marine Environment of the North-East Atlantic) amendment for the storage of CO_2 in geological formations under the seabed has been ratified since 2011. The IEA GHG has started a process to identify how trans-boundary CO_2 transport can be performed now and until the London Convention has been ratified by the required number of members.

Cost effective CCS will require trans-boundary transportation and shared pipeline networks. Availability of large storage sinks suggests there will be a requirement for early and close cooperation of different industries and government at all level (GCCSI, 2011). Strategic planning to reduce the long term costs, due to the large scale of CCS, was identified as a vital hurdle to overcome, along with the development of clusters, over-sized pipelines and cross-border restrictions removed. Finally, the scale of CCS transport infrastructure will rival the hydrocarbon industry and thus an efficient legislative and regulatory system must be in place by 2030 at the latest (ZEP, 2011).

Early planning of infrastructure for linking sources and sinks is essential to ensure early deployment of CCS. One example is Northern Europe where there is a huge storage capacity in the North Sea. Developing transport infrastructure for the North Sea would accelerate CCS deployment, especially given that there is low public

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acceptance for onshore storage; a hurdle for CCS in many countries. Such infrastructure should be planned and built large enough to include all larger CO_2 sources in countries close to the North Sea.

2. Technical

Pipeline

According to the Global Status of CCS report (GCCSI, 2011), overall it appears that the construction of infrastructure required for the transportation of CO_2 at a commercial scale is large, especially in the 2020-2030 timeframe. However, it is modelled that the construction of pipeline in Europe, which requires 2,300km by 2020 and 22,000km by 2050, and the United States (8,000-21,000km by 2020; 35,000-58,000km by 2050) is achievable. The scale and cost of the transport of CO_2 will mean it will become an important industrial sector. Both the pipeline and shipping industries are mature, but scale and costs are the major burden.

Clusters proximate to a CO_2 source is identified as a significant step to reduce costs (reduction of over 25% of expenditure), which can be achieved through the participation of multiple stakeholders, speeding up deployment and connecting smaller emitters. Issues relating to hub pipelines include the large diameter pipes required and variation of gas composition from different emitters. The GCCSI have identified two hubs in Australia (Collie, Western Australia and CarbonNet, Victoria), which will use hub-style pipeline design. In Europe the two identified clusters (Rotterdam, Netherlands; South Yorkshire-Humber region, UK) both incorporate a small region of intense major carbon emitting sources with access to depleted fields and reservoirs of the North Sea. The design of both projects will incorporate pipeline and possibly shipping logistics and may incorporate EOR. In Canada the Alberta Carbon Trunk Line is a pipeline development funded partly by the Government of Alberta, which focuses on collecting CO_2 sources for use in EOR in central Alberta.

The ZEP (2011) study is a comprehensive analysis on the economics and feasibility of transport costs in CCS. Results are shown in Tables below. The cluster network of emission sources to storage sites is identified as the most cost effective method. The base case for all assumptions was 20Mtpa capacity. Overall, pipeline costs are mainly CAPEX (>90%) and costs are proportional to distance. Shipping has less CAPEX (<50%) as distance is a small factor to overall costs. It was identified that combining pipe and ships in offshore hub networks are lower risk and cost effective. For example, in the early period during pipeline construction, shipping could provide the major initial transport means.

Although pipeline CO_2 transport has been active in North America for decades, it is important to solve issues related to impurities in the CO_2 stream. Transporting near-pure CO_2 is not challenging, but CO_2 captured from power plants could have impurities at ppm levels that can cause challenges. If small amount of water is present the impurities can cause corrosion, or they can lead to precipitation of solids that could clog the injection well.

Shipping

Design work on larger CO_2 carrier vessels is underway in Norway and Japan, focussing on designs comparable to semi-refrigerated LPG carriers (GCCSI, 2011).

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The CO2Europipe project suggests shipping will be important during the start-up process of a CCS project, not only due to quick start up, but also enables fluctuating volumes of CO_2, and can target small offshore and remote fields. However, these fields need a relatively high injection rate to reduce the turn around time of shipping (Neele et al. 2010). Furthermore, shipping is more cost effective with increasing distance form source to sink and enables the sourcing of several hubs to different sinks.

A feasibility study by the Chiyoda Corporation and the University of Tokyo on a CO_2 carrier for ship-based CCS was conducted where a ship connects directly to injection points without a platform (Chiyoda, 2011). The focus of this preliminary study was an in depth analysis on the regulations, logistics and technical aspects of bulk CO_2 ship-based carriers and supporting infrastructure, including ship times, loading and unloading facilities, and injection design.

The design model focused on a LNG-style ship with injection facilities. It is concluded that ship-based transport is cost-effective for long distances, or where there is uncertainty in matching the scales of source to sink. In the latter, a series of small to medium sized ships prove feasible. Finally, in terms of economics, where intermediate storage is required, ship-based is the best option. The study identified that all the components of transport and associated infrastructure are present; however the complete system will be a new technology (Source: Chiyoda, 2011).

The ROAD project is one of the more advanced studies completed (Tetteroo et al. 2011). It combines a CO_2 Hub, comprising power generation (pre- and post-combustion capture) and industrial including refinery and hydrogen production within the Port of Rotterdam. It will involve onshore pipelines to a central hub (intermediate storage site), whereby offshore pipelines and shipping will transport CO_2 to offshore storage sites (depleted fields). The key points of the ROAD study for this review is a focus on multiple source, multiple sink, but single intermediate hub system and that ship transport will be used over long distances (>150-200km).

Short-term resolutions to be reached

1. Complete Technical Roadmap Gaps and identify Projects (both CSLF and non-CSLF) which address the gaps.
2. Confirm the new version of gaps analysis checklist for the CSLF-Project Submission or retain previous version (see below).
3. Confirm the incorporation of CO_2 compression, both at the capture facility and downstream, within the Transport WG (from CSLF TG Minutes, Beijing: CSLF-T-2011-08)
4. Confirmation of a CSLF Workshop focusing on Transport and Infrastructure.
    CSLF TG Minutes, Beijing: “Vice Chair Tony Surridge noted that South Africa plans to have a workshop on transportation towards the end of 2012, in October or November. He suggested that it would be another opportunity to hold a CSLF workshop on CO_2 transportation in conjunction with this meeting.” CSLF-T-2011-08.
5. Confirm Transport and Infrastructure WG under the Technical Issues. The Task Force will also address goals of Action Plan 5: CO_2 Compression and Transport Milestones (CSLF Beijing).

Plan: The Technical Group will review technologies and assess pipeline standards for CO_2 transport, in particular in relation to impurities in the CO_2 stream. Issues such as thermodynamics, fluid dynamics, and materials of construction, will be considered. Alternatives to pipelines, such as ship transport, will also be assessed.
Technical Barriers: Lack of CO_2 Transport infrastructure
Outcomes: Identification of optimum technical CO_2 transport strategies, both for pipeline and non-pipeline alternatives. Assessment of purity issues as they apply to CO_2 transport. Identification of optimal compression options and alternatives.

i. CO_2 transport workshop- TBD 2014
ii. Interim Report TBD 2015
iii. Final Report TBD 2016

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Technical Issues (Gaps) Tables

Technical Roadmap Priority Activities (2011)

▪ Conduct cost-benefit analysis and modeling of CO_2 pipeline networks and transport systems for tankers and trucks	
▪ Issues related to the composition of the gas transported in pipelines:	Develop detailed specification with respect to the impurities present from various processes (power station, refineries, industry), which are not present in current CO_2 production units
	Acquire experimental thermodynamic data for CO_2 with impurities (H_2, SOx, NOx, H_2S, O_2, methane, other hydrocarbons etc), develop improved equations of state and establish phase diagram database for the most likely compositions of the CO_2 stream to be transported
	Understand the effects impurities may have on CO_2 compression and transport, including evaluation of corrosion potentials
	Gain experience and develop flow models for dense CO_2 streams in pipelines, including depressurization
	Understand the effects of supercritical CO_2 as a solvent on sealing material (e.g., elastomers in valves, gaskets, coatings and O-rings)
▪ Conduct further research into leaks and running ductile fractures to improve understanding of the effects and impacts of a burst in the pipeline, including experiments and model development	
▪ Improve dispersion modeling and safety analysis for incidental release of larger quantities of CO_2 from the transport system, including the marine setting (e.g., CO_2 pipeline, CO_2 ship, other land transport or intermediate storage tank at harbor)	
▪ Develop proper mitigation measures and design, to ensure safe establishment and operation of CO_2 pipelines through densely populated areas	
▪ Identify and define proper safety protocols for CO_2 pipelines, including response and remediation	
▪ Update technical standards for CO2 transport as new knowledge become available	

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Summary of Technical Roadmap Priority Activities (2011)

Element: Transport R&D	
Need	**Gaps**
Create the ability to optimize transport infrastructure to accept CO_2 from different sources, to ultimately reduce the risks and high costs	**Pipeline transport** ▪ Better understanding of the behaviour of CO_2 with impurities and the effects on CO_2 transport ▪ Response and remediation procedures developed in advance of the possibility of CO_2 pipeline accidents **Infrastructure planning** ▪ Better modeling capability of transport network of CO_2 between sources and potential sinks, including compression and optimization

CSLF-Project Submission Checklist (Proposed 2011)

General	
Tanker Transport	
Pipeline Transport	
Ship transport	
Specifications for impurities from various processes	
Regulations, standards and safety protocols, including response and remediation	

CSLF-Project Submission Checklist (2010)

General	
Cost benefit analysis and modeling of CO_2 pipeline and transport systems	
Tanker transport of liquid CO_2	
Specifications for impurities from various processes	
Dispersion modeling and safety analysis for incidental release of large quantities of CO_2	
Safety and mitigation of pipelines through urban areas	

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Safety protocols to protect CO_2 pipelines, including response and remediation	
Identify regulations and standards for CO_2 transport	
Integration	
Identify reliable sources of information and data related to the design, cost, and space requirements, operation, and integration of CCS with energy facilities	
Conduct periodic technical reviews of all aspects of recognized large-scale CCS demonstration projects and report on the "lessons learned"	
On a periodic basis, update the Technology Roadmap to include technology gaps identified during the technical assessment of demonstration projects	
Integrate with existing infrastructure	
Cross-Cutting Issues	
Energy price issues would encourage the take-up of CCS	

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BACKGROUND DATA

Economics (ZEP, 2011)

Transport cost estimates for CCS demonstration projects, 2.5Mtpa

DISTANCE (KM)	180	500	750	1500
Onshore pipe (€/t of CO_2)	5.4	n/a	n/a	n/a
Offshore pipe (€/t of CO_2)	9.3	20.4	28.7	51.7
Ship (€/t of CO_2)	8.2	9.5	10.6	14.5
Liquefaction (for ship transport) (€/t of CO_2)	5.3	5.3	5.3	5.3

Source: ZEP 2011

Transport cost estimates for large-scale networks of 20Mtpa

SPINE DISTANCE (KM)	180	500	750	1500
Onshore pipe (€/t of CO_2)	1.5	3.7	5.3	n/a
Offshore pipe (€/t of CO_2)	3.4	6.0	8.2	16.3
Ship (including liquefaction) (€/t of CO_2)	11.1	12.2	13.2	16.1

Source: ZEP 2011

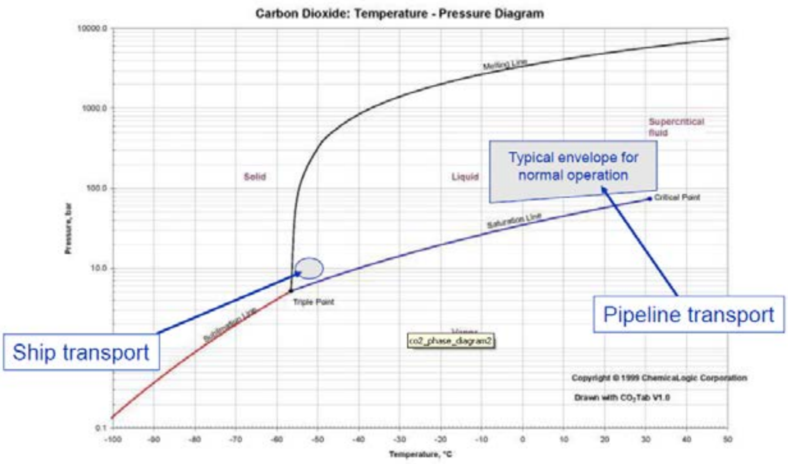

Figure: Phase state of CO2 during transportation. Courtesy of Kaare Helle (DNV), 2011

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APPENDIX C.

STORAGE AND MONITORING REPORT

Carbon Sequestration Leadership Forum

Technical Group

Assessing Progress on Technology Issues Affecting CCS

Report from Working group on CO_2 Storage and Monitoring

Stefan Bachu

Alberta Innovates – Technology Futures

and

Lars Ingolf Eide

Research Council of Norway

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Summary, Conclusions and Recommendations

Based on the previous Gaps Analysis List, the CSLF Working Group on Storage prepared a modified list of gaps with 34 topics. The 25 CSLF recognized projects with a storage component were then examined and analyzed and a list of gaps vs. project was compiled. In the summer of 2011 a questionnaire with the following questions was sent to the 25 projects:

1. Do you agree to the above list of gaps for your project, or should gaps be added or deleted from the list?
2. Would it be possible for you to let us have
    a. The full objectives of the project, e.g., as stated in the application for funding?
    b. The time schedule of the project with important milestones, original and, if relevant, revised?
    c. A summary of the present status of your projects with emphasis on how far you have progressed towards the objectives and the gaps identified for your project?
    d. Your opinion on any additional work that may be needed when the present project is completed?

Responses were received from 18 projects. As one project had been terminated, the response factor was 75%. Responses varied from a few words for each topic to five pages reports.

In the ensuing analysis we also included projects that did not respond, based on the analysis of available information.

Conclusion/recommendations:

- The survey of the CSLF recognised projects revealed that the following technical issues in the area of CO_2 storage are either poorly addressed or important, and should be focus areas relevant to CCS projects and to the advancement of CO_2 storage:
    - Storage in unconventional media (coals, shales, basalts)
    - Enhanced in-situ mineral trapping and mineralization
    - Storage engineering for pressure and CO_2 plume control
    - Monitoring technologies and leakage detection
    - Effects, risks and remediation of leakage
    - Site management
    - Consolidation of various guidelines and “best practices” manuals
    - Outreach, addressing public concerns, and educating the public and decision makers (political, regulatory, industry)
- The majority of projects are addressing technical and deployment issues, not scientific issues and this should be reflected in the Project Recognition Questionnaire
- The Project Recognition questionnaire should be simplified
- The CSLF Technical Group should refocus its attention and activities in the next 5-10 years to implementation and deployment issues

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1. Background

Following meetings of the CSLF Projects Interaction and Review Team (PIRT) in Canberra (1-3 February 2010) and in Pau (15 March 2010), the CSLF Technical Group accepted the recommendation that a new Task Force be formed to assess the progress on closing technology-related gaps that affect the deployment of CCS. The Task Force would complement an ongoing activity of the PIRT to assess the level of CCS readiness of the existing 30 CSLF-recognized projects. However, at the PIRT meeting in Al Khobar on 3 March 011 it was decided to terminate the CCS Technology Readiness Assessment activities and instead undertake only the gap analysis.

The Task Force comprises four Working Groups:

- Capture Technologies Working Group, chaired by George Guthrie, USA
- Transport and Infrastructure Working Group, chaired by Harry Schreurs, Netherlands
- Storage and Monitoring Working Group (hereafter called S&M WG), chaired by Stefan Bachu, Canada
- Integration Working Group, chaired by Kathy Hill, Global CCS Institute

The Working Groups were asked to focus on the progress of each of the technical key elements in the respective field that will affect the deployment of CCS.

As a guide to this effort, the PIRT developed preliminary Gap Analysis Checklists (GAC) of technology-related gaps for each working group during its Canberra meeting. In order to provide an opportunity for project managers to verify the accuracy of the matrix created containing the gaps and the CSLF-recognized projects, the CSLF Secretariat prepared and sent out an individual gap analysis worksheet based on the matrix to each of the 27 active or completed CSLF-recognized projects. Responses were received from 15 projects, and corrections provided in these responses were incorporated into the matrix. The analysis was ready in September 2010 and presented to PIRT in the Warsaw meeting 6 – 8 October 2010. An update version that included responses from a few more projects became available on 18 April 2011, covering 18 projects in total.

Each Working Group was asked to examine the GACs used by the CSLF Secretariat and identify any mistakes, wrong issues, and missing issues relevant to that Working Group, which would allow the Task Force to produce a revised gaps checklist. Each Working Group should then assess how the current CSLF-recognized projects address these gaps, and monitor other projects that address the same gaps.

One application of the GAC would be to help identify new projects that would address any remaining gaps.

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2. The Storage and Monitoring (S&M) Checklist

As the S&M WG members worked on the S&M GAC, its granularity increased because Working Group members were adding very detailed subjects and details in their own areas of expertise to the point where it was becoming unmanageable.

It was also noted a certain mismatch between the CSLF Technology Roadmap (TRM) and the GAC in terms of categories – the “Gaps Identification” module of the Roadmap covers only Capture, Transportation, Storage, and Integration, and does not identify Monitoring as a separate category (it is included in Storage). Nor were all items in the TRM addressed by the GAC and vice versa. It was therefore suggested that the Roadmap and the Gap Analysis Checklist should be synchronized at a later stage.

Efforts to balance the granularity of the S&M GAC between the desired and the manageable continued throughout the spring of 2011 and the final version, consisting of 34 items, was approved at the Edmonton meeting of the PIRT and Technical Group on 18 – 20 May 2011. The final GAC as used towards the projects is included as Appendix 1 to this report.

3. Approach

The S&M WG used the list of CSLF recognized projects according to the list as of June 2011 and selected the projects that included storage and/or monitoring. These are listed in Table 1, for a total of 25 projects.

Table 1. CSLF Projects with a storage and/or monitoring component as of June 2011 in alphabetic order

Project Name
Alberta Enhanced Coal-Bed Methane Recovery Project (*project completed*)
CASTOR (*project completed*)
CCS Belchatów Project
CCS Northern Netherlands
CCS Rotterdam
China Coalbed Methane Technology / CO_2 Sequestration Project (*project completed*)
CO_2 Capture Project (Phase 2) (*project completed*)
CO2CRC Otway Project
CO_2 Field Laboratory
CO_2 GeoNet

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CO_2 SINK *(project completed)*
CO_2STORE *(project completed)*
Dynamis *(project completed)*
Fort Nelson Carbon Capture and Storage Project
Frio Project *(project completed)*
Geologic CO_2 Storage Assurance at In Salah, Algeria
Gorgon CO_2 Injection Project
Heartland Area Redwater Project
IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project
Lacq CO_2 Capture and Storage Project
Quest CCS Project
Regional Carbon Sequestration Partnerships
Regional Opportunities for CO_2 Capture and Storage in China *(project completed)*
SECARB Early Test at Cranfield Project
Zama Acid Gas EOR, CO_2 Sequestration, and Management Project
ZeroGen Project (Terminated, not included in analysis)

The following questions were asked of all 25 projects along with the GAC:

"The WG on storage has used information on the recognized projects that is available from the CSLF website and other easily available information to identify which projects are addressing the various gaps. From the information at hand we have found that your project "NN" is addressing the following gaps:

XX,YY, ZZ, …. and ...

However, we feel that the information at hand is insufficient to identify the full extent to which your project addresses the gaps and to what extent it will contribute to closing the gap. We will therefore appreciate your feedback on the following:

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1. *Do you agree to the above list of gaps for your project or should gaps be added or deleted from the list?*
2. *Would it be possible for you to let us have*
   - a. *The full objectives of the project, e.g. as stated in the application for funding?*
   - b. *The time schedule of the project with important milestones, original and, if relevant, revised?*
   - c. *A summary of the present status of your project with emphasis on how far you have progressed towards the objectives and the gaps identified for your project?*
   - d. *Your opinion on any additional work that may be needed when the present project is completed? "*

The questionnaire was sent out in two batches, the first in early July and the second in early August 2011. The survey closed on 9 September 2011. By that time 17 responses had been received. It turned out that one project had been terminated without being completed, thus there were in reality only 24 projects. One response came in late, so the final response was 18 out of 24, or 75%.

Several of the projects in Table 1 are completed as CSLF recognized projects. However, many of them have continued in a new phase and some projects included the activities of the new phase in their responses. To the extent that the continuation addresses one or more gaps, this is included in the results.

For the six projects that did not respond to our survey, the S&M WG used information at hand to find what gaps these projects are addressing. These interpretations are included in the analysis and introduce a small uncertainty in the results.

It should be noted that two of the projects are networks and that their objectives, status and responses may be difficult to interpret in the setting of the gap analysis checklist.

4. Results

The character of the responses varied significantly, from a few words or just a list of gaps that the project addresses, to reports of five pages or more. All responses answered question 1 above by either agreeing or suggesting gaps that should be added to, or deleted from the list.

4.1 Question 1 – projects vs. gaps

The results in terms of "which projects are addressing what gap" were entered into a matrix and the number of projects that are addressing the gaps was summed up. The results are shown in Table 2.

Two general items stand out as not being addressed by any CSLF recognized project:

1. Other storage media than deep saline aquifers
2. Development of guidelines

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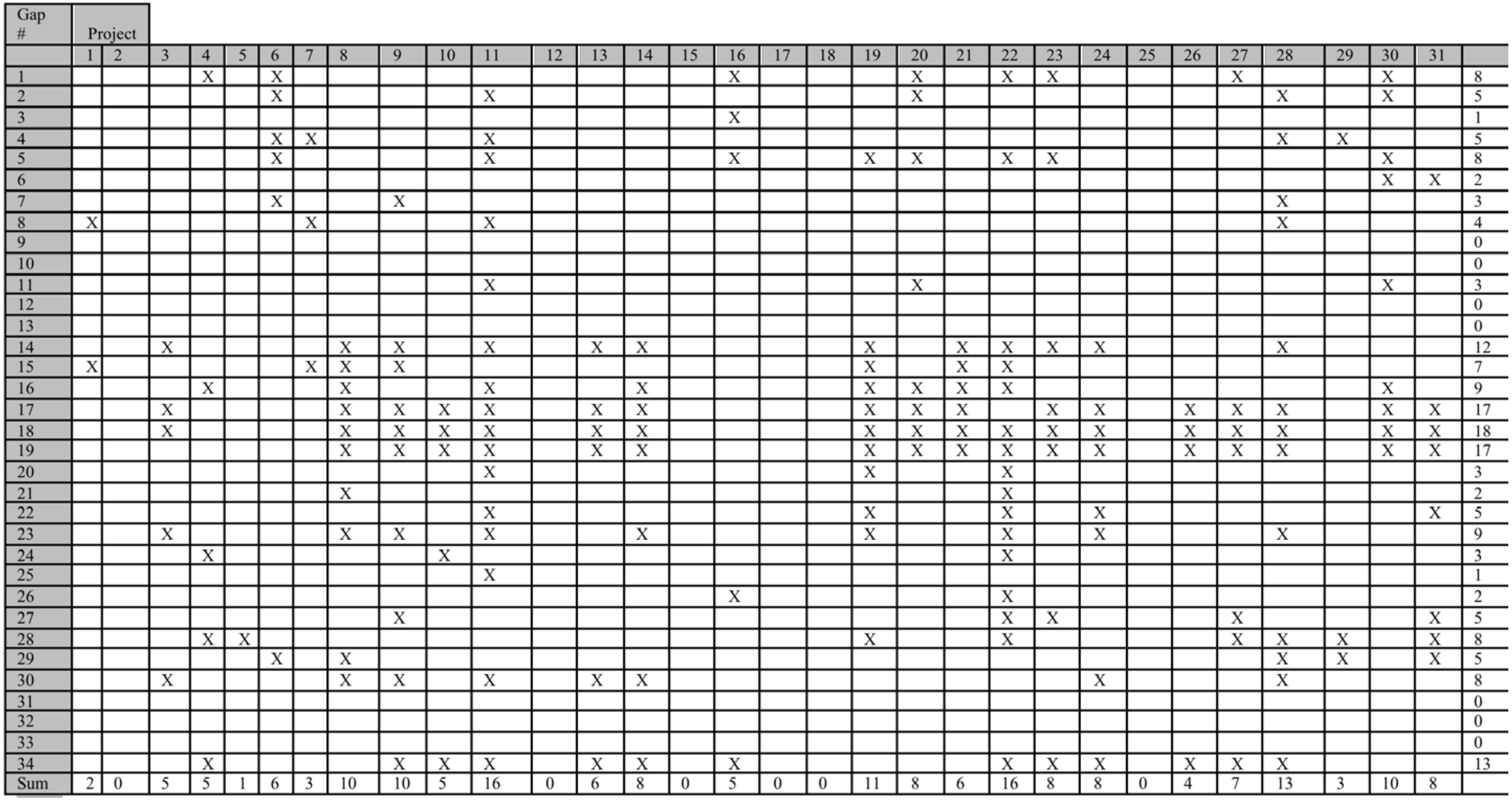
Table 2. Matrix showing projects that address the different gaps, including non-responses



Gap #	Project																														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	
1				X		X										X				X		X	X				X			X		8
2						X					X									X								X		X		5
3																X																1
4						X	X				X																	X	X			5
5						X					X					X			X	X		X	X							X		8
6																														X	X	2
7						X			X																			X				3
8	X						X				X																	X				4
9																																0
10																																0
11											X									X										X		3
12																																0
13																																0
14			X					X	X		X		X	X					X		X	X	X	X				X				12
15	X						X	X	X										X		X	X										7
16				X				X			X			X					X	X	X	X								X		9
17			X					X	X	X	X		X	X					X	X	X		X	X		X	X	X		X	X	17
18			X					X	X	X	X		X	X					X	X	X	X	X	X		X	X	X		X	X	18
19								X	X	X	X		X	X					X	X	X	X	X	X		X	X	X		X	X	17
20											X								X			X										3
21								X														X										2
22											X								X			X		X							X	5
23			X					X	X		X			X					X			X		X				X				9
24				X						X												X										3
25											X																					1
26																X						X										2
27									X													X	X				X				X	5
28				X	X														X			X					X	X	X		X	8
29						X		X																				X	X		X	5
30			X					X	X		X		X	X										X				X				8
31																																0
32																																0
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34				X					X	X	X		X	X		X						X	X	X		X	X	X				13
Sum	2	0	5	5	1	6	3	10	10	5	16	0	6	8	0	5	0	0	11	8	6	16	8	8	0	4	7	13	3	10	8	

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For the item “storage medium” no activities reported for the following:

- Unmineable coal seams: Improve understanding the effects of coal rank, quality, stress and other properties on storage potential and capacity, as well as injectivity
- Mineral carbonation: Further investigation of the possibilities of enhancing in-situ mineral trapping of CO_2 and impurities in specific types of settings (basaltic and ultramafic rocks, highly saline aquifers, geothermal)
- Mineral carbonation: Enhancement of trapping and reduction of costs to improve viability; assessment of the techno-economic viability of mineral storage of CO_2
- Other geological formations: Improved understanding of the effect of oil and/or gas production from shale (which normally constitute caprocks) on storage integrity (confinement) and capacity

and modest (i.e. $\leq$ 4 projects) activities reported for the following gaps

- Mineral carbonation: Improved knowledge of thermodynamics and kinetics of chemical and microbiological reactions, as well as impacts on fluid flow, injectivity, and geomechanics (1 project)
- EOR: Co-optimization of CO_2 storage and oil production, and conversion from CO_2-EOR to CCS – lessons to be applied to other storage reservoirs (2 projects)
- EGR Validation: of enhanced gas recovery (EGR) (3 projects)
- ECBM: Technical validation of enhanced coalbed methane recovery (ECBM) and proving feasibility on large scale (4 projects)

Within Guidelines Development no activities were reported for the following gaps:

- Development of protocols for assessing well material alteration and forward simulation of well barrier stability over time
- Development of guidelines and procedures for handling saline produced water at onshore as well as offshore sites in the case of engineered sites where water production is used for pressure and CO_2 plume control
- Consolidation of various “best practices” manuals developed or issued by various individual projects or agencies (e.g., Weyburn Project, NETL, IEA-GHG, etc.) into general sets under the auspices of an international agency or organization (e.g., CSLF, GCCSI, etc.).

Other gaps where there are modest ($\leq$ 4 projects) activities are

- Conducting a comprehensive assessment of storage resource data required for estimation of effective storage capacity worldwide, covering separately DSF (deep saline formations), DOGR (depleted oil and gas reservoirs) and UCS (unmineable coal seams).
- Development and application of improved well abandonment practices for CO_2-rich environments
- Extension, development and adaption of a portfolio of remediation measures if leakage occurs
- Deep Saline Formations: Increased knowledge regarding pressure build-up and use of relief wells and water production (“storage engineering”) as a way to

regulate the pressure during CO_2 injection, advantages as well as disadvantages, utilizing data from the petroleum industry

- Improved understanding of, and ability to monitor and assess, the impacts of CO_2 leakage on ecosystems, including marine settings. This formulation is Gap # 25, which is very similar to Gap # 20. Together, four – 4 – projects reported activities here.

The most popular topics addressed by projects are related to monitoring storage complexes and are (all projects are included, not only those that responded):

- Development and application of low cost and sensitive monitoring technologies, including non-intrusive, passive and long term methods, remote sensing and autonomous sampling techniques, onshore and offshore, for both CO_2 and displaced native fluids (e.g., brine) (19 projects)
- Combination and integration of a range of monitoring techniques to improve resolution, temporal as well as spatial, and reduce costs (18 projects)
- Development and application of monitoring techniques and methodologies that allow for detection and quantification of subsurface leakage (18 projects)

followed by Outreach, Modelling activities and Managing the storage site:

- Development of procedures and approaches for communicating the impacts and risks of geological storage to the general public, media and decision makers in the public and private sectors, from the initiation of a CCS project to its closure and liability transfer (14 projects)
- Further development of appropriate coupled models that include multi-phase fluid flow, thermo-mechanical-chemical effects and feedback to predict the fate and effects of the injected CO_2, including faults and other possible leakage pathways (12 projects)
- Improvement and application of risk assessment tools to identify and quantify the likelihood and consequence of CO_2 leaks and inform effective decision making (11 projects).

4.2 Question 2 – Objectives, status and further work

2a – Objectives

The first part of this question was related to the objectives of the project. None of the projects reported changes to the original objectives.

The majority of projects are addressing technical and deployment issues, not scientific issues, whereas the gaps analysis appears skewed towards scientific issues. This raises a question as to the relevance of Project Recognition Questionnaire.

Completed projects reported advances on addressed issues of general, non-site specific nature, e.g. within

- Fluid flow and flow simulations
- Geomechanics
- Monitoring technologies and strategies
- Best Practice Manual

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- Issues related to Environmental Impact Statements (EIS)

2b,c – time schedule and status

Of the 25 storage project in the CSLF portfolio nine had been completed and one had been terminated at the time of the survey. Of the remaining eight responses, none reported serious deviations from the original schedule although a few reported that they have applied for extending the project, e.g. to prolong an injection period to allow more time for collection of important and relevant data.

2d – need for additional work

This question was intended for completed or close-to-completed projects. Of the nine completed projects five had a strong site-specific character. However, some of these suggested topics for further work that have a more general character. Summing up responses to these questions it appears that the following general issues should be further addressed in the future:

- Develop and test monitoring technologies for different
    - geological formations
    - depths (improving the upscaling)
- Testing of different, specific CO_2 qualities. The chemical and physical behaviour of these impure CO_2 qualities can be monitored by different well-established monitoring techniques at existing test sites.
- Testing different injection regimes and accelerating storage, e.g., capillary trapping. monitoring and determining the residual gas saturation.
- Performing well-bore leakage tests with monitoring the behaviour of the leaking CO_2 and the influences on well cements, casings and installations.
- Testing different abandonment strategies for the wells. Testing different cementations in combination with smart casing concepts.
- Study fracturing processes / effect of fractures, with respect to CO_2 (directly or indirectly) under controlled conditions
- Further progress in geo-modelling based on results from the projects, e.g. improve predictive reservoir modelling through dual-porosity models and incorporate changes in geochemical and geophysical characteristics.
- Further develop and implement protocols and certification schemes
- Integration of observation well data with other monitoring and field data.
- Near surface monitoring and soil characterization and determining seasonal biogenic CO_2 emissions.

5. Discussion

Large scale storage is taking place today and even larger projects have been approved and are under construction. Thus it is difficult to say that there are gaps in form of technical show-stoppers. One respondent pointed this out:

“ We don’t see any gaps that need closing for our project to proceed. At the end of the day the only real gap that the widespread deployment of CCS suffers from is that today it is terribly expensive and can’t compete with industries that continue to simply vent their emissions. Perhaps reframe your question to one of what areas will the project provide further insights/technical demonstrations of the technology.”

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To this one could add two other potential non-technical showstoppers:

- A lack of public acceptance, in particular for onshore storage, as seen in e.g. the Netherlands and Germany
- A lack of international regulations and agreements concerning the storage of CO_2 in marine environments. Although there are positive signs at the national and regional levels, relevant international conventions like OSPAR and London are still not ratified by sufficient number of parties to be legally binding.

A lesson learned during this exercise is the fact that a definition of “gap” may be subjective. Reading through the project descriptions and objectives it appears that many projects have vague or general objectives and that projects interpreted to address the same gaps may have a range of objectives. To determine whether there is a “gap” to close or not, one needs a clear picture of where one is, i.e. state-of-the-art, as well as well where one wants to be, i.e. well defined targets are needed to really identify gaps. CSLF has the former in form of a Technology Roadmap but as group it does not have the latter.

Seen in this context “Technical issues” will be a more relevant concept or a better terminology than “gaps”. We are really looking at activities that will improve tools and reduce uncertainties in CO_2 storage. This in turn may lead to reduced costs and increased confidence in CCS as a climate mitigation option.

This survey has shown that the CSLF recognized projects address most of the identified technical issues but that the majority of the storage projects, as well as the integrated projects with a storage component, are site specific. Therefore, it is recommended that the Project Recognition Questionnaire should be simplified to reflect this fact.

Furthermore, as there appears to be no technical showstoppers and that further work on the technical issues is really a question of improvements rather than removing technical hurdles, it is recommended that the CSLF Technical Group should refocus its attention and activities in the next 5-10 years to implementation and deployment issues.

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APPENDIX 1

CSLF List of Gaps
Storage and Monitoring

In this document, the following acronyms are being used:

- **DSF**: deep saline formations;
- **DOGR**: depleted oil and gas reservoirs;
- **EOR, EGR, ECBM**: enhanced oil recovery, enhanced gas recovery and enhanced coalbed methane recovery, respectively.
- **UCS**: unmineable coal seams;
- **OGF**: other geological formations;
- **MC**: mineral carbonation

If no acronym is being used to specify the type of storage unit, it means that the respective gap applies to all categories

According the CSLF Technology Roadmap 2010 the following actions have been identified to close gaps in knowledge and experience for storage and monitoring of CO_2 in geologic formations:

Gap #	**Storage site characterization and capacity assessment, general**	**Project #**	**Total # of projects**
1	Identification of the exploration and data characterization requirements, and lead times required to underpin the development of demonstration projects, for onshore and offshore.		
2	Improving coefficients for storage capacity efficiency in any storage medium based on modelling and field data, and development and adoption of a system of classification of storage resources similar to the ones used in the petroleum and mining industries.		
3	Conducting a comprehensive assessment of storage resource data required for estimation of effective storage capacity worldwide, covering separately DSF, DOGR and UCS.		
4	Production of digitally-based national, regional and worldwide atlases of CO_2 storage capacity, including both quantitative and qualitative assessments of storage potential, and covering separately DSF, DOGR and UCS.		

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	Issues specific to the storage medium		
5	**DSF:** Increased understanding and modelling of injecting CO_2 into laterally open aquifers to allow a robust storage capacity estimation under dynamic conditions,		
6	**EOR**: Co-optimization of CO_2 storage and oil production, and conversion from CO_2-EOR to CCS – lessons to be applied to other storage reservoirs		
7	**EGR** Validation of enhanced gas recovery (EGR)		
8	**ECBM**: Technical validation of ECBM and proving feasibility on large scale		
9	**UCS**: Improve understanding the effects of coal rank, quality, stress and other properties on storage potential and capacity, and on injectivity		
10	**MC**: Further investigation of the possibilities of enhancing in-situ mineral trapping of CO_2 and impurities in specific types of settings (basaltic and ultramafic rocks, highly saline aquifers, geothermal reservoirs, shale, etc.) and map these. Build on pioneer studies and prove the concept.		
11	**MC**: Improved knowledge of thermodynamics and kinetics of chemical and microbiological reactions, as well as impacts on fluid flow, injectivity, and geomechanics		
12	**MC**: Enhancement of trapping and reduction of costs to improve viability; assessment of the techno-economic viability of mineral storage of CO_2		
13	**OGF:** Improved understanding of the effect of oil and/or gas production from shale (which normally constitute caprocks) on storage integrity (confinement) and capacity		
	Modelling the storage complex		
14	Further development of appropriate coupled models that include multi-phase fluid flow, thermo-mechanical-chemical effects and feedback to predict the fate and effects of the injected CO_2, including faults and other possible leakage pathways.		
15	Improving tools for automated history matching of models with field observations		
16	Assessing long-term post-injection site security using verified mathematical models of storage		

	Monitoring the storage complex		
17	Development and application of low cost and sensitive monitoring technologies, including non-intrusive, passive and long term methods, remote sensing and autonomous sampling techniques, onshore and offshore, for both CO_2 and displaced native fluids (e.g., brine).		
18	Combination and integration of a range of monitoring techniques to improve resolution, temporal as well as spatial, and reduce costs		
19	Development and application of monitoring techniques and methodologies that allow for detection and quantification of subsurface leakage		
20	Monitoring impacts (if any) on the environment, including sub-aquatic and aquatic		
	Managing the storage site		
21	Development and application of improved well abandonment practices for CO_2-rich environments		
22	Improvement of knowledge of the impact of the quality of CO_2 (that is, purity of CO_2 and effects of other compounds contained in the injection stream) on storage capacity and evolution (behaviour), and interactions with the formation brine, rocks and well cements.		
23	Improvement and application of risk assessment tools to identify and quantify the likelihood and consequence of CO_2 leaks and inform effective decision-making.		
24	Extension, development and adaption of the portfolio of remediation measures if leakage occurs.		
25	Improved understanding of, and ability to monitor and assess, the impacts of CO_2 leakage on ecosystems, including marine settings		
26	**DSF**: Increased knowledge regarding pressure build-up and use of relief wells and water production ("storage engineering") as a way to regulate the pressure during CO_2 injection, advantages as well as disadvantages, utilizing data from the petroleum industry		
27	Development and of application cost-effective engineering solutions to secure long term well bore integrity, including well design, construction, completion, monitoring and remediation		

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	Costs and cost evaluation		
28	Investigating the costs associated with storage, including drilling and establishing wells, and monitoring		
	Guidelines development		
29	Improved methodologies and standards to determine practical and matched storage capacity for all types of geological media under current consideration		
30	Development of best practice guidelines (manuals) for storage site selection, operation, monitoring and closure, including risk assessment and response and remediation plans in case of leakage		
31	Development of protocols for assessing well material alteration and forward simulation of well barrier stability over time		
32	Development of guidelines and procedures for handling saline produced water at onshore as well as offshore sites in the case of engineered sites where water production is used for pressure and CO_2 plume control		
33	Consolidation of various “best practices” manuals developed or issued by various individual projects or agencies (e.g., Weyburn Project, NETL, IEA-GHG, etc.) into general sets under the auspices of an international agency or organization (e.g., CSLF, GCCSI, etc.).		
	Outreach and public concern		
34	Development of procedures and approaches for communicating the impacts and risks of geological storage to the general public, media and decision makers in the public and private sectors, from the initiation of a CCS project to its closure and liability transfer		

Additional details used when evaluating projects vs. gap:

Storage site characterization and capacity assessment, general:

Improving coefficients for storage capacity efficiency in any storage medium.

Activities considered for gap closing include*:*

- Development of a robust storage capacity classification system
- Summarizing data needs for storage capacity estimation and site characterization
- Understanding better the effects of variability in rock properties and characteristics on injectivity

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- Understanding better the effects of caprock variability and properties on containment and storage capacity
- Proving the concept of storing CO_2 in basalts, organic-rich shale, gas and oil shale, unconventional hydrocarbon reservoirs (heavy oil, tar sands, tight sands)
- Improving data availability
- Understanding the effects of coal rank, quality and other properties on storage potential and capacity (UCS)
- Improved interpretation of cased hole logs for characterization
- Improved functionality and resolution of available logging tools for characterization
- Improved recognition and interpretation of the nature and characteristics of faults and fractures

Comprehensive assessment of storage resource data required for estimation of practical storage capacity world-wide, covering separately DSF, DOGR and UCS.

The compilation must

- Collate and integrate existing national and regional atlases and apply a consistent methodology for storage capacity estimation
- Identify key data gaps for the main emissions-intensive regions in eastern and south Asia, Western Europe and North America
- Identify the exploration operations required to fill the key data gaps in each region
- Estimate the time, resources and expenditure required for the exploration operations

Formation specific issues

DSF*: Increase geological knowledge and process modelling performance that….*
Activities considered for gap closing include*:*

- Further investigates the key reservoir and cap rock characteristics of deep saline formations relevant to storage injectivity, capacity and integrity (geometry, structure, mineralogy, fluid chemistry, petro-physics, hydrodynamics, geomechanics, geothermal gradient, relative-permeability and displacement pressure, etc.)
- Increases the understanding and modelling of injecting CO_2 into open aquifers (laterally open)
- Provides tools for predicting spatial variability in reservoir and cap rock characteristics, with assessment of uncertainties based on data availability and distribution
- Provides a robust storage capacity classification system and informs the legal end of storage licensing procedures

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Modelling the storage complex

Further development of appropriate coupled models that include multi-phase fluid flow, thermo-mechanical-chemical effects and feedback to predict the fate and effects of the injected CO_2, including faults and other possible leakage pathways.

Activities considered for gap closing may address one or more components of a coupled system and include:

DSF

- Understanding/determination and documentation of residual gas trapping (relative permeability effects) at laboratory and field scales
- Predicting and modelling spatial reservoir and cap rock characteristics with uncertainties
- Understanding CO_2/water/rock interactions and effects on CO_2 trapping and migration, including effects on porosity and permeability
- Evaluation of basin-wide pressure build-up as a result of CO_2 storage at multiple sites, including assessing sustainability of high injection rates in open and closed systems
- Evaluation of petroleum field development impact on aquifer hydrodynamic regime and storage capacity (this refers to decreased pressure, hence higher storage capacity)
- Impact of the quality of CO_2 (composition of the CO_2 injection stream) on interactions with the aquifer water, rocks and caprock, including impact on storage capacity and containment
- Development of coupled HTMC (hydro-thermo-mechanical-chemical) models for CO_2 injection, migration and leakage for a wide range of in-situ conditions (pressure, temperature, water salinity, rock mineralogy), including the feedback loop
- Improvement of databases of parameters needed for modelling geochemical effects
- Improvement in models and software for basin wide geological, reservoir engineering and hydrodynamic modelling, including the behaviour of the displaced formation fluid

UCS

- UCS: Effects of depth, pressure and stress on coal permeability/injectivity
- UCS: Effects of CO_2-coal interactions, particularly for supercritical CO_2 (swelling, plasticization) and methane displacement

MC

- Thermodynamics and kinetics of chemical and microbiological reactions, and impact on injectivity, geomechanics and fluid flow

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Monitoring the storage complex

Development and application of low cost and sensitive CO_2 *monitoring technologies, including non-intrusive, passive and long term methods, remote sensing and autonomous sampling techniques.*

Technologies and actions to be considered for gap closing may address one or more components of a coupled system and include:

- Seismic and non-seismic geophysical techniques
- Evaluation of permanent or semi-permanent sampling points in an observation well
- Improved wellbore monitoring techniques
- Detection of leakage pathways in confining zones at depth before progressing further
- Estimation of leakage flux rates of anthropogenic and natural systems, including use of improved remote sensing
- Detection and monitoring of CO_2 seeps into subaqueous settings and ground surface
- Use of vegetation changes in hyperspectral surveys changes to identify gas levels in the vadose zone
- Identification and development of monitoring techniques (they should meet the requirements of emission credits and trade system)

Development and application of instruments capable of measuring CO_2 *levels close to background and to distinguish between* CO_2 *from natural processes and that from storage*

- Identification of measurement techniques and thresholds for natural and anthropogenic (leaked) CO_2

Managing the storage site

Improved knowledge of the impact of the quality of CO_2 *(that is, purity of* CO_2 *and effects of other compounds) on interactions with the formation brine, rocks and well cements, and storage behaviour*

- Understanding of how geochemical buffering limits pH decrease by carbonic acid, thus avoiding the need for expensive materials in new well construction and old wells remediation

Improvement and application of risk assessment tools to identify the likelihood and consequence of CO_2 *leaks and inform effective decision making.*

Activities considered for gap closing include:

- Detection of initiation of, and sealing of leakage flowpaths in confining zones
- Including induced seismicity and ground movement

- Quantification and modelling of potential subsurface and surface leakage impacts
- Development of risk minimization methods and strategies, including that of leakage
- Assessment of long-term site security post-injection including verified mathematical models of storage

Extension, development and adaption of the portfolio of remediation measures if a leakage occurs. Activities considered for gap closing include*:*

- Detection of initiation of, and sealing of leakage flowpaths in confining zones
- Techniques that can be used to divert CO_2 migration pathways from undesired zones

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APPENDIX D.

INTEGRATION REPORT

CCS PROJECT INTEGRATION WORKSHOP – SUMMARY REPORT

Context and Objective of the Workshop

A key function of the Global CCS Institute is to facilitate collaboration and knowledge sharing between CCS projects and participating researchers, governments and industry. This function is achieved primarily through accessing project knowledge through direct support relationships with Members' CCS projects, and from there, disseminating knowledge to Members and the broader CCS community via the Institute's digital knowledge sharing platform.

In addition to direct acquisition of knowledge from individual projects, the Institute organises thematic workshops focused on initial commercial-scale CCS demonstration projects, and in particular, the key challenges facing their development and the lessons learnt that can be derived from them.

One of the key CCS topics identified by Members of the Institute and Carbon Sequestration Leadership Forum (CSLF) Technical Group was that of CCS Project Integration. It is recognised that the current portfolio of proposed industrial-scale projects includes a large proportion of power-related projects which extend the scope of project integration, and for which the project proponents may have or may not have experience or expertise in all of that scope, particularly the storage components. There is a body of CCS project development history and experience that, if documented, would be of value to the newer generation of projects and proponents.

The Institute's achievements to date in the area of CCS project integration include:

- the development of a generic CCS project development framework, including all activities/task to be undertaken in each stage of a CCS project for each CCS component;
- publication, together with American Electric Power, of 'an Integration report' on the Mountaineer project;
- ongoing work with the advanced projects like ROAD (Netherlands), Trailblazer (US), GETICA (Romania) and Pioneer (Canada) to make available the learnings from their FEED/Feasibility processes.

To build on this work and inform the work programs of the Institute and the CSLF Technical Group, a workshop was organised in November 2011 with primary aims to:

- establish a set of priority actions in relation to technical integration, in particular of a capture facility into a host plant; and
- assess support for, and contents of 'A CCS Project Management Handbook' outlining decision gates/criteria across the whole chain and identifying key integration and critical path issues within/between components of the full CO2 chain.

Workshop Format and Presentations

As a part of the Global CCS Institute's focus on assisting CCS projects through knowledge sharing, a one-day workshop was organised in collaboration with the

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CSLF to share experiences on CCS project integration, and to identify priority integration topics that need further attention to facilitate CCS project development and deployment.

Attendance at the event was restricted to 50 individuals, and to those directly involved in active commercial-size CCS projects, and/or those that could offer a particular relevant experience. This allowed and encouraged open discussions on a range of technical topics related to CCS project integration. The workshop participants also drilled down into the opportunities and challenges associated with integrating the CCS (value/cost) chain from a commercial and management perspective.
The open panel discussions were chaired by Nick Otter, member of the Institute's Technical Advisory Committee, and fed into by a number of high quality presentations from leading projects with experience on key integration themes.

Project Integration – Integrating a capture facility into a host plant

- Matt Usher, CCS Engineering Manager, American Electric Power (AEP). *Presentation and discussion on the level of integration and key interface points between AEP's Mountaineer generating station and the proposed 235MW application of CO2 capture.*
- Olav Falk-Pedersen, Technology Manager, European CO2 Technology Centre Mongstad (TCM) Project. *Presentation and discussion on performance and availability issues in relation to integrating different capture processes into a natural gas combined heat and power plant.*
- Kevin J. McCauley, Director Strategic Planning, Global Technology, Babcock & Wilcox. *Presentation and discussion on a large-scale validation project of oxy-combustion technology, with a particular focus on integration issues.*

Integrating the CCS Chain – adding transport and storage

- Tony Booer, Marketing and Technique Manager, Schlumberger Carbon Services. *Presentation on the timing of storage site characterisation, taking into account the impacts on overall project schedule and key integration issues within the storage part of the CCS chain.*
- Guy Konings, Market Manager Business Development, Stedin. *Stedin is leading the development of the CO2 collection network in the Rotterdam Port area and presented on integration issues related to CO2 specifications and infrastructure design.*

Integrating the CCS Chain – a commercial and management perspective

- Lewis Gillies, Managing Director – Don Valley Power Project, 2Co Energy. *Presentation and discussion on project integration challenges encountered in 2Co Energy's Don Valley Power Project – primarily from a commercial perspective.*
- Gerbert van der Weijde, Funding Agreement Manager, Maasvlakte CCS Project CV – ROAD. *Presentation and discussion on the project integration requirements from a project management perspective during the FEED phase of a CCS project.*

Highlights of Workshop Discussions and Next Steps

The workshop presenters provided a comprehensive overview of the state of play in relation to CCS project activity in different parts of the world. In addition to sharing experiences, the workshop allowed for open discussions on a range of technical and risk management topics related to CCS project integration, including project element (storage, capture, transport) development schedule staging, heat integration, plant operability, environmental control, CO2 specifications, scale-up challenges, the size of equipment and the physical space required.

CCS Plant Integration

Even though it was agreed amongst most of the participants that the focus of the first large scale CCS demonstration plants in the power sector should be on ‘making CCS work at scale’ and that real innovation and integration was more something for next of a kind projects. In these ‘next of a kind’ projects, integration and learning could drive down the costs of CCS, but for now it is importance to strike the right balance between plant operation and integration. Having said that, CCS industry experts acknowledged that more work is needed now in the following areas:

- Integration/regeneration of plant heat (and cooling) in the CO2 capture process;
- integration of environmental control systems (SOx, NOx, and CO2 removal) to maximise
- improvement of options for operational flexibility, while ensuring CCS system reliability;
- impacts of CO2 compositions and impurities for CCS operations (in particular for transportation systems); and
- understanding the scale-up risks of CO2 capture processes.

The speakers also emphasised that one of the keys to successful project integration is to facilitate intensive collaboration and communication between the various entities involved in the project. Indentifying the project team and ‘getting them all in the same tent’ is key for successful project integration. In the case of oxyfuel technology for example, the industrial gas companies and the power companies have different design philosophies that need to come together in a project.

CCS Project Integration

In the afternoon session, the workshop participants engaged in a dialogue around the commercial opportunities and challenges associated with integrating a CCS project. It was found that in order to establish the commercial structure of a CCS project in a prudent way, it is important to clarify the risks and rewards for each party involved in the project from the start. The discussions on this topic centered around the risk of private sector investment in CCS projects, including project financing, and the role of governments in derisking a project. Furthermore, project economics were compared for projects that utilise CO2 for enhanced oil recovery (EOR) versus ones that are not looking to create an additional revenue stream.

In relation to project integration from a project manager’s/project director’s perspective, interesting insights were presented on the timing of storage site characterisation and issues associated with balancing transportation systems for CCS. It was mentioned several times that for many individual CCS projects storage is on the critical path and that ideally it is best to first secure a CO2 sink (i.e. storage adequately defined (characterised and permitted)) before commencing on a capture FEED study. In order to manage this scheduling risk, it is recommended to start exploring a portfolio of storage options from the start of the project. The need to

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invest more heavily on the front end of the project (front end loading or FEL) in order to mitigate risks and cost escalations at a later stage in the project was shared by most workshop participants.

The workshop participants encouraged the Institute and CSLF to continue their work in relation to the development of a generic CCS project management handbook that would highlight key integration issues and associated risks and provide guidance on how they could be addressed. Herein it is important to focus firmly on the more costly aspects of the projects first and to make sure it reads as a practical guideline instead of being prescriptive and academic.

Next Steps

Both the CSLF and the Institute found the workshop discussions a very useful input into their future work programs. The outcomes of the workshop will feed into upcoming events supported/organised by the Institute and CSLF, including an Institute sponsored event in Alberta, Canada on CCS Systems Integration in May 2012 and a CSLF workshop on CO2 capture technologies in Bergen, Norway in June 2012.

Moreover, the Institute will continue with the development of its online CCS project management guide, taking into account the feedback received in the workshop. The Institute will also focus more on the commercial and financial issues related to CCS project development, and has embarked on several studies that look into the nature of business cases for CCS projects, as well as the commercial structure of CCS networks.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2012-03
09 May 2012

TECHNICAL GROUP

Phase II Final Report from CSLF Risk Assessment Task Force

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2012-03
09 May 2012

PHASE II FINAL REPORT FROM CSLF RISK ASSESSMENT TASK FORCE

Note by the Secretariat

Background

At its meeting in November 2006 in London, the CSLF Technical Group created a Task Force to Examine Risk Assessment Standards and Procedures. This Task Force is chaired by the United States with representation from Australia, Canada, France, India, Japan, Netherlands, Norway, the United Kingdom, the United States, and the IEA Greenhouse Gas R&D Programme. A Phase I Final Report was completed in 2009, and included an overview of risk assessment and related methodologies, a review of the existing literature on risk assessment for geologic storage of CO_2, a summary of ongoing risk-assessment activities in various countries, a highlight of critical issues, and an identification of areas where additional information was needed. Phase II activities included a gap assessment to identify CCS-specific tools and methodologies that will be needed to support risk assessment, and a feasibility assessment of developing general technical guidelines for risk assessment that could be adapted to specific sites and local needs. This document is a Phase II Final Report from the Task Force.

Action Requested

The Technical Group is requested to review and approve the Phase II Final Report from the CSLF Risk Assessment Task Force.

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Carbon Sequestration Leadership Forum
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Phase II Report from CSLF Risk Assessment Task Force

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1. Background

At the joint meeting of the Technical and Policy Groups of the Carbon Sequestration Leadership Forum (CSLF) in London (14–15 November 2006), the CSLF Technical Group (CSLF-TG) formed a task force to examine risk assessment standards and procedures.

This task force was formed to address a need identified in the CSLF strategic plan: the development of recommendations for risk assessment standards and procedures.

In Phase I of its activities, the Risk Assessment Task Force (RATF) focused on the identification of potential risks from CCS activities and the examination of risk assessment standards and procedures that can be used to place these risks in context based on their likelihood to occur and their potential impacts.

RATF completed Phase I activities in November 2009. The Phase I Report included an overview of risk assessment and related methodologies, a review of the existing literature on risk assessment for geologic storage of CO_2, a summary of ongoing risk-assessment activities in various countries, a highlight of critical issues, and an identification of areas where additional information was needed.

1.1 Status of Recommendations from RATF's Phase I Report

The Phase I report provided a number of recommendations. The following summarizes those recommendations and any subsequent actions taken by the CSLF:

- *The link between risk assessment and liability should be recognized and considered.* This recommendation was passed to the CSLF Policy Group (CSLF-PG), which then formed a joint task force between the CSLF Policy and Technical Groups. This joint task force initiated action following the CSLF Ministerial Meeting in Beijing (2011). In July 2012, the joint task force will conduct a workshop in Paris at which a range of CCS stakeholders will help to clarify needs in the area of risk and liability.

- *Establish acceptable risk levels – Storage-integrity goals for sites should be discussed.* This recommendation was taken up in Phase II of the RATF and resulted in a white paper discussing performance goals (see Appendix II).

- *The use of risk assessment to ensure successful storage at sites should be considered in the context of stakeholder outreach and communication.* This recommendation was passed to the CSLF-PG, which, through its communication task force, developed a series of fact sheets that were vetted with the CSLF-TG and posted on the CSLF website (cslforum.org/education/index.html#inFocus; see Appendix I).

- *The CSLF-TG's Projects Interaction and Review Team (PIRT) should conduct a gap assessment to identify CCS-specific tools and methodologies that will be needed to support risk assessment.* The PIRT conducted this analysis as part of its overall gap assessment. To augment that analysis, RATF developed two additional assessments as part of its Phase II activities, both of which are summarized in this report. Section 2 presents a brief summary of potential needs/gaps in risk assessment associated with CO_2 storage in conjunction with the use of CO_2 for enhanced oil recovery (EOR). Section 3 presents a brief outline of the variation of risks associated with different

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phases of a project, recognizing that types and likelihoods of risks vary over the course of the project and are likely to be handled by different approaches to liability.

- *The CSLF-TG should consider the feasibility of developing general technical guidelines for risk assessment practices that could be adapted to specific sites and local needs, and subsequently development of such guidelines.* This recommendation was tabled by RATF, pending outcomes from the joint task force on risk and liability.

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2. CO_2-EOR/Storage R&D Needs

The recent emphasis on CO_2 capture, utilization, and storage (CCUS) has added a new dimension to considerations related to risk assessment for CO_2 storage. This section provides a brief overview of these factors.

2.1 Integrity of Pre-Existing Wells

All EOR/storage projects will take place in reservoirs with existing wells that were required for exploration, production and/or injection of water or other fluids for secondary or even tertiary (non-CO_2) recovery. The age of these wells will vary, with some potentially being old. Consequently, completion histories for the wells will also vary. Although well work-overs are common industry practice in conjunction with CO_2-EOR, most wells developed solely in consideration of oil production needs are unlikely to have been drilled, completed and/or abandoned according to requirements specific for long-term CO_2 storage. Some oil fields, particularly in North America, may have hundreds and even thousands of wells. Both the number and condition of these wells must be considered in any assessment of storage integrity, because wellbores that penetrate the primary seal are potential pathways for leakage from the reservoir. In the future, there may also be interest in re-entering fields which are currently idle, where information on the condition of the existing wells, and, possibly even their location, may be absent. Hence, research is needed in a number of areas to mitigate the potential for CO_2 leakage through existing wells:

- Further work on methodologies to detect the presence and location of pre-existing wells.

- Development of new, more quantitative, methods to evaluate the condition (with respect to leakage) of existing wells – e.g., corrosion, cements, and in particular, characterization of the annular region between the casing and the rock.

- Development of statistical methods to characterize the condition of wells in oil fields with a very large number of wells where not every well can be individually evaluated.

- Further work on monitoring of wellbores for leakage.

- Development of improved technologies for remediating old wellbores- can “cement squeeze” technology be improved?

2.2 Optimization of EOR and Storage

Conventional CO_2 EOR production strategies, ie, well spacing, injection interval location, injection pressures, WAG strategies, etc, have been developed in order to maximize oil production while minimizing “loss” of CO_2, where “loss” refers to the CO_2 which remains underground and not reclaimed from produced oil for re-injection. In the future, if CO_2 storage affects the economics of EOR, operators may be interested in optimizing injection strategies for both production of oil and storage of CO_2 (co-optimization of oil production and CO_2 storage). While some work has already been done on this topic (e.g., Kovscek and Cakici, 2005), further research is needed to understand what variables affect this optimization, and how they might be manipulated to affect it.

2.3 Utilization of the Residual Oil Zone (ROZ)

Below what is conventionally recognized as the oil/water contact, oil may still be present, though at a saturation where it is immobile under primary production techniques. CO_2 could be used to mobilize the oil, while at the same time producing pore space for storage. Limited work to date suggests that the potential reserves of oil in ROZs, as well as the potential CO_2 storage volume, may be large. It is noted that currently available storage resource estimates do not take ROZ storage into account. Considerable research needs to be done to assess the feasibility of ROZ EOR plus CO_2 storage:

- The size of the ROZ resource, both for oil production and CO_2 storage, needs to be better defined

- Methods for site-specific characterization of the ROZ and its production and storage potential need to be developed

- Strategies for production and storage need to be developed, including laboratory studies of basic processes, numerical simulations, and field testing

2.4 Utilization of Other Oil Resources

Not all oil reservoirs are considered appropriate for conventional CO_2 EOR. In particular, CO_2 is not conventionally used for enhanced recovery operations if it is immiscible with the oil. Miscibility is a function of mainly pressure and oil properties (gravity). Though immiscible CO_2 EOR is not a new research area, it remains a challenge.

2.5 CO_2 Enhanced Gas Recovery (EGR), and Enhanced Coal Bed Methane (ECBM) and Shale Gas Recovery

In the broader context of linking CO_2 storage with value-added technologies, further research should be undertaken in all three areas related to use of CO_2 for enhanced methane recovery. Use of CO_2 to enhance recovery of natural gas from conventional petroleum reservoirs is not a conventional technology. Studies however suggest that CO_2 could be used as a displacing fluid and/or a re-pressurization fluid to enhance production of methane in conventional reservoirs. However, due to the low pressure in natural gas reservoirs at depletion, the injected CO_2 expands rapidly and mixes with the remaining gas, such that gas mixed with CO_2 would be produced. The field of enhanced gas recovery in a co-optimization scenario should be looked into. The use of CO_2 to enhance production of methane from coal has been field tested, but more research is warranted to understand the processes of CO_2 adsorption onto coal and of coal swelling. The same physicochemical processes which make CO_2 ECBM attractive should also operate in some methane-bearing organic shales, though much research remains to be done.

2.6 Other Miscellaneous Topics

None new, but further research nonetheless is needed:

- Measurement (relative permeability in particular) for fluids consisting of multiple phases and multiple components, specifically water or brine, liquid hydrocarbon (oil), and gas (including CO_2, CH_4, and potentially H_2S). Reported measurements of relative permeability for more than two phases are extremely rare, if they exist at all.

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- Development and validation of reservoir simulators for the prediction of multiphase fluid flow in porous and fractured systems that account for the relative permeability measurements as discussed above.

- Development of monitoring approaches to determine phase saturations in multi-phase systems.

3. Risk-assessment considerations related to various phases of a storage project

As noted in the RATF Phase I report and in many technical studies on CO_2 storage, types and likelihoods of risks vary with different phases of a project (i.e., site-development phase, injection phase, post-injection phase, and long-term phase). Given this

Phase	Issue - Concern	Reason - Rationale
Development Phase	Identification of wells/faults/fractures	Necessary for assess containment integrity. Also identification of faults is important in predicting potential for ground motion associated with fluid injection
	Characterization of natural (background) seismicity	Background seismicity is important both for prediction of potential induced seismicity (which could impact public perception/opinion and could impact containment integrity, surface facilities, other surface structures, etc.)
	Geologic site characterization	Identification and characterization of potential receptors for consideration in risk assessment (e.g., subsurface resources, groundwater, ecosystems, and the public)
		Assess capacity/injectivity

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Phase	Issue - Concern	Reason - Rationale
Injection Phase	Pressure management	Maintenance of maximum bottomhole pressures below the limit imposed by the regulatory agency; Prevention of induced seismicity Prevention of pressure effects beyond the storage complex approved by the regulatory agency Prevention of pressure effect on underground resources (water production, geothermal production, O&G, natural gas storage, …) – on water recharge capacity for open aquifers (risk of flooding)
	Plume tracking	Validate containment integrity, migration of CO_2, capacity and injectivity Verification of stored CO_2 for credits
	Brine tracking	Control displacement and migration of brine
	Leakage detection	Validate containment integrity, protection of subsurface resources, groundwater, ecosystem and the public

Phase	Issue - Concern	Reason - Rationale
Post-Injection Phase	Strategic monitoring for plume/pressure tracking	Define timeframe for monitoring period
		Validate plume stabilization and pressure recovery, ensure long term containment
		Ensure plume does not impinge on pore space not covered under deed or agreement, including other storage reservoirs
		Ensure plume does not impinge on other subsurface resources

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Phase	Issue - Concern	Reason - Rationale
Long-Term Phase	Strategic monitoring	Ensure CO_2 and other potentially displaced gases (such as methane) are not released to the atmosphere Ensure groundwater protection from potential impacts associated with CO_2 or brine

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Appendix I: Risk-Related InFocus Fact Sheets

CCS

inFocus Carbon Capture & Storage

CO_2 Capture — Does it Work?

THE PROCESS OF CAPTURING CARBON DIOXIDE (CO_2) FROM PLANT EMISSIONS IS ALREADY A PHYSICAL REALITY ON A SMALL SCALE. CURRENT RESEARCH EFFORTS ARE FOCUSED ON SYSTEMS FOR CAPTURING CO_2 FROM LARGE COAL-BASED POWER PLANTS, BECAUSE THEY ARE THE LARGEST STATIONARY SOURCES OF CO_2 EMISSIONS. THE ONGOING RESEARCH AND DEVELOPMENT (R&D) CHALLENGE IS CAPTURING CO_2 FROM THESE FACILITIES IN A WAY THAT IS BOTH EFFICIENT AND ALSO MAINTAINS AFFORDABLE PRICES FOR ELECTRICITY. ADDITIONALLY, R&D IS ALSO FOCUSED ON APPLYING CARBON CAPTURE AND STORAGE (CCS) TO NATURAL GAS-FIRED POWER PLANTS AND INDUSTRIAL SOURCES. ADDITIONAL RESEARCH THAT INCLUDES INTEGRATING AND SCALING UP CCS TECHNOLOGY BY BUILDING AND OPERATING COMMERCIAL-SCALE FACILITIES IN A VARIETY OF SETTINGS IS ESSENTIAL FOR MEETING R&D CHALLENGES.

OVERVIEW

CO_2 capture technology is not new or particularly unique — it has long been used by industry to remove CO_2 from gas streams where it is not wanted, or to separate CO_2 as a product gas.[1] What is novel about it in terms of the climate change debate is the research effort to integrate and optimize existing and emerging technologies for the purpose of reducing human-made atmospheric CO_2 emissions. CCS is a combination of technologies for not only capturing, but also transporting and storing CO_2 emissions from fossil fuels.

The carbon capture process has been used for several decades in the petroleum, chemical, and power industries for a variety of reasons relevant to those industrial processes.[2] Capturing all, or even just three-fourths, of the CO_2 in a typical power plant with current technology would require equipment many orders of magnitude larger — a very expensive and highly energy-intensive option.

> "New or improved technologies for CO_2 capture, combined with advanced power systems and industrial process designs, can significantly reduce the cost of CO_2 capture in the future."
>
> United Nations Intergovernmental Panel on Climate Change, Carbon Capture and Storage (2005), 344.
>
> Did You Know?

Worldwide, there are today several operational large-scale projects, along with numerous smaller facilities, demonstrating specific elements of the carbon capture process. According to the Global CCS Institute, at the end of 2010 there were 234 active or planned CCS projects globally, identified across a range of technologies, project types

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[1] OECD/IEA, "Technology Roadmap: Carbon Capture and Storage," 2009, 9.

[2] National Energy Technology Laboratory, "Carbon Sequestration: FAQ Information Portal," n.d., http://www.netl.doe.gov/technologies/carbon_seq/faqs/carbon-capture.html.

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and sectors. Of these, 77 are large-scale integrated projects at various stages of development. Combined, these efforts have successfully demonstrated CCS as a technically feasible CO$_2$ mitigation technology.[3] However, there are no fully integrated, commercial-scale power plants in operation equipped with CCS. Continued research is needed to aggressively pursue the development of low-CO$_2$ technologies and deploy cost-competitive CCS for both new and existing plants.

How is CO$_2$ captured from power plants?

Energy from fossil fuels (coal, oil, and natural gas) is released in the combustion (burning) process. The same chemical reaction that allows fossil fuels to release energy upon combustion also results in the emission of CO$_2$ as a by-product of the combustion process. In pulverized coal systems, which make up the vast majority of America's existing fleet of coal-based power plants, the CO$_2$ must be separated at fairly diluted concentrations from the balance of the combustion flue gases; in other systems, such as coal gasification, it can be more easily separated. After separation, the CO$_2$ is compressed to a liquid-like state (called a "supercritical fluid"), transported (usually by pipeline) to an injection well, and then pumped underground into a secure and continuously monitored geologic storage area, the final stage in the CCS process.

There are three basic types of CO$_2$ capture: post-combustion, pre-combustion, and oxy-combustion.

- **Post-combustion processes** separate CO$_2$ from combustion exhaust gases. CO$_2$ can be captured using a liquid solvent, such as aqueous amine solution. Once absorbed by the liquid solvent, the CO$_2$ is then released by heating to form a pure CO$_2$ stream. This technology is widely used to capture CO$_2$ for use in the food and beverage industry. Post-combustion capture has been carried out successfully, but so far on a relatively small scale.
- **Pre-combustion processes** convert fuel into a gaseous mixture of hydrogen and CO$_2$. The hydrogen is then separated and can be burned without producing any CO$_2$ in the exhaust gas. The remaining CO$_2$ can then be compressed for transport. Compared with post-combustion processes, the pressure and concentration of CO$_2$ in pre-combustion processes is relatively high — making separation easier to achieve and offering the potential to apply novel capture technologies, such as membranes. The fuel conversion steps required for pre-combustion are more complex than the processes involved in post-combustion. This makes the technology more difficult to apply to existing power plants. Pre-combustion capture is used in industrial processes but has not been demonstrated in much larger coal gasification concepts.
- **Oxyfuel combustion processes** use oxygen rather than air for combustion of fuel. This produces exhaust gas that is mainly water vapor and CO$_2$, which are easily separated to produce a pure CO$_2$ stream. Oxyfuel combustion systems are being developed on a small scale, in laboratory or pilot projects. This process can be applied to existing power plants.

Is CO$_2$ currently being captured from plants that generate electricity from coal?

No one is currently capturing CO$_2$ at full scale from plants that generate electricity from coal. However, there are a few CO$_2$ capture applications at coal-fired plants at small scale. Post-combustion separation processes (amine scrubbers) are currently used commercially in industrial coal-fueled boilers to supply CO$_2$ to food and beverage processors and in chemical industries, but these applications are at a scale much smaller than that needed for power-producing pulverized coal or Circulating Fluidized Bed (CFB) plants. CO$_2$ separation processes suitable for Integrated Gasification Combined Cycle (IGCC) plants are used commercially in the oil and gas and chemical industries at a scale close to that ultimately needed, but their application requires the addition of more processing equipment to an IGCC plant and the deployment of gas turbines that can burn nearly pure hydrogen.

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[3] World Coal Institute, "Securing the Future: Financing Carbon Capture and Storage in a Post-2012 World," November 2009, 5.

inFocus: CO_2 Capture — Does it Work?

CAN CO_2 BE CAPTURED FROM ALL TYPES OF PLANTS THAT GENERATE ELECTRICITY FROM COAL?

It is technically feasible to integrate CO_2 capture technologies into all types of new coal-based power plants. However, CCS represents a significant financial investment; cost has been identified as perhaps the greatest single hurdle to CCS deployment.[4] The cost of CO_2 capture using currently available technology is very high — on the order of \$100–\$150 per tonne of CO_2 avoided for first-of-a-kind plants and \$30–\$50 per tonne of CO_2 avoided for n^{th}-of-a-kind plants.[5] A new coal-fired plant can be designed to incorporate CCS from the very beginning, or it can be built to include upfront investments that lower the cost of later adding the technology. Retrofitting existing plants for CCS is expected to be more expensive (in terms of dollars per tonne of CO_2 avoided and the incremental impact on the levelized cost of electricity). The incremental cost of CCS varies depending on the choice of capture technology, the percentage of CO_2 captured, the type of coal used, and the distance to and from the geologic storage area. Capture technologies can also be retrofitted to existing power plants but at an even higher cost and provided that sufficient space is available for the equipment. There are also significant integration and engineering considerations that need to be addressed.

ARE THERE ANY OTHER TECHNICAL CHALLENGES?

All capture systems currently require large amounts of energy for their operation, resulting in decreased plant efficiencies and reduced net power outputs when compared to the same plants without CCS. These "penalties" mean commercially available CCS technologies would add around 80 percent to the cost of electricity for a new pulverized coal plant and around 35 percent to the cost of electricity for a new advanced gasification plant.[6] Research is aggressively pursuing ways to reduce these costs to less than a 10 percent increase in the cost of electricity for new gasification-based energy plants, and less than a 30 percent increase in the cost of electricity for traditional pulverized coal plants. In addition, research is attempting to identify "best practices" that researchers and technology users believe will allow consistently safe and effective long-term CO_2 collection, injection, and storage and provide the basis for a consistent global legal and regulatory framework.

WHERE DOES CARBON CAPTURE TECHNOLOGY GO FROM HERE?

Carbon capture has been clearly demonstrated on a small scale — the vital next step is the successful demonstration of fully integrated, large scale CCS systems on commercial-size power generating stations. There is a global need for significant financial investments to bring numerous commercial-scale demonstration projects on-line in the near future.

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[4] Bryan Hannegan, VP Environment, Electric Power Research Institute, "Future of Coal: Testimony before the U.S. Senate Committee on Energy and Natural Resources," 22 March 2007, 3, 5.

[5] Mohammed A. Al-Juaied and Adam Whitmore, "Realistic Costs of Carbon Capture," Belfer Center for Science and International Affairs, July 2009.

[6] Scott M. Klara, National Energy Technology Laboratory, "Testimony before the U.S. Senate Committee on Appropriations, Subcommittee on Energy and Water Development," 6 May 2009, 3–4, 10–11.

Interesting Facts About Carbon Capture

- One million tonnes of captured CO_2 (in a super-critical liquid state) every year would nearly fill the volume of the Empire State Building in New York City (32 million cubic feet, or 906,000 cubic meters) — source: U.S. National Energy Technology Laboratory (NETL).
- Worldwide there are 234 planned or active CCS projects, 77 of which are large integrated projects in various stages of development — source: Global CCS Institute.
- A 500 megawatt pulverized coal-fired plant produces about 10,000 tons per day of CO_2; a 1000 MW plant emits 6–8 megatonnes (one megatonne = 1 million metric tons) annually — source: Carbon Dioxide Capture and Storage, Howard Herzog, Massachusetts Institute of Technology, pages 265 and 268.
- Total global CO_2 emissions resulting from human activity are currently around 24 gigatonnes per year; the CO_2 storage capacity of hydrocarbon (coal, oil, and gas) reservoirs is estimated to be around 800 gigatonnes (one gigatonne = 1 billion tonnes). The world's deep saline formations may have a storage capacity far greater than this — source: International Energy Agency, Storing CO_2 Underground, page 10.
- Globally there are more than 8,100 CO_2 point sources (primarily fossil fuel electric power plants and industrial facilities) that could conceivably adopt CCS technologies as a means for delivering deep and sustained CO_2 emissions reductions. Collectively these facilities emit about 15 gigatonnes (gigatonne = 1 billion tonnes) of CO_2 annually — source: Global Energy Technology Strategy Program, Carbon Dioxide Capture and Geologic Storage, page 13.
- Governments and businesses need to invest as much as USD $3.4 trillion in 3,400 carbon capture projects worldwide by 2050 as just one measure to cut fossil fuel CO_2 emissions by half from 2005 levels — source: International Energy Agency.

SOURCES FOR ADDITIONAL INFORMATION

- United Nations Intergovernmental Panel on Climate Change, http://www.ipcc.ch/
- International Energy Agency, http://www.iea.org/
- World Coal Institute, http://www.worldcoal.org/
- The World Bank, http://www.worldbank.org/
- European Zero Emissions Platform, http://www.zeroemissionsplatform.eu/

OTHER INFOCUS FACTSHEETS:

- Is Geologic CO_2 Storage Safe?
- Underground CO_2 Storage: A Reality?
- Why Carbon Capture and Storage?
- CO_2 Transportation — Is it Safe and Reliable?
- 10 Facts About CCS

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inFocus CCS
Carbon Capture & Storage

CO_2 Transportation — Is it Safe and Reliable?

SAFELY AND RELIABLY TRANSPORTING CARBON DIOXIDE (CO_2) FROM WHERE IT IS CAPTURED TO A STORAGE SITE IS AN IMPORTANT LINK IN THE CARBON CAPTURE AND STORAGE (CCS) PROCESS. CO_2 TRANSPORT IS ALREADY A REALITY, OCCURRING ON A DAILY BASIS FOR ENHANCED OIL RECOVERY (EOR), INDUSTRIAL, FOOD AND BEVERAGE, AND OTHER USES. BUT TO ACCOMPLISH CCS ON THE SCALE NEEDED TO REDUCE ATMOSPHERIC GREENHOUSE GAS (GHG) BUILDUP, CO_2 TRANSPORT WILL HAVE TO BE GREATLY EXPANDED BEYOND WHAT CURRENTLY EXISTS.

OVERVIEW

Once CO_2 is separated and captured as part of CCS, in most cases it must be transported to a storage area, usually a geologic reservoir. As part of this process, CO_2 is compressed to a dense state — about 150 times atmospheric pressure — to make both transportation and storage more efficient. This is called a supercritical fluid, where density resembles a liquid but with qualities that allow it to move and fill a space like gas.

This supercritical CO_2 can be transported by pipeline, truck, rail, or ship, with pipelines the most common method for transporting large quantities over long distances, such as CCS usually requires. Many experts consider CO_2 pipeline technology to be mature, stemming from its use since the 1970s for enhanced oil recovery and in other industries. Tanker and ship CO_2 transportation is very limited, and mainly found in the food and beverage industries. About 100,000 short tons (91,000 tonnes) of CO_2 are transported annually for these industries — far less than the amounts expected to be associated with a commercial-scale power plant.[1]

Pipeline construction or conversion of existing natural gas pipelines to carbon dioxide transport is under consideration globally. However, at present, nearly all existing major CO_2 pipelines are located in the United States and Canada. There are 47 high-pressure pipelines of 10 miles in length or greater in North America (see table). These pipelines total some 6,600 kilometers (4,100 miles) in length and transport 3 billion cubic feet of CO_2 daily, or 99 million tonnes (90 million short tons) annually (see "Interstate Oil and Gas Compact Commission: A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide," December 2010, pages 14-21).

> **Achieving ambitious global CCS deployment rates over the next decade will require approximately $15 billion to $20 billion per year in additional investment to finance transport infrastructure and storage sites through 2020.**
>
> International Energy Agency, Technology Roadmap: Carbon Capture and Storage, 24.
>
> Did You Know?

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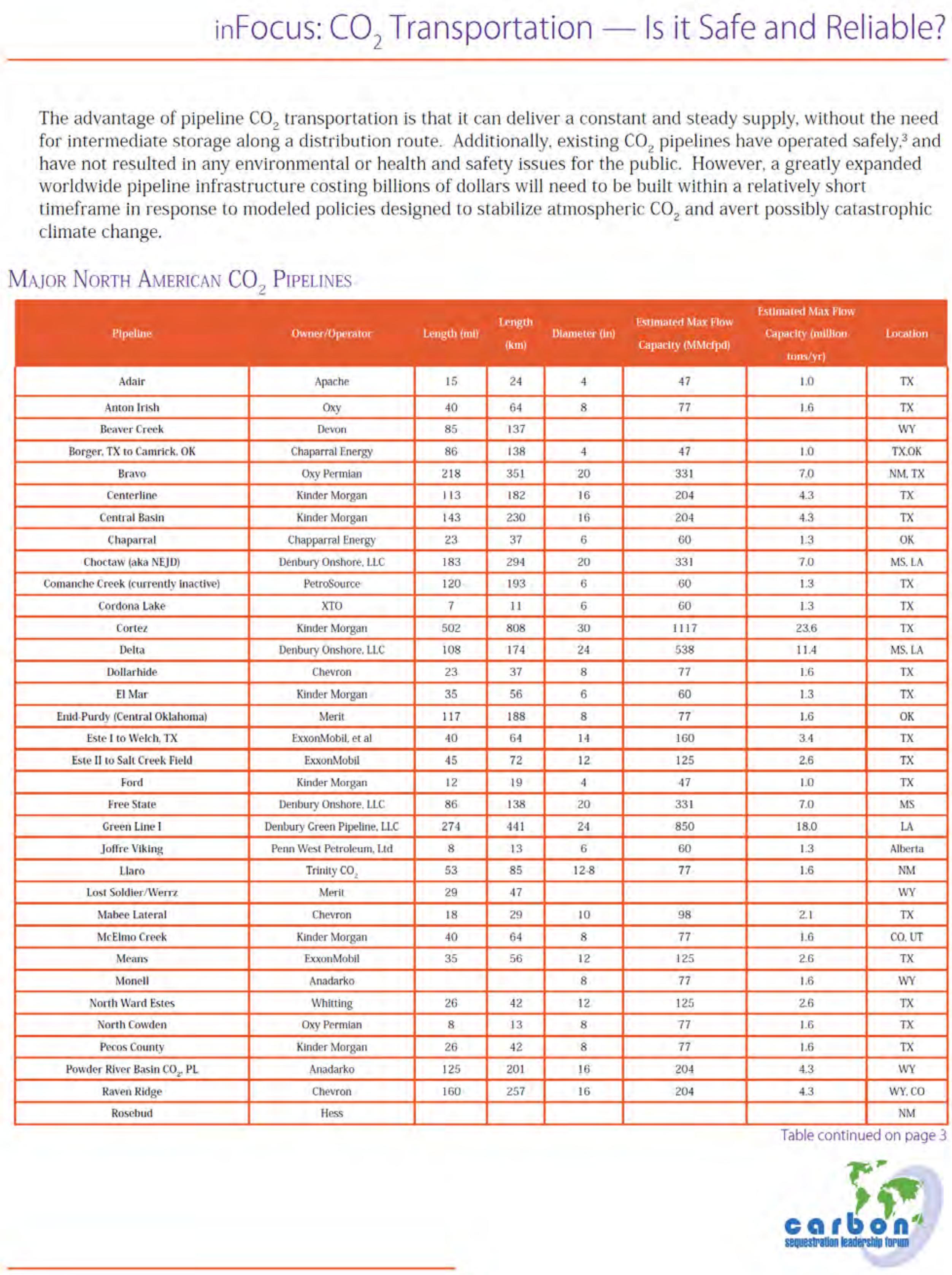
[1] World Resources Institute, "Guidelines for Carbon Dioxide Capture, Transport, and Storage," October 2008, 42–43.



inFocus: CO_2 Transportation — Is it Safe and Reliable?

The advantage of pipeline CO_2 transportation is that it can deliver a constant and steady supply, without the need for intermediate storage along a distribution route. Additionally, existing CO_2 pipelines have operated safely,[3] and have not resulted in any environmental or health and safety issues for the public. However, a greatly expanded worldwide pipeline infrastructure costing billions of dollars will need to be built within a relatively short timeframe in response to modeled policies designed to stabilize atmospheric CO_2 and avert possibly catastrophic climate change.

MAJOR NORTH AMERICAN CO_2 PIPELINES

Pipeline	Owner/Operator	Length (mi)	Length (km)	Diameter (in)	Estimated Max Flow Capacity (MMcfpd)	Estimated Max Flow Capacity (million tons/yr)	Location
Adair	Apache	15	24	4	47	1.0	TX
Anton Irish	Oxy	40	64	8	77	1.6	TX
Beaver Creek	Devon	85	137				WY
Borger, TX to Camrick, OK	Chaparral Energy	86	138	4	47	1.0	TX,OK
Bravo	Oxy Permian	218	351	20	331	7.0	NM, TX
Centerline	Kinder Morgan	113	182	16	204	4.3	TX
Central Basin	Kinder Morgan	143	230	16	204	4.3	TX
Chaparral	Chapparral Energy	23	37	6	60	1.3	OK
Choctaw (aka NEJD)	Denbury Onshore, LLC	183	294	20	331	7.0	MS, LA
Comanche Creek (currently inactive)	PetroSource	120	193	6	60	1.3	TX
Cordona Lake	XTO	7	11	6	60	1.3	TX
Cortez	Kinder Morgan	502	808	30	1117	23.6	TX
Delta	Denbury Onshore, LLC	108	174	24	538	11.4	MS, LA
Dollarhide	Chevron	23	37	8	77	1.6	TX
El Mar	Kinder Morgan	35	56	6	60	1.3	TX
Enid-Purdy (Central Oklahoma)	Merit	117	188	8	77	1.6	OK
Este I to Welch, TX	ExxonMobil, et al	40	64	14	160	3.4	TX
Este II to Salt Creek Field	ExxonMobil	45	72	12	125	2.6	TX
Ford	Kinder Morgan	12	19	4	47	1.0	TX
Free State	Denbury Onshore, LLC	86	138	20	331	7.0	MS
Green Line I	Denbury Green Pipeline, LLC	274	441	24	850	18.0	LA
Joffre Viking	Penn West Petroleum, Ltd	8	13	6	60	1.3	Alberta
Llaro	Trinity CO_2	53	85	12-8	77	1.6	NM
Lost Soldier/Werrz	Merit	29	47				WY
Mabee Lateral	Chevron	18	29	10	98	2.1	TX
McElmo Creek	Kinder Morgan	40	64	8	77	1.6	CO, UT
Means	ExxonMobil	35	56	12	125	2.6	TX
Monell	Anadarko			8	77	1.6	WY
North Ward Estes	Whitting	26	42	12	125	2.6	TX
North Cowden	Oxy Permian	8	13	8	77	1.6	TX
Pecos County	Kinder Morgan	26	42	8	77	1.6	TX
Powder River Basin CO_2 PL	Anadarko	125	201	16	204	4.3	WY
Raven Ridge	Chevron	160	257	16	204	4.3	WY, CO
Rosebud	Hess						NM

Table continued on page 3

carbon sequestration leadership forum

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MAJOR NORTH AMERICAN CO_2 PIPELINES (CONTINUED)

Pipeline	Owner/Operator	Length (mi)	Length (km)	Diameter (in)	Estimated Max Flow Capacity (MMcfpd)	Estimated Max Flow Capacity (million tons/yr)	Location
Sheep Mountain	Oxy Permian	408	656	24	538	11.4	TX
Shute Creek	ExxonMobil	30	48	30	1117	23.6	WY
Slaughter	Oxy Permian	35	56	12	125	2.6	TX
Sonat (reconditioned natural gas)	Denbury Onshore, LLC	50	80	18	150	3.2	MS
TransPetco	TransPetco	110	177	8	77	1.6	TX, OK
W. Texas	Trinity CO_2	60	97	12-8	77	1.6	TX, NM
Wellman	PetroSource	26	42	6	60	1.3	TX
White Frost	Core Energy, LLC	11	18	6	60	1.3	MI
Wyoming CO_2	ExxonMobil	112	180	20-16	204	4.3	WY
Canyon Reef Carriers	Kinder Morgan	139	224	16	204	4.3	TX
Dakota Gasification (Souris Valley)	Dakota Gasification	204	328	14-13	125	2.6	ND, Sask
Pikes Peak	SandRidge	40	64	8	77	1.6	TX
Val Verde	SandRidge	83	134	10	98	2.1	TX
	Totals:	4,111	6,611				

*Tabulation does not include many shorter high pressure truck lines to individual fields

Adapted from "A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide," Interstate Oil and Gas Compact Commission, September 10, 2010, pages 20-21.

WHY ARE PIPELINES CONSIDERED BY MANY EXPERTS AS THE BEST CHOICE FOR CCS-RELATED CO_2 TRANSPORT?

CO_2 pipelines are an existing, safe, and efficient technology, with significant long-term operating experience in the EOR industry in the United States. While the nature and extent of a more extensive CO_2 pipeline network in the U.S. and elsewhere will depend on many factors, it is expected that early projects are likely to rely on a mix of options. These options may include not only the use of existing infrastructure, but also the development of dedicated pipelines sized and located for individual projects. Tanker ship transportation of large quantities of CO_2 may be possible for some long distance or overseas shipments; however, many human-generated carbon dioxide sources are located far from navigable waterways, meaning pipelines between sources and port terminals would still have to be built. While rail cars and trucks can also transport CO_2, these modes would be logistically impractical for large-scale CCS operations.[2]

HOW DO WE KNOW THAT CO_2 PIPELINES WILL LIKELY BE SAFE AND RELIABLE?

Experience from decades of pipeline operations suggests that designing and operating CO_2 pipelines do not pose any new challenges. In the United States, pipeline companies have successfully operated a substantial CO_2 pipeline infrastructure for nearly 40 years, mainly for use in EOR. The oldest of these is the 225 kilometer (140-mile) Canyon Reef Carriers pipeline, which has operated since 1972 in regional Texas oil fields. The longest, the 502-mile (808 kilometers) Cortez pipeline, has been delivering about 20 million tonnes of CO_2 annually to Denver City, Texas, since 1984.[3] To date, U.S. CO_2 pipelines have experienced few incidents — 12 leaks were reported from

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[2] Ibid, 4.

[3] World Resources Institute, "Guidelines for Carbon Dioxide Capture, Transport, and Storage," October 2008, 42.

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1986 through 2006, none resulting in injuries to people, making them among the safest pipeline systems used industrially.[4] Even as the number of CO_2 pipeline networks expands significantly to support CCS, existing operational experience combined with adequate risk assessment and the use of best practices is expected to result in generally safe design, construction, and operation.[5]

HOW LARGE WILL THE CO_2 PIPELINE INFRASTRUCTURE NEED TO BE FOR CCS?

The nature and extent of pipeline networks that would be necessary to transport the large quantities of CO_2 resulting from CCS will depend on many factors, including the proximity of storage sites to the capture facilities; the costs to acquire pipeline rights-of-way and associated permits; the cost to construct the pipelines; and additional costs to operate the pipelines and comply with operational and maintenance regulations. However, even in the United States where there is an existing CO_2 pipeline network that aligns relatively well with potential geologic storage areas, additional pipelines will still need to be built. A study by a Pacific Northwest National Laboratory (PNNL) team estimates the United States would need up to 23,000 miles (37,000 kilometers) of additional dedicated CO_2 pipeline between 2010 and 2050 under the 450 parts-per-million (ppm) emissions target suggested by the Intergovernmental Panel on Climate Change; this figure would drop to 11,000 miles (17,700 kilometers) under a 550 ppm scenario.[6] In the European Union (EU), where there currently are no dedicated CO_2 pipelines, one recent estimate calls for the need to transport 400 million tonnes (440 million short tons) per year by 2030 to meet EU interim targets for carbon dioxide removal.[7] To put this amount in perspective, the number of 20-ton CO_2 trucks needed to hold 400 million tonnes would circle the earth 15 times, according to one study.[8] A 2010 study by the International Energy Agency, "Global CCS Pipeline Infrastructures," estimates the cumulative transport of 1.44 gigatonnes (GT) of carbon dioxide annually from 358 sources to storage will be needed worldwide by 2030, at a cost of $60 billion. In short, any of these and other scenarios will require a large and expensive global CO_2 pipeline infrastructure.

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[4] Congressional Research Service, "Carbon Dioxide (CO_2) Pipelines for Carbon Sequestration: Emerging Policy Issues," 19 April 2007, 16.

[5] J. Barrie, K. Brown, P.R. Hatcher, H.U. Schellhase, Carbon Dioxide Pipelines: A Preliminary Review of Design and Risks, 2004, 6.

[6] J.J. Dooley, R.T. Dahowski, C.L. Davidson, "Comparing Existing Pipeline Networks with the Potential Scale of Future U.S. CO_2 Pipeline Networks," February 2009, 4–5.

[7] McKinsey & Company, "Carbon Capture and Storage: Assessing the Economics," 22 September 2008, 12.

[8] David L. Coleman, "Transport Infrastructure Rationale for Carbon Dioxide Capture and Storage in the European Union to 2050", February 2009, 1676.

inFocus: CO_2 Transportation — Is it Safe and Reliable?

What are the major challenges facing the creation of a CO_2 transportation infrastructure?

The cost of building new infrastructure could be steep, especially for countries or areas lacking adequate geologic storage sites. Consequently, governments may need to provide financial incentives that reduce costs for pipeline developers and operators. Aside from costs, there are also additional challenges, including pipeline network requirements, economic regulation, siting, regulatory classification of CO_2 itself, safety and health issues, and liability. Pipeline transport of CO_2 through populated areas will require that special attention be paid to design factors, overpressure protection, and leak detection. However, there is no indication that potential problems for CO_2 pipelines are any more challenging than those faced by hydrocarbon pipelines in similar areas (such as natural gas and petroleum), or that they cannot be resolved. In the final analysis, a balance must be struck between the need to protect people and the environment, and the impending requirement to rapidly deploy CCS to help mitigate the effects of climate change. Progress will be accelerated by countries working together to develop common regulatory and infrastructure approaches.

Sources for Additional Information

- United Nations Intergovernmental Panel on Climate Change, http://www.ipcc.ch/
- International Energy Agency, http://www.iea.org/
- World Coal Institute, http://www.worldcoal.org/
- The World Bank, http://www.worldbank.org/
- European Zero Emissions Platform, http://www.zeroemissionsplatform.eu/

Other inFocus Factsheets:

- Is Geologic CO_2 Storage Safe?
- Underground CO_2 Storage: A Reality?
- Why Carbon Capture and Storage?
- CO_2 Capture: Does it Work?
- 10 Facts About CCS

CCS
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Underground CO_2 Storage: A Reality?

CAPTURING AND STORING CARBON DIOXIDE (CO_2) UNDERGROUND IS NOT A NEW OR EMERGING TECHNOLOGY — IT IS ALREADY A REALITY ON A SMALL SCALE. THERE ARE LARGE CARBON DIOXIDE STORAGE RESERVOIRS THROUGHOUT THE WORLD THAT EXPERTS BELIEVE CAN ACCOMMODATE CENTURIES WORTH OF INJECTED CO_2. ADDITIONALLY, THE VARIOUS TECHNICAL COMPONENTS OF CARBON CAPTURE AND STORAGE (CCS) HAVE BEEN SEPARATELY PROVEN. BUT USING THE TECHNOLOGY ON THE COMMERCIAL SCALE NECESSARY TO IMPACT GLOBAL CLIMATE CHANGE REMAINS PROHIBITIVELY EXPENSIVE. CONTINUED RESEARCH IS NEEDED TO LOWER COSTS OF THE TECHNOLOGY ITSELF AND CONFIRM ALL ASPECTS OF GEOLOGIC STORAGE, INCLUDING RESERVOIR SIZE, SAFETY, AND RELIABILITY.

OVERVIEW

There are decades of operational experience from CCS projects, including underground CO_2 injection for enhanced oil recovery (EOR) and the use of technologies analogous to carbon capture and storage, such as acid gas injection and natural gas storage. Three large-scale storage projects — injecting 1 million to 2 million tonnes of CO_2 annually — have been operating for several years, and five smaller projects are now actively capturing and storing carbon dioxide. There are also capture-only projects for industrial use. These industrial-level experiences are complemented by numerous research-scale CCS projects, intergovernmental and industry partnerships, research programs, and stakeholder networks. No adverse safety, health, or environmental effects have ever resulted from any of these operations.

Scientists believe the earth has extensive capacity for storing injected carbon dioxide. The United Nations Intergovernmental Panel on Climate Change (IPCC) estimates the world's potential capacity at 2 trillion tonnes, although there could be a "much larger potential."[1] The bottom line is that many pieces of the CCS puzzle have been deployed and verified separately but no commercial-scale power plants using the technology have yet been constructed. This is an essential step before CCS can be deployed commercially. Meanwhile, existing projects and research initiatives are helping researchers and operators acquire the real-world experience and data needed to advance the technologies, lower costs, and validate CCS potential and storage capabilities.

In the United States, CO_2 has been injected underground for enhanced oil recovery operations for decades; about 63 million tonnes of mostly naturally produced CO_2 are injected annually for this purpose.

U.S. Department of Energy, National Energy Technology Laboratory, "The Role of Underground CO_2 Accumulations in the Emergence of CO_2 Enhanced Oil Recovery," June 2011, Executive Summary, 1.

Did You Know?

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[1] U.N. IPCC, "Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers," 2005, 12.

inFocus: Underground CO_2 Storage: A Reality?

What is a geologic formation and how does it sequester CO_2?

The concept involves storing CO_2 deep underground (typically at depths greater than 800 meters, or more than 2,600 feet) in geologic formations[2] with characteristics that would trap large volumes of CO_2 and not allow it to leak. Some of these characteristics include tiny microscopic spaces generally filled with salty water, known as porosity; sufficient connection between the open spaces so that CO_2 can flow sideways or move around within the formation, known as permeability; and a confining layer that can "cap" the upward flow so that CO_2 is trapped underground.

Many types of geologic formations have these features, such as sandstones and limestones, and some geologic formations are tens to hundreds of feet thick and may extend laterally for miles.

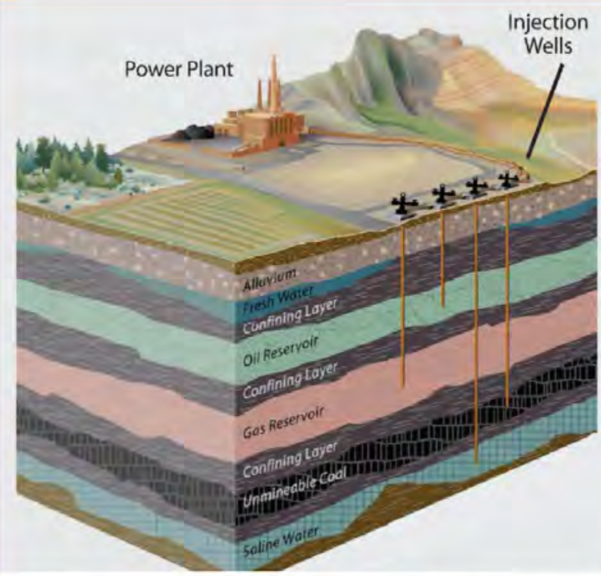
Geologic formations that are potential CO_2 reservoirs are the same as reservoirs that trap oil and gas and naturally occurring CO_2. Oil and gas can be found in sandstones, limestones, and other permeable formations, trapped for millions of years until tapped by wells drilled from the surface to extract the oil.

An overlying layer of low permeability rock, commonly referred to as a caprock or geologic seal (such as shales or siltstones), prevents oil and gas from traveling out of the permeable formation. Similarly, a caprock or geologic seal would be expected to trap CO_2 and prevent it from migrating upwards.

How is CO_2 injected underground and why does it stay there?

CO_2 is compressed into a dense fluid then pumped — via one or more wells — into a porous geological formation. At first, being more buoyant than water, the CO_2 rises to the top of the formation, where it becomes trapped beneath a confining layer of impermeable caprock (see description above) which acts as a seal: Caprocks have trapped oil, gas, and CO_2 underground for millions of years.

However, it is not long before other trapping mechanisms also start to take effect: during injection, and as the CO_2 shifts within the formation, some of it becomes trapped in the tiny pore spaces of the rocks and does not move. The CO_2 also starts dissolving into the saline formation (the way sugar dissolves in hot tea) and being heavier than the water around it, the carbonated water sinks to the bottom of the formation, trapping it indefinitely. Finally, the dissolved CO_2 reacts chemically with the rocks to produce minerals, much like shellfish use calcium and carbon from seawater to form their shells. Depending on the chemistry of the rocks and water, this process can be very rapid or very slow, but it effectively binds the CO_2 to the rocks.



Schematic illustrating the process of carbon capture and storage (also known as sequestration). Adapted from Energy and Geosciences Institute, The University of Utah illustration.

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[2] To classify and map layers of rock, geologists created a basic unit called a formation. A formation is a rock unit that is distinctive enough in appearance that a geologic mapper can tell it apart from the surrounding rock layers. It must also be thick enough and extensive enough to plot on a map.

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WHY ARE SCIENTISTS SO OPTIMISTIC THAT GEOLOGIC CO_2 STORAGE WILL WORK?

No emissions control technology, including carbon capture and storage, is risk-free. But several projects are already successfully storing millions of tonnes of CO_2 underground. To date, five large-scale CO_2 storage projects (greater than 1 million tonnes of CO_2 per year — enough to fill the Empire State Building — over the storage period) are underway worldwide — two in Norway, and one each in Algeria, Canada, and the United States.

The Sleipner Project, located approximately 150 miles (241 kilometers) off the coast of Norway in the North Sea is storing more than 2,700 tonnes of CO_2 per day, injected 2,600 feet (792 meters) below the seabed. Over the lifetime of the project, more than 20 million tonnes of CO_2 are expected to be injected into the saline formation, which is sealed at the top by an extensive and thick shale layer. Monitoring surveys of the injected CO_2 indicate that over the past 13 years, the gas has spread out over nearly two square miles underground without moving upwards or out of the storage reservoir. Long-term simulations also suggest that over hundreds to thousands of years the CO_2 will eventually dissolve in the saline water, becoming heavier and less likely to migrate away from the reservoir.

Additionally, oil and natural gas companies have more than 40 years of experience storing natural gas deep underground and using injected CO_2 to "push" oil toward producing wells (i.e., EOR). According to the International Energy Agency (IEA), the success of these projects, as well as the increasing number of research demonstrations, provides "growing confidence in the potential to store large quantities of CO_2 underground — safely and securely."[3]

The IPCC notes:

> "Information and experience gained from the injection and/or storage of CO_2 from a large number of existing enhanced oil recovery (EOR) and acid gas projects, as well as from the Sleipner, Weyburn, and In Salah projects, indicate that it is feasible to store CO_2 in geological formations as a CO_2 mitigation option. Industrial analogues, including underground natural gas storage projects around the world and acid gas injection projects, provide additional indications that CO_2 can be safely injected and stored at well-characterized and properly managed sites."[4]

Globally, there are currently more than 8,100 large CO_2 point sources (accounting for more than 60 percent of all anthropogenic CO_2 emissions) that could conceivably adopt CCS technologies as a means for delivering deep and sustained CO_2 emissions reductions.

"Carbon Dioxide Capture and Geologic Storage," Global Energy Technology Strategy Program, April 2006, 8.

Did You Know?

WHERE WOULD LARGE AMOUNTS OF CO_2 LIKELY BE STORED?

The IPCC has identified prospective areas in sedimentary basins (see map) where saline formations, or oil, gas, and coal fields potentially suitable for CO_2 storage are located.[5] These formations are widely distributed around the world and many are near large groupings of power plants and other industrial facilities.

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[3] IEA Greenhouse Gas R&D Programme, "Storing CO_2 Underground," 2007, 2.

[4] U.N. IPCC, "Special Report on Carbon Dioxide Capture and Storage," 2005, 197.

[5] U.N. IPCC, "Special Report on Carbon Capture and Storage: Summary for Policymakers," 2005, 9.

inFocus: Underground CO_2 Storage: A Reality?

ROCKS IN DEEP SEDIMENTARY BASINS ARE SUITABLE FOR CO_2 STORAGE

IPCC, "Special Report on Carbon Capture and Storage," 2005, Figure 5.14, "Distribution of Sedimentary Basins Around the World," 214.

Depleted oil and gas fields, deep saline formations, and unmineable coal seams have been suggested as favorable CO_2 geological storage sites. Here, various physical (e.g., highly impermeable caprock) and geochemical trapping mechanisms would prevent the CO_2 from escaping to the surface. In the future, companies may be able to inject CO_2 into coal seams and produce natural gas from the seams as an added benefit.

Saline formations contain highly mineralized brines (or very salty water) that are unsuitable for agriculture or human consumption. Saline formations have been used for storage of chemical waste in a few cases. The main advantages of saline formations are their large potential storage volume and their common occurrence. Other possibilities include deep basalt formations and shales.

HOW MUCH CO_2 CAN BE STORED UNDERGROUND?

As scientists work to refine methodologies, estimates of global geologic storage capacity can be highly variable. Nevertheless, numerous studies suggest there is extensive worldwide potential for permanently storing large quantities of CO_2 in geological formations.

As previously noted, the IPCC has identified a technical potential of at least 2 trillion tonnes of worldwide CO_2 storage capacity in geological formations and they also note: "There could be a much larger potential for geological storage in saline formations, but the upper limit estimates are uncertain due to lack of information and an agreed methodology."[6]

A more recent report prepared by the United States Department of Energy (DOE) has documented between 1.85 trillion and 20.5 trillion tonnes of CO_2 storage potential in oil and gas reservoirs, coal seams, and saline formations across the United States and Canada. Preliminary estimates suggest the availability of centuries worth of CO_2 storage for the United States and Canada in these geologic formations.[7]

A preliminary estimate by scientists at DOE's Pacific Northwest National Laboratory (PNNL) indicates there is nearly 11 trillion tonnes of potential global deep geologic storage capacity, "which, assuming other advanced energy technologies (such as nuclear and renewables) are developed and deployed along with CCS, should be more than enough to address global CO_2 storage needs for this century."[8]

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[6] U.N. IPCC, "Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers," 2005, 12.

[7] National Energy Technology Laboratory, "Carbon Sequestration Atlas of the United States and Canada — Third Edition, 2010, page 155.

[8] James Dooley, Robert Dahowski, and Casie Davidson, Pacific Northwest National Laboratory, "CCS: A Key to Addressing Climate Change," Chapter 4 in "Fundamentals of the Global Oil and Gas Industry," 2007, vol. 2007, 67–69.

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In Europe, the EU project GESTCO estimated the CO_2 storage capacity in oil and gas fields in and around the North Sea at 37 billion tonnes, which would enable this region to inject CO_2 for several decades once the fields are depleted.[9]

One report notes: "In a world in which there is a broad portfolio of complementary carbon management technologies that can be drawn upon (e.g., energy efficiencies, renewable energy, nuclear power, etc.), it would appear that the deployment of CCS systems will not be constrained by a lack of overall storage capacity."[10] Meanwhile, as part of ongoing research, the Carbon Sequestration Leadership Forum (CSLF) is seeking to develop a clear set of definitions and methodologies to allow scientists to provide consistent assessments of worldwide CO_2 storage capacity.

It Seems Like Geologic Storage is Pretty Promising. Why is More Research Needed?

There is scientific consensus that CO_2 storage in deep underground geologic reservoirs has great potential as one of several climate change mitigation strategies. But there are substantial financial, institutional, regulatory, and technical challenges that need to be overcome before CCS can be widely deployed. One of these involves completing the database necessary to assure we can safely and effectively store the large volumes of CO_2 necessary to achieve significant emissions reductions from fossil-fuel power plants. Rapid progress is being made in this area, but continued field tests to fully characterize geologic storage sites, validate models and prior findings, and develop measurement, monitoring, and verification (MMV) instrumentation is essential.

> "Observations from engineered and natural analogues as well as models suggest that the fraction (of stored CO_2) retained in appropriately selected and managed geological reservoirs is very likely to exceed 99 percent over 100 years and is likely to exceed 99 percent over 1,000 years."
>
> IPCC, Special Report on Carbon Dioxide Capture and Storage, "Summary for Policymakers," 2005, 14.
>
> **Did You Know?**

Sources for Additional Information

- United Nations Intergovernmental Panel on Climate Change, http://www.ipcc.ch/
- International Energy Agency, http://www.iea.org/
- World Coal Institute, http://www.worldcoal.org/
- The World Bank, http://www.worldbank.org/
- European Zero Emissions Platform, http://www.zeroemissionsplatform.eu/

Other inFocus Factsheets:

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- Why Carbon Capture and Storage?
- CO_2 Capture — Does it Work?
- CO_2 Transportation — Is it Safe and Reliable?
- 10 Facts About CCS

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[9] European Union Fifth Framework Programme for Research and Development, "Geological Storage of CO_2 from Combustion of Fossil Fuels," November 2004, 9.

[10] Global Energy Strategy Technology Program, "Carbon Dioxide Capture and Geologic Storage," April 2006, 8.

CCS

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Carbon Capture & Storage

Is Geologic CO_2 Storage Safe?

THERE IS SCIENTIFIC CONSENSUS, AND GROWING EVIDENCE, THAT GEOLOGIC STORAGE HAS GREAT POTENTIAL FOR SAFELY AND PERMANENTLY STORING CARBON DIOXIDE (CO_2). ADDITIONAL RESEARCH IS UNDERWAY TO ACQUIRE THE DATA NEEDED TO COMPLETELY VALIDATE CO_2 STORAGE POTENTIAL, CAPABILITY, RELIABILITY, AND SAFETY.

OVERVIEW

The idea of injecting large quantities of CO_2 underground and having it stay there without leaking or causing environmental harm is a concern for some people unfamiliar with carbon capture and storage (CCS) technology. But there is a growing body of evidence that geologic storage is both safe and effective. Ongoing global research is helping scientists accumulate information needed to conclusively verify all operational and safety aspects of long-term CO_2 storage in depleted or declining oil and natural gas fields, saline reservoirs, unmineable coal seams, and other significant geologic formations. The goal is to scientifically confirm storage safety across the diversity and composition of storage sites, both necessary predecessors of large-scale commercial CCS deployment. CCS is widely considered a key component of a portfolio response strategy (including renewable and nuclear energy, and increased energy efficiencies) necessary for meeting ambitious worldwide atmospheric CO_2 reduction goals.

> "The reason CO_2 storage works is simple: it uses the same natural trapping mechanisms which have already kept huge volumes of oil, gas, and carbon dioxide underground for millions of years."
>
> European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP)
>
> Did You Know?

CAN CO_2 BE SECURELY STORED IN DEEP UNDERGROUND GEOLOGIC FORMATIONS?

Evidence, both natural and human-generated, strongly suggests the answer is a definitive "yes." The United Nations Intergovernmental Panel on Climate Change (IPCC) notes there are many natural geologic deposits of CO_2 trapped in rock formations underground: "**Underground accumulation of carbon dioxide (CO_2) is a widespread geological phenomenon, with natural trapping of CO_2 in underground reservoirs.**"[1] Natural trapping mechanisms, including pressure and physical and chemical characteristics of rock and geologic formations, have kept large volumes of not only CO_2, but also oil and natural gas deep underground for millions of years.

[1] United Nations Intergovernmental Panel on Climate Change (U.N. IPCC), "Special Report on Carbon Dioxide Capture and Storage: Chapter 5, Underground Geologic Storage," 2005, 5-4.

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Additionally, the oil and gas industry has used CO_2 injection and storage for more than 40 years to recover oil from depleted or declining fields (known as "Enhanced Oil Recovery," or EOR). Currently in the United States (which accounts for 94 percent of worldwide CO_2-EOR oil production), more than 48 million tonnes (or 52.8 million short tons) per year of CO_2 are used for this purpose.[2]

Finally, there is the experience gained from demonstration projects around the world.

EIGHT PROJECTS ACTIVELY CAPTURING AND STORING CO_2

PROJECT NAME	LOCATION	STARTED STORAGE (YEAR)	TONNES STORED ANNUALLY*
Sleipner EOR	Norway	1996	1.0
Weyburn-Midale EOR	Canada	2000	2.7–3.2
In Salah Gas Storage EOR	Algeria	2004	1.2
Crust K12-B Test	Netherlands	2004	0.2
Zama (EOR)	Canada	2005	0.067
Snøhvit Field LNG and CO_2 Storage	Norway	2008	0.75
SECARB Cranfield EOR	United States	2009	1.0–1.5
Mountaineer CCS	United States	2009	0.1

* Million Tonnes

As of 2010, the three longest operating projects — Sleipner, Weyburn-Midale, and In Salah — had a cumulative total of 11 million, 18 million, and 3 million tonnes of CO_2 stored, respectively.

Three large-scale projects — Sleipner, Weyburn, and In Salah — have been injecting and successfully storing 1 million to 3 million tonnes of CO_2 annually for several years; five others have more recently begun operations; no adverse safety, health or environmental effects have resulted from any of these projects. Through these and other projects that are operating or will be soon, scientists are acquiring the data needed to completely validate the capacity and potential impact of geologic CCS. Continuing this research is vital to deploying the technology on a commercial basis. Based on the success encountered thus far, experts believe good site selection and characterization, proper CO_2 injection rates, appropriate monitoring, and safe operational and remedial practices will assure the long-term viability of CCS technology.

BUT WHAT HAPPENS IF A CO_2 LEAK OCCURS?

Potential geologic storage sites will need to be carefully selected and managed so as to minimize any chance of CO_2 leakage. Given the complexity of most geologic reservoirs and the potentially huge volumes of CO_2 that may be injected, the possibility of some leakage over time may never be completely eliminated. But scientists expect the reservoir characterization process (using geologic and engineering data to quantify a potential storage area's characteristics) will rule out geologic formations that do not have adequate caprocks or other geologic seals, are intersected by faults or fractures that might be pathways for escaping CO_2, or are in areas prone to earthquake or volcanic activity. Additionally, measuring, monitoring, and verification programs will be used to plot the migration of injected CO_2 over time to detect potential reservoir leakage.

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[2] National Energy Technology Laboratory, "Carbon Sequestration Through Enhanced Oil Recovery," http://www.netl.doe.gov/publications/factsheets/program/Prog053.pdf, April 2008, 2.

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inFocus: Is Geologic CO_2 Storage Safe?

The geological formations that would be used to store CO_2 are porous rock (not open underground caverns), making massive releases extremely unlikely. In fact, because the CO_2 becomes trapped in the tiny pores of rocks, any leakage through the geological layers would be extremely slow, allowing plenty of time for it to be detected and dealt with. Any such leak would not raise local CO_2 concentrations much above normal atmospheric levels.[3]

Higher concentration leaks could come from man-made wells and are likely to diffuse quickly. In addition, the oil and gas industry already has 50 years of experience in monitoring wells and keeping them secure. Storage sites will not, of course, be located in volcanic areas.

Should movement of CO_2 from the storage reservoir occur during or after injection, methods are generally available to fix the leak. Most of these methods have long been used to fix leaks from other types of wells (used for natural gas storage and liquid waste disposal). These techniques can also be used for CO_2, with the advantage that unlike those other materials, CO_2 is not explosive, flammable, or toxic. It is reasonable to expect that these techniques would work for CO_2. Because it has not been necessary to fix leaks at existing geologic storage projects, they have not yet been used for this purpose.

> **"... evidence from natural systems demonstrates that reservoir seals exist that are able to confine CO_2 for millions of years and longer."**
>
> United Nations Intergovernmental Panel on Climate Change, "Special Report on Carbon Dioxide Capture and Storage," 5-61.
>
> **Did You Know?**

CAN STORED CO_2 EXPLODE?

CO_2 does not burn or explode; in fact, it is a flame retardant commonly used in extinguishers. CO_2 is only problematic at very high concentrations in closed settings.

Although it is a major greenhouse gas, CO_2 is also a fundamental and essential part of nature. Plants need it to grow, while animals and humans exhale it. It also leaks naturally from volcanoes and geysers.

CAN INJECTING CO_2 UNDERGROUND CAUSE EARTHQUAKES?

CO_2 storage operations are designed to avoid inducing earthquakes. A detailed survey takes place to identify any potential leakage pathways (including seismic faults) before a CO_2 storage site is selected — if these are discovered, then the site will not be selected for CO_2 injection.

During injection, scientists and engineers can ensure that the pressure of the CO_2 does not exceed the strength of the rock by limiting injection rates and volumes, thereby avoiding over-pressurization of the reservoir.

Additionally, CO_2 storage sites have demonstrated the ability to retain injected carbon dioxide even if a natural earthquake occurs nearby. In October 2004, a major earthquake measuring 6.8 on the Richter scale occurred 12 miles from the injection site of a CO_2 geologic storage site at Nagaoka, Japan. This project stored CO_2 in a saline formation nearly a mile deep. Injection activities were halted immediately after the earthquake, but were resumed shortly thereafter. The storage formation was monitored before, during, and after the earthquake and no leakage has ever been detected.[4] Further evidence that earthquakes would not cause leaks is that a large number of producing oil and gas fields in California are near seismically active faults. They have virtually the same trapping mechanisms as CCS and earthquakes over many years have not caused them to leak.

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[3] European Technology Platform for Zero Emission Fossil Fuel Power Plants, "Frequently Asked Questions," n.d., http://www.zeroemissionsplatform.eu/faq.html/carbon-dioxide-capture-and-storage.

[4] Hiroshi Yamagata, Japan Ministry of Economy, Trade, and Industry, "Carbon Capture and Storage Activities in Japan," n.d., http://www.cslforum.org/publications/documents/Japan_CCS.pdf, 4.

inFocus: Is Geologic CO_2 Storage Safe?

CAN GEOLOGIC CO_2 STORAGE CAUSE GROUNDWATER CONTAMINATION?

To date, no known contamination of groundwater has occurred from the capture and geologic storage of CO_2.[5] Storage sites must be properly selected/designed, fully characterized, and appropriately monitored. If a site was to be improperly characterized or designed and leakage occurred that was not subsequently controlled, then CO_2 could migrate toward the surface.

CO_2 injection will be much deeper (more than a mile underground) than usable sources of groundwater and will generally be contained by one or more layers of thick, impermeable caprock.

CO_2 injection is proposed for deep saline formations containing water, but this water is unusable because of its high salt and mineral content. Given proper site selection and operation, the risks to usable water supplies would be extremely small. In the unlikely event that CO_2 would migrate upward toward shallower groundwater, seismic monitoring, groundwater analysis, and chemical tracers can detect any CO_2 that migrates upward into groundwater reservoirs and evaluate its effect on water quality.

> "On the surface, air and soil sampling can be used to detect potential CO_2 leakage while changes deep underground can be monitored by detecting sound (seismic), electromagnetic, gravity, or density changes within the rock formations."
>
> World Coal Institute, "IEA Greenhouse Gas R&D Programme," 4.
>
> **Did You Know?**

WHAT IS AT RISK IF CO_2 LEAKS?

CO_2 is not toxic, flammable, or explosive (like methane or propane gas, for example), but if allowed to accumulate in enclosed spaces at high concentrations, CO_2 could displace oxygen and cause unconsciousness or asphyxiation. The chances of such high concentrations forming during CO_2 injection for carbon storage are remote, assuming the reservoir is well characterized.

The effects of CO_2 on terrestrial ecosystems are well known as there are many places worldwide where CO_2 seeps naturally to the surface before harmlessly dispersing in the air. We also know that soils commonly contain high concentrations of natural CO_2 produced by the respiration of soil organisms and many soil animals are tolerant of CO_2 levels in the 10–15 percent range. The effects on other animals and humans are also well known — man has been living in high CO_2 flux areas (e.g., near volcanoes) since prehistoric times.

HOW WOULD LEAKS BE DETECTED?

Before a CO_2 storage site is chosen, a detailed survey takes place to identify any potential leakage pathways and assess the storage integrity of the site. Only sites with a high level of integrity are selected for CO_2 storage. In the United States, Europe, and other parts of the world, underground gas storage (natural gas and hydrogen) has an excellent safety record, with sophisticated monitoring techniques that are easily adaptable to CCS.

Surface air and soil sampling can be used to detect potential CO_2 leakage, while underground changes can be monitored by detecting sound, electromagnetic, gravity, or density changes (see World Coal Institute reference in box above).

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[5] Sally M. Benson, "Carbon Dioxide Capture and Storage: Assessment of Risks from Storage of Carbon Dioxide in Deep Underground Geological Formations," 2 April 2006, 22.

The risk of leakage through man-made wells is expected to be minimal because they can easily be monitored and fixed, and closed, if necessary.

SOURCES FOR ADDITIONAL INFORMATION

- United Nations Intergovernmental Panel on Climate Change, http://www.ipcc.ch/
- International Energy Agency, http://www.iea.org/
- World Coal Institute, http://www.worldcoal.org/
- The World Bank, http://www.worldbank.org/
- European Zero Emissions Platform, http://www.zeroemissionsplatform.eu/

OTHER INFOCUS FACTSHEETS:

- Why Carbon Capture and Storage?
- CO_2 Capture — Does it Work?
- Underground CO_2 Storage: A Reality?
- CO_2 Transportation — Is It Safe and Reliable?
- 10 Facts About CCS

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Appendix II: White Paper on Performance Based Standards

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Performance based standards for site safety and integrity

The CSLF Technical Group, during the meeting of 1-2 April, 2009, noted that the Policy Group required specifying ins and outs raised by four of the recommendations resulting from the 3rd workshop on Near-Term Opportunities for CCS.

Among these four recommendations, the Technical Group decided that the recommendation n°14 " Governments working with stakeholders need to develop performance-based standards for storage site safety and integrity ", required specific work to produce a document which could review the state of the art on this question, and could identify the principal gaps to be addressed in this area.

This work was assigned to a specific Working Group. France proposed to lead it and the following countries volunteered to contribute:

- Canada (S. Bachu)
- France (O. Bouc, L. de Lary de Latour, D. Bonijoly, H. Fabriol)
- Japan (M. Akai)
- Netherland (H. Schreurs)
- SA (F. Goede)
- USA (G. Guthrie)

At a subsequent Technical Group meeting in March 2010 it was proposed and agreed that this Working Group should merge into the Task Force on Risk Assessment.

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Introduction

The reduction of Greenhouse Gas emissions is an objective shared by many countries in order to limit the harmful effects of climate change. International agreements tend to quantify these objectives of reduction, and in parallel, to propose technical solutions making it possible to achieve these goals.

Among the proposed technical solutions, the CO_2 Capture, transport and Storage (CCS) in the geological media, addresses the need for urgency for action and for volumes of emissions to be reduced, while guaranteeing the access to energy which will remain, for the decades to come, based on the use of fossil fuels.

Although geological storage of CO_2 seems a reliable and secure solution in the short term, thanks to the experience acquired in the field of geological storage of natural gas and through all the operations of pumping and/or injection of various fluids in the underground (oil industry: EOR, acid gas injection), this technical solution raises the particular question of long-term safety, because of the requirement for long term retention (several hundreds to a thousand of years). Thus, it is necessary to demonstrate that, for long periods of time, the stored gas is located in the place where it was permitted to be through the regulatory process of application and permitting, and that, in the case of abnormal events which would lead this gas to move towards the surface, the risk it would present with respect to the environment and to humans, would be sufficiently negligible to be acceptable. This is why all stakeholders (operators, governments and the public) are asking for clear and transparent performance criteria, to make it possible to guarantee the safety and integrity of CO_2 storage.

This document provides a progress report on the state of the art in this field as of 2010.

First, it presents a review of the technical requirements necessary for the establishment of performance and safety standards.

Second, it reports the current various regulatory approaches to be used possibly to guarantee the safety and integrity of storage sites on the basis of the technical criteria described previously.

In the end, it identifies the main knowledge gaps which need to be covered in order to make this technology acceptable to the various stakeholders.

In the following, “performance” of a storage site is referred to as its ability to contain CO_2 underground long enough to make a valuable contribution to the mitigation of global change, *i.e.* to achieve the purpose it was designed for. This notion is distinct from storage safety, which refers to the absence of significant adverse effects to humans and the environment resulting from this activity.

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Technical requirements for performance-based standards for storage site safety and integrity

Which performance objective for a CO_2 storage site?

A review of the literature dedicated to CO_2 storage risk assessment reveals a high variability in the time frames suggested for CO_2 retention in the subsurface, usually ranging from 100 years to 10,000 years. However, since the publication of the IPCC Special Report on CCS (IPCC, 2005), the value of 1,000 years seems to become more widely adopted. The required duration of effective CO_2 storage to mitigate climate change is highly uncertain, due to limited knowledge of the magnitude of CCS implementation and the relative importance of stored CO_2 compared to future emissions, of the kinetics of climate response to CO_2 storage, and more broadly to uncertainties inherent in future climate evolution scenarios (dependent in particular on the availability and cost of fossil fuels and on future energy policies).

In its Special Report on CCS, the IPCC (2005) suggested a number of elements to address this question:

- From a technical point of view, the authors stated that "for large-scale operational CO_2 storage projects, assuming that sites are well selected, designed, operated and appropriately monitored":
    - It is "very likely" (*i.e.* with "a probability of 90 to 99%") that "the fraction of stored CO_2 retained is more than 99% over the first 100 years", which corresponds to a mean annual release[1] rate of 10^{-4} of the amount stored;
    - It is "likely" (*i.e.* with "a probability of 66 to 90%") that this fraction "is more than 99% over the first 1000 years", which corresponds to a mean annual release rate of 10^{-5} of the amount stored.
- The report authors also quoted research indicating the effectiveness of atmospheric CO_2 mitigation through CCS for annual release rates as high as 10^{-3} of the amount of CO_2 stored.

Given these statements, some subsequent researchers have used an annual release rate of 10^{-3} of the amount of CO_2 stored as the performance objective for a CCS project, while others used the "likely" value of "99% retained over 1000 years" as performance objective. It must be underlined though that none of these two figures, which differ by two orders of magnitude in terms of release rate, was recommended as a performance objective by the authors of the IPCC Special Report on CCS and by IPCC itself.

The 10^{-3} release rate should be considered cautiously, as it results from studies considering CO_2 storage sites around the world as a whole (global effects). There is therefore a mean effect behind this value, which should hence not be taken as the performance objective for specific CCS operations. As stated by the IPCC, it is expected that most sites should perform much more efficiently. Several authors (e.g. Bradshaw et al., 2005, Stenhouse et al., 2006) pleaded for the use for risk assessment purposes of much more realistic release rates from a geological perspective, for instance in the order of 10^{-7}.

Furthermore, the figures mentioned above are based either on technical and geological considerations, or on modelling of the global effects of CO_2 releases. None of them relates to the potential impacts that such a leak could cause locally on humans or on the

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[1] In this document, we use "release", "seepage" or "emissions" to designate a movement of the injected fluid from the storage site to the atmosphere or the water column (in the case of an offshore storage), and "leakage" to designate a movement of the injected fluid out of the geological formations intended for its storage

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environment and valuable resources. In other words, no quantitative threshold on leakage rates has been established at the local scale following a risk approach. Stenhouse *et al.* (2009) pointed out that “to date, […] assessments of storage projects have focussed more on the performance of the storage reservoir in terms of its ability to contain the CO_2 or at least prevent its leakage to the surface or near-surface environment, rather than determine the potential impacts of leakage of CO_2 (together with any gases such as H_2S or radon that may be transported with the CO_2) on specific environmental targets”. Pearce *et al.* (2005) underlined that “repository performance criteria based on risks to human health or the environment […] might differ significantly from [an acceptable leakage rate defined in terms of the emissions reduction performance of geological storage], depending on local conditions”. As an illustration of the lack of references with respect to safety, the EU Directive on CO_2 geological storage requires the operator “to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health”, but does not set a limit for tolerable leakage rates or CO_2 concentrations.

Which evaluation criteria for assessing safety and integrity of a CO_2 storage site?

Based on the above, a risk-based approach should be taken to analyse whether a proposed storage site is safe. Risks should be assessed specifically for every storage site. However, so far, no methodology has been agreed and recognized worldwide as a standard for assessing risks related to CO_2 geological storage (see *e.g.* Oldenburg *et al.*, 2009, Bouc *et al.*, 2009), though various approaches were developed such as the FEP (Features, Events, Processes) approach (Wildenborg *et al.*, 2004, Savage *et al.*, 2004) or the RISQUE method (Bowden & Rigg, 2004). In addition to the methodological gap, benchmarks are needed to compute the level of risk (as defined by the combination of the severity of an adverse effect to humans or environmental assets and the likelihood of its occurrence) and to evaluate it against agreed thresholds.

Understanding and evaluating the risk caused by a leak implies knowing, in addition to its likelihood, the corresponding levels of exposure and the effects they could cause on the various targets at stake. Both points raise difficulties in the case of CO_2 geological storage. It appears indeed that the potential effects of releases on the environment (on ecosystems and, to a lesser extent, on human health) cannot yet be fully described due to some crucial knowledge gaps, described below.

Effects of exposure to CO_2

Stenhouse *et al.* (2009) highlighted the « lack of information or data on the nature of the potentially broad range of environmental impacts that might arise from elevated levels of CO_2 in the environment ».

Effects on human health

Health consequences of human exposure to CO_2 are well documented. Carbon dioxide is a biologically active gas which has effects on numerous physiological functions (breathing, chemical balance control, pH control). This is the reason why high CO_2 concentrations are toxic. The effects of CO_2 can be summed up as follows (Hepple, 2005): at or below 1% CO_2 nearly no effect is noted; chronic exposure to 1.5-3% results in physiological adaptation without adverse consequences; above 5% CO_2 irreversible effects are observed and loss of consciousness can occur; death is imminent at 30% CO_2 concentrations.

However, the currently available data are based on studies involving only healthy volunteers. No long-term epidemiological studies have been carried out to study the effects of long-term exposure to CO_2 on highly susceptible subgroups (children, elderly people, people with respiratory deficiencies) (IEA GHG, 2007).

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Effects on ecosystems

Impacts of CO_2 on terrestrial, subsurface and marine ecosystems are generally poorly understood (West *et al.,* 2005). Data on CO_2 effects are only available for few taxa. Furthermore, there is a very wide range of sensitivity depending on the species and the ecological environment. Thus, it is very difficult to draw general conclusions.

Here is a summary of available information and existing knowledge gaps:

- Surface-dwelling animals: Few data are available about the toxicity of CO_2. Nevertheless, thresholds for human may be appropriate proxies for surface-dwelling animals (U.S. EPA, 2008). Generally, concentrations above 5% lead to respiratory poisoning for animals (Sage, 2002). Surface-dwelling animals can suffer secondary effects if plants are adversely impacted (U.S. EPA, 2008).
- Insects: The heart of insects is stimulated by 5% CO_2 concentrations, but it stops beating at very high concentrations. Surprisingly, this can happen without damage to the insect (Nicolas and Sillans, 1989). Thus, insects generally show higher resistance to CO_2 than other animals. However, their behaviour can be affected by very low variations of CO_2 concentrations (Sage, 2002).
- Soil-dwelling animals: They may begin experiencing negative physiological effects at 2% CO_2 and concentrations of approximately 15% could be lethal (U.S. EPA, 2008). Invertebrates response to CO_2 has been studied for some taxa (Sustr and Simek, 1996).
- Freshwater: Few data exist on the effects of increased CO_2 concentrations on lakes and rivers (IEA GHG, 2007). Aquatic animals may be adversely impacted or killed by pH variations of a few tenths (Hepple, 2005).
- Microbes: Some microbes are killed by concentrations above 10% CO_2, and 50% CO_2 has generally a significant inhibitory or lethal effect (Hepple, 2005). Experiments have been carried out at (natural or artificial) test sites where CO_2 is released. It appears that CO_2 exposure may influence microbial activities and the total number of microorganisms (Kruger *et al.,* 2009; Beaubien *et al.,* 2008; West *et al.,* 2008). However, tolerances are extremely wide. Some microorganisms (Archaea) may be enhanced by increasing CO_2 concentrations (Kruger *et al.,* 2009). Microbial population may be affected by biogeochemical changes due to CO_2 exposure, which may change nutrients availability (ex: nitrogen) and impact the whole ecosystem (IEA GHG, 2007). The effects on deep subsurface microbial populations are not well known (U.S. EPA, 2008).
- Plants: A critical threshold seems to be around concentrations of 20 to 30% CO_2 (IEA GHG, 2007). A slight increase of atmospheric CO_2 can enhance plant photosynthesis. However, an important increase of CO_2 concentration (in soil or in air) has adverse physiological effects. Plants responses have been studied at test sites where CO_2 is released (Kruger *et al.,* 2009; Beaubien *et al.,* 2008; West *et al.,* 2008). According to those experiments and depending on CO_2 exposure, impacts may range from subtle changes in vegetation diversity or composition to total disappearance of plants (die-out). Some plants appear to be more tolerant than others to high levels of CO_2 (ex: monocotyledonous).

There is no documented case of environmental impacts due to CO_2 leakage from an anthropogenic geological storage reservoir. Studies on natural sites where deep-origin CO_2 is released (e.g., Latera Caldera in Italy, Laacher See in Germany) provide interesting results. However, in these sites where CO_2 has leaked for considerable time periods ecosystems may have adapted to high CO_2 concentrations. Thus, observed impacts may not be representative of the short-term or middle-term local impacts in case of leakage from a geological storage reservoir (West *et al.*, 2008).

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Exposure to CO_2 may impact ecosystems diversity, soils and crop growth, but little information is available in those areas. Nearly no data exist about the ecosystems capacity to recover following releases events. There are also very few studies of ecosystems long-term exposure to chronic concentrations (<10% CO_2) (West et al., 2005).

Few data are available on the indirect impacts of CO_2 exposure (habitat loss, changing soil pH…).

Effects on groundwater

The literature about the effects of CO_2 leakage into an aquifer used as a source of drinking water is relatively scarce so far. Most simulations for CO_2 geological storage investigate the consequences of physico-chemical reactions induced by the injection of CO_2 into the reservoir formation. The main purpose of these simulations is the understanding and the forecast of the long-term CO_2 behaviour. But waters from storage formations investigated for CO_2 storage are typically unusable for industrial or human consumption purposes because of their high salinity. Hence water quality alteration in these aquifers is not a concern and is not assessed in those studies. Concern about quality changes in drinking water aquifers following CO_2 leakage from an underlying reservoir has been addressed only recently.

Potential geochemical effects of CO_2 leakage into an aquifer are complex and widely dependent on aquifer's lithology, therefore requiring site-specific assessments. In addition to flow perturbation due to pressure changes, CO_2 leakage into an aquifer could affect:

- mineral dissolution / precipitation equilibria, thus changing water mineral composition and potentially liberating trace elements;
- metal sorption, precipitation or aqueous complex formation;
- mobilisation of organic compounds, for which CO_2 is an excellent solvent;
- microbial activity.

A study at the scale of the US territory (Apps *et al.*, 2009, Birkholzer *et al.*, 2008) identified arsenic (As), lead (Pb), zinc (Zn), barium (Ba) antimony (Sb) as potentially critical elements whose concentration in an aquifer could exceed the quality limits as a result of a release from the rock matrix, under reducing conditions (which are characteristic of most groundwaters). The rate of CO_2 leakage into an aquifer would affect the geometrical extent of groundwater contamination more than the concentration levels, which basically do not change once the CO_2 solubility limit of water has been exceeded (Zheng *et al.*, 2009).

Concentration limits for the above-cited elements, as well as pH references defining the range of acceptable acidity, exist in the requirements for potable water. The difficulty here lies in the site-specific nature of the studies required to assess water quality alteration, which research so far has not excluded.

Effects of impurities

Depending on the capture process and the CO_2 source, different "impurities" could be co-injected with CO_2 (H_2S, SO_2, NOx, Hg…). The fate of co-injected species is not well understood (IEA GHG, 2007). A CO_2 leak may act as a carrier of naturally-occurring subsurface gases (hydrogen sullfide, radon and methane). Impurities potentially have a very wide range of effects (cancer, fertility decline, malformations…) and may impact receptors by different exposure pathway (inhalation, ingestion, dermal contact, surficial contact). Though current research in various projects seeks to address this concern, insufficient information is available to assess the risks associated with gas impurities at present time (IPCC, 2005).

Exposure assessment

The effects of CO_2 (and/or impurities) depend much more on the level of exposure (concentration and duration) than on the total quantity of CO_2 released. Consequently, safety assessments should be based on the potential concentrations that could result from a leak from a CO_2 geological storage site, rather than primarily focussing on leakage rates and/or volumes. A leakage rate or volume by itself is not representative in terms of safety; it must be converted into an exposure level to evaluate the consequences it generates.

Exposure assessment is currently an important challenge because it supposes to know the behaviour and fate of the leaking CO_2 (IPCC, 2005). Little information is available in this area. The concentrations in soil porosity is often very high (nearly 100% CO_2) at natural test sites where deep-origin CO_2 is released. In the atmosphere, it seems that dispersion generally quickly dilutes CO_2 seepages. As a consequence, biological receptors are susceptible to be exposed to higher CO_2 concentrations in soil than in atmosphere (IPCC, 2005). Nevertheless, CO_2 is a high density gas which tends to migrate downwards and accumulate in low-lying areas or in confined spaces. This property may create locally high concentration zones in places lacking wind or ventilation. Only few studies so far (*e.g.* Bogen *et al.*, 2006, Chow *et al.*, 2009, Stenhouse *et al.*, 2009) have investigated the fate of CO_2 at the surface and the potential for accumulation either outdoor (*e.g.* in topographic depressions) or indoor (*e.g.* in basements). Such studies require taking account of site-specific geographic as well as meteorological conditions.

Acceptable concentration limits for human and ecosystems

In regard to human exposure to CO_2 and impurities, some standards containing exposure thresholds exist in the area of industrial hygiene, ambient air quality, hazard assessment or health risk assessment (Table 1).

	Limit value	Duration of exposure	Country/Entity	Reference
Occupational exposure limit 8h/day (Workers)	0.5 %	8h/day	Europe, United Sates, Canada	European commission, 2007; Hepple, 2005
Short-Term Exposure Limit (Workers)	3 %	15 minutes	United Sates	Hepple, 2005
Level immediately dangerous to life and health	4 %	-	United Sates	Hepple, 2005
Irreversible Effects (risk assessment)	5 %	30 minutes	France	Ministry of ecology, 2007
First lethal effects (risk assessment)	10 %	30 minutes	France	Ministry of ecology, 2007
Significant lethal effects (risk assessment)	20 %	30 minutes	France	Ministry of ecology, 2007

Table 1 – Examples of CO_2 thresholds from regulations.

Concerning ecosystems, there are only few data about the toxicity of impurities and CO_2. There is no clear definition of acceptable limit for specific ecosystems (IEA GHG, 2007). To date, neither acceptable limits nor key indicator organisms have been established. These would probably be site-specific and dependent on the use of the ecosystems.

Computation of a risk level

Thus, CCS faces the difficulty of providing a reliable estimate of the risk level due to the processes and time scales involved. Risk assessment for common industrial activities usually combines the estimated severity and probability of occurrence of an undesirable event. In the case of CO_2 storage, uncertainties about the geological medium and the long-term behaviour of the storage complex, as well as limited experience imply that any

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probability estimation for the occurrence of such an event is subjective and can be disputed, given the time scales considered.

Acceptable risk levels

Finally, assuming an estimation of the risk can be provided, CCS currently lacks a definition for an acceptable level of risk, expressed in terms of probabilistic number of fatalities per year for instance.

In France, a note from the Ministry in charge of Ecology, dated 16 November 2007, defines the thresholds on CO_2 atmospheric content to be considered in the risk assessment carried out for surface industrial activities (Table 1). These thresholds are designed for population; different severity categories are defined depending on the number of human beings potentially exposed to these levels of CO_2 concentration. This allows integrating CO_2 fatalities on humans in the common severity / probability grid defined for assessing whether risk caused by an industry is acceptable. It should be made clear whether these thresholds and this approach also apply to CO_2 geological storage; at the international level, similar guidance appears desirable. Nevertheless, in the case of France, the indicated values do not compensate for the lack of data for evaluating the impacts on the environment; they do not allow assessing the potential effects on other targets than humans. This comment must be mitigated however in regard to other industrial activities: although the assessment of risks caused by an industry to the environment is obviously mandatory, there is no agreed-upon methodology prescribing how to take into account potential impacts on the environment, unlike impacts on humans.

Which techniques and capabilities for monitoring CO_2 storage performance and safety?

Setting performance objectives and expecting a demonstration of them being met is not sufficient by itself; for safety to be guaranteed, it is required to be able to actually monitor in respect of these goals and to intervene in the case they are not achieved. Risk management plans should explicit the thresholds on monitoring results that should trigger corrective measures.

In the EU approach, the two main goals for CO_2 storage are that CO_2 must be stored permanently in such a way that any adverse impact to the environment and human health could not occur in a normal situation. This implies that:

1. Monitoring and reporting of the stored CO_2 must inform on the performance of the storage, i.e. quantify, if any, vented and fugitive emissions from injection and/or from EOR operations, and leakage of CO_2 from the storage reservoir in the geological medium;
2. In case of leakage, the operator should be able to:
    a. Identify and quantify the impacts and inform, in the monitoring report, on the impacted targets ("physical environment", flora, fauna and humans) and the level of impact ;
    b. Mitigate these impacts according to the remediation plan.

The European Commission issued a Decision on the 8th June 2010 regarding monitoring and reporting guidelines for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide under the EU Emissions Trading Scheme (EU ETS)[2]. According to these guidelines, monitoring dedicated to emissions accounting shall start in

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[2] As laid out in Directive 2003/87/EC establishing a scheme for greenhouse gas emission allowance trading within the Community.

the case that any leakage results in emissions to the air or release into the water column in the case of offshore storage.

But the underground cannot be managed as a classical physical medium because of the lack of tools allowing a continuous description of its different components. This is the reason why probabilistic approaches may be necessary. For the same reason, with the currently available tools, not all leaks that could occur in the geological medium could be identified, because of the insufficient resolution of monitoring methods.

In the short term and during operations, it is usually considered that the main risk of leakage from a geological storage site is associated with the failure of the features which intersect the storage unit (injection, observation or abandoned wells) or unsuited operating conditions (injection pressure too high) (*e.g.* Damen et al., 2003; Bowden and Rigg, 2004; Oldenburg et al., 2009). Proper monitoring of the installations will thus make it possible to guarantee that a possible escape will be detected as soon as possible and to start fast and effective remediation actions (well work-over, casing substitution; injection pressure decrease or even pumping of the injected CO_2). In some cases, ground deformation monitoring by remote sensing is a useful method to detect an anomalous behaviour of the storage complex.

In the longer term, the risks of seepage are primarily associated with a failure of the geological containment or of the abandoned wells. These seepages can then occur anywhere in the storage unit and the volume of gas escaping from the reservoir could be sufficiently low to be detected only a long time after the start of the escape. In this case, the main issues are (1) leakage / seepage detection, and (2) leakage / seepage quantification.

Leakage detection will be site-dependant. For instance, a recent study in the case of CO_2 injection in a French carbonate reservoir seems to demonstrate that the 4D seismic detection threshold would be in the order of 100,000 t of CO_2. At the opposite end, in the case of the Sleipner CO_2 storage, the 4D seismic detection threshold is likely 4000 m^3 (or 2500 t). Other geophysical methods, such as gravity or electrical-electromagnetic, could be able to produce a realistic quantitative assessment of the mass of CO_2 in place, but they are still at the research stage.

The most accurate monitoring plan will certainly be a combination of physical and chemical techniques. Pressure monitoring at the injection well will allow the detection of any abnormal behaviour of the stored CO_2, and sampling in a control aquifer immediately overlying the storage reservoir will allow detecting any modification of water chemistry and pressure. These two techniques will be able to alert on a leakage occurrence. But the location of the leak point and quantification of the released CO_2 are more complex. No real technical solution is available currently except a very costly geological, geochemical and geophysical survey.

In summary:

- Quantification of CO_2 in place needs an integrated approach using a mix of different techniques: geophysical surveys from the surface and downhole measurements in observation wells, geophysical and geochemical logging, gas and fluid sampling at different depths and *in situ* monitoring with permanent sensors;
- Several geophysical techniques are not really able to detect dissolved CO_2,
- Reliability of the permanent sensors for long period of time is certainly not demonstrated. ,
- The use of airborne and remote sensing techniques is still under development.

Conclusion

Besides the lack of a risk assessment methodology tailored for CCS, gaps in knowledge concerning the environmental impacts of CO_2 leaks, or the difficulties to calculate a reliable risk level based on the probability and magnitude of exposure to elevated CO_2 or impurities concentrations, there is a need for determination of either acceptable risk levels or acceptable leakage rates from CO_2 geological storage sites.

It is emphasized that performance standards (in terms of fraction of CO_2 kept away from the atmosphere) are only loosely connected to safety standards (in terms of potential adverse consequences that could occur from a CO_2 release). Indeed safety assessments have to be based on potential exposure. It necessitates converting fluxes and volumes into concentrations, which depend on the conditions of exposure of the vulnerable assets. Exposure is then conditioned by the release rate and/or volume, but not by the size of the storage. Therefore, if reporting a release rate to the total mass of CO_2 stored in the reservoir has a sense in terms of national greenhouse gas reduction commitment or in respect of individual quota obligation, it makes no sense, in terms of safety, to do so for a leakage flux leading to critical exposure. The percentages (fractions) of the amount stored stated as performance standards have to be considered as mean objective for the whole of the storage sites and are not relevant to local safety issues. Moreover, they do not rely on a geological basis.

Monitoring for health and safety is very different to monitoring for storage integrity and greenhouse gas accounting. The methodologies, the equipment, the costs and the objectives are quite different from each other. Monitoring for safety can be done with less precision than for greenhouse gas accounting but it needs to have wide coverage and in real time. Most groundwater, soil and air monitoring methods measure concentrations, not fluxes or volumes (total amount), which poses the problem of whether safety/performance assessment criteria should be site specific, namely concentration and time of exposure, or global, based on leakage flux and/or volume, or both.

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Regulation requirements for performance-based standards for storage site safety and integrity

The safety and integrity of CO_2 storage will have to be guaranteed by the various regulations in place or to be defined in order to manage this activity. This one can be divided into five principal stages:

- Site identification phase: selection and qualification (exploration)
- Design and construction phase – drilling and baseline monitoring
- Operational phase - injection, monitoring and reporting,
- Post closure phase - monitoring and reporting,
- Post abandonment phase - monitoring and reporting as necessary.

For these different phases, the regulator faces two major options:

1. to define as precisely as possible the different thresholds that operators will have to meet (means and resulting obligations), which is a prescriptive-based approach; or
2. to define the main goals attributed to an activity in term of impact and to ask the operator for the demonstration that he will meet these general goals (resulting obligation), which is a performance-based approach.

EU approach

The EU approach is presented hereafter as an example.

The EU Directive for CO_2 geological storage defines in its first article the main goal for any operator who would propose to store CO_2: "*The purpose of environmentally safe geological storage of CO_2 is permanent containment of CO_2 in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health*."

But neither this Directive, nor the Guidance Documents that support its implementation (European Commission, 2011), never define what could be an acceptable risk through the definition of particular values or thresholds, as the leakage rate or concentration (see chap. 2.1) or the CO_2 purity, and so on.

In this case, the regulator is waiting for results that will demonstrate the absence of risks, and in case of abnormal processes, the complete management of their impact through adapted remediation actions.

Annexes can be integrated in this type of regulation that define the minimum requirements as intermediate results considered being essential.

The CCS field is recent, so that dedicated industrial best practices are still not mature, especially with respect to long term CO_2 containment. At the opposite end, the EU Directive of the European Parliament and the Council on industrial emissions (Integrated Pollution Prevention and Control, IPPC) is a very detailed directive. One of the main elements concerns the achievement of environmental improvements while at the same time ensuring cost-effectiveness and encouraging technical innovation.

The IPPC Directive covers emissions to air from industrial installations that represent a large share of total emissions of key pollutants. The central element of such an approach is the implementation of Best Available Techniques (BAT). This is defined as using established techniques which are the most effective in achieving a high level of environmental protection as a whole and which can be implemented in the relevant sector under economically and technically viable conditions, taking into account the costs and advantages. An information exchange on BAT is being organized by the Commission with Member States and other

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stakeholders to establish BAT reference documents (BREFs) indicating what is regarded as BAT at EU level for each industrial sector. The Directive defines all the concerned chemical elements, and defines for each element or molecule, the acceptable thresholds on emission rates.

In this case, performance standards are published and known. The regulator has to monitor and control the respect of all these extensively defined recommendations.

International regulatory review

A gap oriented review was carried out in 2008-2009 under the EU-funded STRACO2 project [3], with the goals of supporting the development and implementation of a comprehensive regulatory framework for CCS in the European Union and of building a basis for EU-China cooperation on CCS. In addition to regulations (*cf.* Table 2), a number of projects were reviewed and a stakeholders' opinion survey was conducted by STRACO2 team.

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[3] STRACO2 consortium:

- European members: BRGM, World Business Council for Sustainable Development, TNO, Mälardalen University, KTH – Royal Institute of Technology;
- Chinese members: DEVELOPMENT Solutions, The Administrative Centre for China's Agenda 21, Institute of Engineering Thermo-Physics, Institute of Policy and Management

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Title	*Country / Entity*	*Year of Publication*
Directive 2009/31/CE of the European Parliament and of the council on the geological storage of carbon dioxide and amending Council Directives 85/337/EEC, Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and 2008/1/EC and Regulation (EC) No 1013/2006. April 23, 2009	Europe	2009
Energy bill – Chapter 3: Storage of carbon dioxide.	United Kingdom	2008
London Protocol - Risk assessment and management framework for CO2 sequestration in sub-seabed geological structures. LC/SG-CO2 1/7, annex 3.	International Convention	2006
London Convention - Final draft specific guidelines for the assessment of carbon dioxide streams for disposal into sub-seabed geological formations.	International Convention	2007
OSPAR guidelines for Risk Assessment and Management of Storage of CO2 Streams in Geological Formation. Reference Number: 2007-12.	International Convention	2007
US-EPA - Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO2) Geologic Sequestration (GS) Wells.	U.S.	2008
US-EPA - Using the Class V Experimental Technology Well Classification for Pilot Geologic Sequestration Projects – UIC Program Guidance (UICPG # 83) March 2007.	U.S.	2007
Storage of Carbon Dioxide in Geologic Structures – A Legal and Regulatory Guide for States and Provinces – Task Force on Carbon Capture and Geologic Storage – September 25, 2007.	Interstate Oil and Gas Compact Commission	2007
Washington State Legislature – Chapter 173-218 WAC – Underground injection control program.	U.S. Washington State	2008
State of Wyoming, House Bill No. HB0090 – Carbon Capture and sequestration.	U.S. – State of Wyoming	2008
Australian Regulatory Guiding Principles - Ministry Council on Mineral and Petroleum Resources.	Australia	2005
Draft Offshore Petroleum Amendment (Greenhouse Gas Storage) Bill 2008. Overview. Reader's guide to exposure draft	Australia	2008
Amendments of the Law relating to the prevention of marine pollution and maritime disaster.	Japan	2007-2008

Table 2 – Regulatory documents reviewed under the STRACO2 project

In regard to safety, the main gaps and recommendations from the STRACO2 project are as follows (STRACO2, 2009):

- The regulatory documents assign goals rather than means to achieve them; they contain few technical criteria such as indicative or thresholds values. Because of the possible future technological developments and the "competition principle", the legislator does not recommend any technique for the acquisition of requested knowledge or parameters. The published frameworks require an application for a licence; it can be anticipated that requirements for each individual project will be set in these permits, given site-specific considerations. Indeed, the risk scenarios to consider, the adequacy of monitoring techniques or the operational parameters, to cite a few, largely depend on site-specific conditions. Moreover, lack of experience about CO_2 storage makes difficult the establishment of criteria at a generic level, and it is probably desirable that regulatory frameworks remain flexible to technological and knowledge developments. Nevertheless, the opinion survey carried out by STRACO2 demonstrated that stakeholders expect from a CCS regulation the setting of precise requirements, commonly accepted standards, guidelines or even techniques, in the field of site characterisation, site closure, risk assessment, emergency measures, monitoring, etc.
- The level of detail for site selection requirements or operational parameters varies among publications; but very few evaluation criteria can be found to determine what is an appropriate site, due to the site-specific nature of the assessment.
- There is a lack of an internationally recognised method for assessing and managing the risk posed by CO_2 geological storage and of quantitative criteria for characterising an acceptable risk. In most cases, the acceptance reference consists of a qualitative statement of the endpoint of the risk assessment. Imprecision about the time scales to be considered was emphasized as well. The project consortium therefore called for pursuing R&D and for the development of harmonised technical guidance as well as metrics on that topic.
- One of the major gaps found in the regulations relates to the impurity issues, with only the Japanese law for offshore storage setting a figure (99%) as criterion to define an acceptable composition for the injected CO_2 stream.
- Recognising the work done in various research projects on monitoring tools and methods, the consortium nevertheless stressed, from the stakeholders’ survey outcomes, the development of commonly accepted best practice standards for CO_2 storage monitoring as a foremost expectation from regulators and a requisite for CCS investment.
- There is a need for regulations to require from an operator a plan for mitigation and remediation in the case of any failure of the storage, in order to meet the performance and safety objectives. The project suggested the development of guidelines for emergency measures and remediation actions for CO_2 geological storage.
- The STRACO2 consortium pointed out the lack in the existing regulations of clear expectations and quantitative references for demonstrating that a site can be abandoned, while acknowledging the site-specific nature of such process. Standards for site closure and abandonment were seen as major needs in the stakeholders’ survey, and building on the lessons from early CCS projects was recommended.

Since then, the IEA published a CCS Model Regulatory Framework (IEA, 2010[a]). It addresses the key issues listed in Table 3. This model framework does not specify methods for assessing and managing risks, and does not provide reference values for evaluating risks or leakage rates.

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Many regulatory developments have taken place over the last few years, as testified by the legal and regulatory reviews carried out by the IEA (2010b, 2011). To our knowledge, these developments do not substantially address the above comments from the STRACO2 project. However, elaborating requirements for long-term security and liability of storage sites, which appear to be one of the most complex aspects of the regulation of CO_2 storage activities, is currently identified as a key task by numerous countries or regions regulators (IEA, 2011). Long-term security is particularly challenging because authorities need to have evidences that the site is behaving as expected and that the predicted behaviour of the site is acceptable (IEA, 2011). In most of the regulations that deal with the long-term behaviour, it is the responsibility of the operators to demonstrate that the CO_2 storage is behaving in a predicable manner and that no significant environmental or health risks exist. Some additional information is also often required depending on the specificity of each site (formation, volume injected, the predominant trapping mechanisms…). Nevertheless, it is worth underlining that detailed technical requirements and performance standards for storage site safety that need to be met before a site closure are still to come.

Broad regulatory issues	1.	Classifying CO_2
	2.	Property rights
	3.	Competition with other users and preferential rights issue
	4.	Transboundary movement of CO_2
	5.	International laws for the protection of the marine environment
	6.	Providing incentives for CCS as part of climate change mitigation strategies
Existing regulatory issues applied to CCS	7.	Protecting human health
	8.	Composition of the CO_2 stream
	9.	The role of environmental impact assessment
	10.	Third-party access to storage site and transportation infrastructure
	11.	Engaging the public in decision making
CCS-specific regulatory issues	12.	CO_2 capture
	13.	CO_2 transportation
	14.	Scope of framework and prohibitions
	15.	Definitions and terminology applicable to CO_2 storage regulations
	16.	Authorisation of storage site exploration activities
	17.	Regulating site selection and characterisation activities
	18.	Authorisation of storage activities
	19.	Project inspections
	20.	Monitoring, reporting and verification requirements
	21.	Corrective measures and remediation measures
	22.	Liability during the project period
	23.	Authorisation for storage site closure
	24.	Liability during the post-closure period
	25.	Financial contributions to post-closure stewardship
Emerging CCS regulatory issues	26.	Sharing knowledge and experience through the demonstration phase
	27.	CCS ready
	28.	Using CCS for biomass-based sources
	29.	Understanding enhanced hydrocarbon recovery with CCS

Table 3 – Key issues relating to CCS regulatory frameworks

In addition to regulatory developments, Guidelines for Selection, Characterization and Qualification of Sites and Projects for Geological Storage of CO_2 have been developed by a Joint Industry Project led by DNV (2009). These guidelines constitute a framework for an appropriate management of a CO2 storage site and of the related risks. In addition to careful site selection and characterisation, they emphasise the need, in an iterative process, to identify and rank uncertainties and risks, and to develop appropriate monitoring and risk reduction measures. However, they do not specify quantitative values for evaluating risks. In the guidelines, “it is proposed that the performance targets shall be tailored to the unique characteristics of each site” (DNV, 2009). These “project specific performance targets” should result from a dialogue between the project developers and the regulator(s).

Conclusion

In conclusion, we can probably assume that the integrity and performance assessment for CO_2 storage will be primarily based on:

- the characterisation of the storage complex;
- the capacity of simulation tools to reproduce and predict the behaviour of the injected CO_2 and the integrity of the complex;
- the ability of the monitoring techniques to detect, locate and quantify the volume of CO_2 present in the underground and the ability of monitoring techniques and technologies to detect and quantify leaks.

We can expect that future progress will allow the development and improvement of new tools in order to reach this objective relatively easily. And in the cases in which geophysical techniques from surface would not be adapted for site-specific reasons, the possibility of obtaining information directly from the sub-surface gives a guarantee to the regulators and the concerned public.

However, concerning safety assessment, the issue is more complex.

- On the one hand, stakeholders (governments, industry, public, NGOs) are waiting for more precise values and thresholds that could provide the framework for monitoring and control of safety criteria.
- On the other hand, the specificity of activities related to geological media cannot allow the precise and continuous description of the solid space in which one intends to store CO_2. Combined with the available data on CO_2 acceptable exposure (concentration and duration), it causes difficulties in defining realistic general values or thresholds that industry will have to meet and that governments will have to regulate.
- Even though *"the indications are also that the accident hazard posed by a CO_2 storage site, whether from rupture at injection or from post-injection leakage, is unlikely to be significant"* (Discussions of the European Parliament, 16/12/2008, Andri Pielsbag *Statement by the Commission on whether carbon dioxide should be a named substance with suitable thresholds in a revised Seveso Directive*), and particularly if the initial phases of the process (selection and qualification of CO_2 storage site) are well carried out, it will be difficult to reach local and global consensus on risks posed by any CO_2 storage project without a very important research effort, in order to lower uncertainties that remain for this important issue.

This is why regular revisions of the existing regulations will be necessary in order to integrate the results of the first research pilots and industrial demo-plants.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2012-04
09 April 2012

TECHNICAL GROUP

CSLF Technical Group Action Plan

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Carbon Sequestration Leadership Forum
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CSLF-T-2012-04
09 April 2012

CSLF TECHNICAL GROUP ACTION PLAN

Note by the Secretariat

Background

At the 4th CSLF Ministerial Meeting, at Beijing, China in September 2011, the Technical Group approved a new multi-year Action Plan. This paper is a listing of individual Actions in the Action Plan, with descriptions of each Action and Projected Outcomes.

Action Requested

The Technical Group is requested to review the updated Action Plan.

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CSLF Technical Group Action Plan, 2011-2016

Action Plan 1: Technology Gaps Closure

Action: The Technical Group will identify and monitor key CCS technology gaps and related issues and recommend any R&D and demonstration activities that address these gaps and issues.

Outcome: Identification of all key technology gaps/issues and determination of the effectiveness of ongoing CCS RD&D for addressing these gaps/issues.

Action Plan 2: Best-Practice Knowledge Sharing

Action: The Technical Group will facilitate the sharing of knowledge, information, and lessons learned from CSLF-recognized projects and other CCS RD&D. (*note: This activity could also be linked with the Capacity Building Task Force*.)

Outcome: Development of interactive references for assisting next-generation commercial CCS projects, which will include links with other CCS entities.

Action Plan 3: Energy Penalty Reduction

Action: The Technical Group will identify technological progress and any new research needs for reducing the energy penalty for CCS, both for traditional CO_2 capture processes and new breakthrough technologies.

Outcome: Identification of opportunities for process improvements and increased efficiency from experiences of "early mover" projects.

Action Plan 4: CCS with Industrial Emissions Sources

Action: The Technical Group will document the progress and application of CCS for industrial emissions sources and will identify demonstration opportunities for CSLF Members.

Outcome: Identification of opportunities for CCS with industrial sources. Identification and attempted resolution of technology-related issues (including integration) unique to this type of application.

Action Plan 5: CO_2 Compression and Transport

Action: The Technical Group will review technologies and assess pipeline standards for CO_2 transport, in particular in relation to impurities in the CO_2 stream. Issues such as thermodynamics, fluid dynamics, and materials of construction, will be considered. Alternatives to pipelines, such as ship transport, will also be assessed.

Outcome: Identification of optimum technical CO_2 transport strategies, both for pipeline and non-pipeline alternatives. Assessment of purity issues as they apply to CO_2 transport. Identification of optimal compression options and alternatives.

Action Plan 6: Storage and Monitoring for Commercial Projects

Action: The Technical Group will identify and review standards for CO_2 storage and monitoring.

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Outcome: Identification of standards for storage and monitoring of injected CO_2. The application of such standards should inform CO_2 crediting mechanisms.

Action Plan 7: Technical Challenges for Conversion of CO_2 EOR to CCS

Action: The Technical Group will determine technical and economic aspects that can affect moving from enhanced oil recovery (EOR) to carbon storage.

Outcome: Identification of permitting, monitoring, and reporting requirements for CO_2 EOR applications that apply for CO_2 credits.

Action Plan 8: Competition of CCS with Other Resources

Action: The Technical Group will examine criteria for assessing competing development priorities between CCS (particularly CO_2 storage) and other economic resources. (*note: This could be undertaken as a Joint Policy and Technical Group activity*.)

Outcome: Identification of criteria for determining relative economic viability of CO_2 storage sites.

Action Plan 9: Life Cycle Assessment and Environmental Footprint of CCS

Action: The Technical Group will identify and review methodologies for Life Cycle Assessment (LCA) for CCS, including life cycle inventory analysis, life cycle impact assessment, and interpretation of results.

Outcome: Identification of criteria for determining the full range of environmental effects for CCS technologies.

Action Plan 10: Risk and Liability

Action: The Technical Group will identify and assess links between technology-related risks and liability.

Outcome: Identification of guidelines for addressing long-term technology-related risks with respect to potential liabilities.

Action Plan 11: Carbon-neutral and Carbon-negative CCS

Action: The Technical Group will investigate technical challenges in use of CCS with power plants that utilize biomass (either pure or co-fired), to determine a pathway toward carbon-neutral or carbon-negative functionality.

Outcomes: Identification of issues and challenges for use of CCS with biomass-fueled power plants.

Action Plan 12: CO_2 Utilization Options

Action: The Technical Group will investigate CO_2 utilization options.

Outcome: Identification of most economically attractive CO_2 utilization options.

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TECHNICAL GROUP

Planning Document: Technical Challenges for Conversion of CO_2-EOR to CCS Task Force

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PLANNING DOCUMENT:
TECHNICAL CHALLENGES FOR CONVERSION OF CO2-EOR TO CCS TASK FORCE

Note by the Secretariat

Background

At the 4th CSLF Ministerial Meeting, at Beijing, China in September 2011, the Technical Group approved a new multi-year Action Plan. “Technical Challenges for Conversion of CO_2-EOR to CCS” is one of the twelve Actions that comprise the Action Plan, and Canada has volunteered to lead a new Task Force to examine the technical challenges in the transition from CO_2-EOR operations to CO_2 storage operations. This paper is a Planning Document for the new Task Force that describes its mandate, timeframe, and expected outcomes.

Action Requested

The Technical Group is requested to review and approve this Planning Document.

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Planning Document for Technical Group Action Plan #7: Technical Challenges for Conversion of CO_2-EOR to CCS

Background

Since its inception in 2003, the Technical Group of the Carbon Sequestration Leadership Forum (CSLF) has focused its efforts on the facilitation of information and knowledge dissemination regarding research, development, demonstration and deployment of effective, low-cost carbon capture and storage (CCS) technologies as a viable option to reduce greenhouse gas emissions in an effort to combat the effects of global warming. On the CO_2 capture side, efforts have focused on a variety of capture technologies applicable to power and industrial plants that use or process fossil fuels, while CO_2 storage technologies focused primarily on geological sequestration. Although deep saline formations have been assessed as having the largest storage potential, possessing also the advantage that they are present worldwide in all sedimentary basins, oil and gas reservoirs have been recognized as having significant storage potential, possessing the advantages that their storage properties have been demonstrated by the presence of oil and/or natural gas and that they are better known (understood) as a result of exploration and production activities.

A particular sub-class of CO_2 storage in hydrocarbon reservoirs is CO_2 storage in enhanced oil recovery (CO_2-EOR) operations where CO_2 is used in tertiary oil recovery to produce additional oil. From a CO_2 storage point of view, this technology presents the economic advantage of reducing CO_2 storage costs by producing oil, which has a well-defined market value. In fact, CO_2-EOR is a form of CO_2 utilization that has not been sufficiently explored to date. In today's economic and financial environment where a market signal regarding CO_2 storage is lacking, this makes CO_2 storage in CO_2-EOR operations particularly attractive. However, although there are currently more than 100 CO_2-EOR operations in the world, only the CO_2-EOR Weyburn-Midale project in Canada has been identified and recognized as a CCS project. Although not supported by any systematic study to date, it seems that there are technical and policy reasons as to why there is a dearth of CO_2-EOR projects whose purpose is also CO_2 storage.

Mandate

At the CSLF Ministerial meeting in Beijing, China (September 19-23, 2011) the CSLF Charter was amended to, among other things, include CO_2 utilization technologies as an important aspect of a CO_2 emission reduction strategy, in addition to carbon capture and storage technologies that have been the main focus of CSLF efforts since its inception in 2003. On the geological-storage side, the focus of CO_2 Utilization is on the use of CO_2 in CO_2-EOR operations. In response, the CSLF Technical Group included in its Five-Year Action Plan (2011-2016) an action item to examine the technical challenges in the transition from CO_2-EOR operations to CO_2 storage operations (Action Plan #7). At the Beijing meeting it was proposed to set up a new task force under the direction of the CSLF Technical Group to examine and report on these challenges. At the September 2011 joint meeting of the Technical and Policy Groups in Beijing, China, the Five-Year Action Plan, including the formation of the task force to implement Action Plan #7, was approved.

The Mandate of the CSLF Task Force on "Technical Challenges for Conversion of CO_2-EOR to CCS" is to review, compile and report on technical challenges that may constitute a barrier to the broad use of CO_2 for enhanced oil recovery and/or for the conversion of CO_2-EOR operations to CO_2 storage operations. There are recognized economic and policy barriers and

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challenges, such as the high price of CO_2, the lack of market value on stored CO_2, and the interest of the operators of CO_2-EOR operations in maximizing oil production and minimizing CO_2 storage. These economic and policy barriers and challenges are outside the scope of the Task Force, which will focus on purely technical challenges.

Outcome and Timeframe

The Task Force on "Technical Challenges for Conversion of CO_2-EOR to CCS" will produce a report that will be submitted for review and approval by the CSLF Technical Group and will be then posted on the open-access CSLF web site.

The proposed timeframe for the Task Force activities is as follows:

- Set up and announcement of Task Force membership at the meeting of the CSLF Technical Group in Bergen, Norway, on June 12, 2012.
- Production of a list of subjects to be covered and a preliminary Table of Contents for the report by the CSLF meeting scheduled for the week of October 22, 2012 in Perth, Australia
- Production of a preliminary draft of the report by the time of the meeting of the CSLF Technical Group in the spring of 2013 (date and place to be decided)
- Dissemination of the Draft Final Report by August 2013 to members of the CSLF Technical Group for review and comments
- Delivery of the Final Report at the CSLF meeting in the fall of 2013 (date and place to be decided)
- Decision about continuation of the Task Force beyond 2013 at the CSLF meeting in the fall of 2013.

Membership

Canada has agreed to lead or co-lead this Task Force (Task Force Chairman: Dr. Stefan Bachu, e-mail: stefan.bachu@albertainnovates.ca) and has invited CSLF member countries that have identified this Action Plan item as a high priority to nominate experts in the field to participate as subject-matter experts on the Task Force.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2012-06
09 April 2012

TECHNICAL GROUP

Planning Document:
CO_2 Utilization Options Task Force

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2012-06
09 April 2012

PLANNING DOCUMENT:
CO_2 UTILIZATION OPTIONS TASK FORCE

Note by the Secretariat

Background

At the 4th CSLF Ministerial Meeting, at Beijing, China in September 2011, the Technical Group approved a new multi-year Action Plan. "CO_2 Utilization Options" is one of the twelve Actions that comprise the Action Plan, and the United States has volunteered to lead a new Task Force that will focus on CO_2 utilization options that have the potential to yield a significant, net reduction of CO_2 emissions in sufficient volumes to make a meaningful contribution to global warming and climate change objectives. This paper is a Planning Document for the new Task Force that describes its mandate, goals, timeframe, and expected outcomes.

Action Requested

The Technical Group is requested to review and approve this Planning Document.

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Planning Document for Technical Group Action Plan #12
CO_2 Utilization Options

Background

Since its inception in 2003, the Carbon Sequestration Leadership Forum (CSLF) has focused its efforts to facilitate the research, development, demonstration and deployment of effective, low-cost carbon capture and storage (CCS) technologies as a viable option to reduce greenhouse gas emissions in an effort to combat the effects of global warming. While these efforts focused on a variety of capture technologies applicable to power and industrial plants that use or process fossil fuels, the CO_2 storage technologies focused primarily on geological sequestration, an option that provides no direct economic benefit.

In recent years the world has become increasingly interested in finding beneficial uses for CO_2 captured from power plant and industrial sources. As a climate change mitigation strategy such beneficial uses include technologies that convert or use anthropogenic CO_2 in volumes sufficient to make a meaningful contribution to greenhouse gas emission goals. Implicit in this strategy is the notion that technology pathways must result in a substantial net reduction of CO_2 emissions. While CO_2 utilization is not a solution to global warming concerns, it is an important pathway to permanent CO_2 storage, providing much needed economic incentives.

CO_2 utilization options are not insignificant. According to the International Energy Agency 2010 report, “Highest Ever Annual Carbon Emission Leave World in Trouble,” CO_2 utilization has the potential to reduce worldwide annual CO_2 emissions by ten percent. Whether converting CO_2 into other useful products such as biofuels or using it as a chemical feedstock, or developing non-conversion uses such as enhanced oil recovery, adding value to CO_2 is an important consideration to achieve widespread commercial deployment of CCS technologies.

For a good overview of CO_2 utilization and a discussion of technology pathways, please visit the CSLF website and see the *inFocus* fact sheet, “What is Carbon Utilization?”

Charter

At the CSLF Ministerial meeting in Beijing, China (September 19-23, 2011) the CSLF Charter was amended to, among other things, include CO_2 utilization technologies as an important aspect of a CO_2 emission reduction strategy, in addition to carbon capture and storage technologies that have been the focus of CSLF efforts since its inception in 2003. In response, the CSLF Technical Group included in its Five-Year Action Plan, 2011-2016, an action item to provide focus to the new suite of technologies associated with an array of CO_2 utilization options. Specifically, the five-year plan includes Action Plan 12: CO_2 Utilization Options. A new task force was proposed to investigate CO_2 utilization options under the direction of the CSLF Technical Group. At the September 2011 joint meeting of the Technical Group and the Policy Group in Beijing, China, the Five-Year Action Plan was approved, and the formation of a task force to implement Action Plan 12 was proposed.

Membership

The United States has agreed to lead or co-lead the task force. Membership of this task force is open to CSLF member countries and interested parties. *[Note: those interested in participating on the task force as a member or co-lead should contact the CSLF Secretariat*

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or Mr. Joseph Giove, Director, Division of CCS Demonstrations, Office of Fossil Energy, U.S. Department of Energy at Joseph.Giove@HQ.DOE.GOV *]*

Goals

The goal of the CO_2 Utilization Options Task Force, as stated in the Technical Group Five-Year Action Plan is the identification of the most economically attractive CO_2 utilization options. In pursuing this goal, the task force will focus on utilization options that have the potential to yield a significant, net reduction of CO_2 emissions in sufficient volumes to make a meaningful contribution to global warming and climate change objectives. For purposes of this task force the term "economically attractive" includes any CO_2 utilization technology or application, the use of which has a reasonable potential for an economically viable venture, or the use of which has a reasonable potential to partially offset the cost of anthropogenic CO_2 capture, thus facilitating the deployment of conventional CCS technology.

The work product of the task force will include a summary of existing information regarding utilization options, an assessment of the state of each relevant technology and application, a gap analysis for the most promising technologies, and an assessment of the relative value of the utilization option to make a meaningful impact on CO_2 emissions. *[Note: the final scope of the work effort will be determined by the task force members]*

The findings of the task force will be reported in an interim report in [date], 2013, with a final report completed by [date], 2014.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2012-07
09 April 2012

TECHNICAL GROUP

Planning Document:
Storage and Monitoring for Commercial Projects Task Force

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2012-07
09 April 2012

PLANNING DOCUMENT:
STORAGE AND MONITORING FOR COMMERCIAL PROJECTS TASK FORCE

Note by the Secretariat

Background

At the 4th CSLF Ministerial Meeting, at Beijing, China in September 2011, the Technical Group approved a new multi-year Action Plan. "Storage and Monitoring for Commercial Projects" is one of the twelve Actions that comprise the Action Plan, and Norway has volunteered to lead a new Task Force that will focus on identification and review of standards for geological CO_2 storage and monitoring as well as for guidelines for communication with and engagement of involved communities and regulators. This paper is a Planning Document for the new Task Force that describes its mandate, scope, goals, timeframe, and expected outcomes.

Action Requested

The Technical Group is requested to review and approve this Planning Document.

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Planning Document for Technical Group Action Plan #6
Storage and Monitoring for Commercial Projects

Background

Since its inception in 2003, the Carbon Sequestration Leadership Forum (CSLF) has focused its efforts to facilitate the research, development, demonstration and deployment of effective, low-cost CO_2 capture and storage (CCS) technologies as a viable option to reduce greenhouse gas emissions in an effort to combat the effects of global warming. For capture these efforts focused on a variety of technologies applicable to power and industrial plants that use or process fossil fuels. For the CO_2 storage the focus has primarily been on geological sequestration.

National and international regulations regarding storage of CO_2 in the underground are appearing. The European Commission has issued its directive 2009/31/EC, which has requirements on how to characterize and monitor a geological storage site. The OSPAR and London Conventions also have such requirements that will come into force when the conventions have been ratified by a sufficient number of parties. Thus, in connection with applications for underground CO_2 storage it will be beneficial to have standards, guidelines or best practice manuals to facilitate the process.

The first articles addressing the subject of site selection go back to around 2003. The first best practice manual was probably the one produced by the CSLF recognized CO2STORE project in 2006. It was later followed by, among others, a generic report on selection and characterizing of a storage sites by CO2CRC; several NETL best practices; guidelines for the entire CCS chain by World Resources Institute; a technical basis for carbon dioxide storage by the CO_2 Capture Project (CCP); and guidelines from Det norske Veritas (DNV). A review of existing best practice manuals for carbon dioxide storage and regulation was published by CO2CRC in March 2011.

At the start of 2012 there were eight large-scale integrated projects in operation and seven under construction, in addition to numerous smaller storage projects worldwide. There will be lessons learned from most of these and the experience is likely to find its way into updated and new standards, guidelines and best practices for CO_2 storage and monitoring.

Mandate

At the CSLF meetings in Beijing, China (September 19-23, 2011) the CSLF Technical Group agreed that the Secretariat should circulate, by the end of the first week of October, a listing of the twelve Actions of its five years Action Plan to Technical Group delegates with the request that that each CSLF Member provide a ranking by priority of importance. Delegates were asked to respond within three weeks and the results were then compiled by the Secretariat. Results from this survey were used to decide which Actions to undertake immediately and which ones to defer. The Secretariat was also asked to solicit ideas for additional Actions from the delegates.

Specifically, the prioritized actions of the five-year plan include Action Plan 6: Storage and Monitoring for Commercial Projects. The formation of a task force to implement Action Plan 6 was proposed.

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Membership

Norway has agreed to lead or co-lead the task force. Membership of this task force is open to CSLF member countries and interested parties. *[Note: those interested in participating on the task force as a member or co-lead should contact the CSLF Secretariat or Mr. Trygve Riis, Research Council of Norway, tur@rcn.no]*

Outcome

The outcome of the Storage and Monitoring for Commercial Projects Task Force, will be regular identification and review of new and updated standards for storage and monitoring of injected CO_2. The application of such standards should inform CO_2 crediting mechanisms.

Action and Scope

To obtain this outcome, the task force will identify and review standards for geological CO_2 storage and monitoring as well as for guidelines for communication with and engagement of involved communities and regulators. As stated above, there are already several guidelines and best practice manuals. The Task Force will produce annual summaries of new as well as updated standards, guidelines and best practice documents regarding geological storage of CO_2 and monitoring of CO_2 sites. One important aspect of the scope will be to keep track of the work within ISO, where a CCS working group has been established and has recommended global standards on CCS to be elaborated It is also expected the Task Force will need to follow the work of other task forces, in particular a new action proposed by Canada, Task Force on Storage Capacity Estimation. *[Note: the final scope of the work effort will be determined by the task force members]*

Milestones

The findings of the task force will be reported in an annual interim reports by [date], 2012, 2013, 2014 and 2015, with a final report completed by [date], 2016.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2012-08
25 April 2012

TECHNICAL GROUP

Planning Document: Technical Gaps Closure Task Force

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2012-08
25 April 2012

PLANNING DOCUMENT:
TECHNICAL GAPS CLOSURE TASK FORCE

Note by the Secretariat

Background

At the 4th CSLF Ministerial Meeting, at Beijing, China in September 2011, the Technical Group approved a new multi-year Action Plan. “Technical Gaps Closure” is one of the twelve Actions that comprise the Action Plan, and Australia has volunteered to lead a new Task Force that will focus on identification and review of new updated critical technology gaps and opportunities for CO_2 capture transport, storage, and environmental monitoring and verification. This paper is a Planning Document for the new Task Force that describes its mandate, scope, goals, timeframe, and expected outcomes.

Action Requested

The Technical Group is requested to review and approve this Planning Document.

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Planning Document for Action Plan #1
Technology Gaps Closure

Background

The Carbon Sequestration Leadership Forum (CSLF) has had a significant focus on encouraging and facilitating research, development, demonstration and deployment of effective, low-cost CO_2 capture, utilization and storage (CCUS) technologies. If CCUS is going to be applied broadly, at large scale, it is essential that the technology is refined to deliver safe, low-cost, efficient storage in a wide range of situations. As a contribution to the global effort on CCUS the CSLF will focus attention on the gaps and opportunities associated with the technology, with a view to speeding up the technology delivery at a global level and getting more focus on the critical gaps and opportunities that can make a significant difference by 2025.

As the global effort on CCS moves increasingly to large scale demonstration, there is an increasing amount of effort going into research and development and an increased number of governments and companies tackling pilots and demonstrations. This is complimented by a growing offering of technology and technology support for CCUS. On the capture side the traditional amine capture technology is being installed or planned on large projects. A number of Original Equipment Manufacturers (OEMs) have developed their own technologies and are offering either enhancements on the amine technologies or new technologies, particularly insolvents.

On the transport and storage side, global experience and knowledge is growing. The decades of experience in enhanced oil recovery, combined with many project-years operating experience in carbon storage projects such as Sleipner, Snøhvit, and In Salah as well as the exploration and planning work that has been undertaken for projects such as Gorgon, Boundary Dam, ROAD, Decatur, etc. represent a substantial body of global knowledge. Research institutions around the world and their associated demonstration projects have also built a strong basis in the science and subsurface engineering.

It is clear however that, despite the efforts and developments in capture, storage and monitoring and verification to date, driving down the costs is still an overriding imperative. This can only be achieved by developing and refining more efficient technology and integrating the learning that comes from deployment in pilot and demonstration facilities around the world.

Mandate

At the CSLF meetings in Beijing, China (September 19-23, 2011) the CSLF Technical Group agreed that the Secretariat should circulate, by the end of the first week of October, a listing of the twelve actions of its five years Action Plan to Technical Group delegates with the request that that each CSLF Member provide a ranking by priority of importance. Delegates were asked to respond within three weeks and the results were then compiled by the Secretariat. Results from this survey were used to decide which actions to undertake immediately and which ones to defer. The Secretariat was also asked to solicit ideas for additional actions from the delegates.

Specifically, the prioritized actions of the five-year plan include Action Plan 1: Technology gaps. The formation of a task force to implement Action Plan 1 was proposed.

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Membership

Australia has agreed to lead or co-lead the task force. Membership of this task force is open to CSLF member countries and interested parties. *[Note: those interested in participating on the task force as a member or co-lead should contact the CSLF Secretariat or Dr. Richard Aldous of CO2CRC, Australia (raldous@co2crc.com.au]*

Outcome

The outcome of the Technology Gaps Task Force will be the identification and review of new updated critical technology gaps and opportunities for CO_2 capture transport, storage, and environmental monitoring and verification. The identification of the significant gaps and opportunities should be of interest to governments, companies and researchers and technology developers around the world. It may be of particular value to those organizations looking to foster international collaboration and optimization of the technology effort.

Action and Scope

To obtain this outcome, the Task Force will identify and review the spectrum of technologies and emergent technologies, looking for any critical gaps but also identifying the opportunities to substantially reduce costs and get better operational and environmental outcomes.

Suggested Approach

1. Identify 2-3 participants interested in each of:
    a. Capture technologies
    b. Transport technologies
    c. Storage(sub surface issues and MMV) technologies
    d. Environment monitoring, including submarine monitoring technologies
2. Define an agreed process to assemble information using an agreed standardized template on each major aspect or sub-element for each of the above technology areas, for example:
    a. **Technology dimension** : eg Adorbent technologies or new solvents etc
    b. **Current status of technology** advanced technology developments only (eg already at pilot scale as a minimum)
    c. **Who are the main players** in this area
    d. **Technology shortfalls gaps risks and opportunities** associated with the technology
    e. **Potential for a major breakthrough** deliverable to market by 2025, (high, medium, low)
    f. **Potential for a deliverable cost reduction** in the next 10 years stated as percentage improvement against of a benchmark CCS system.
    g. **Estimated cost to deliver improvement or cover gap**
    h. **Collaboration potential**
3. **Synthesize data from the above into a report** to be delivered by June each alternate year starting in 2013.

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4. **The reports will** set out high level gaps and opportunities, with recommendations on how the global technology development pathway could be sped up or enhanced to further drive down costs and get better outcomes.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CHARTER FOR THE CARBON SEQUESTRATION LEADERSHIP FORUM (CSLF) A CARBON CAPTURE AND STORAGE TECHNOLOGY INITIATIVE

The undersigned national governmental entities (collectively the “Members”) set forth the following revised Terms of Reference for the Carbon Sequestration Leadership Forum (CSLF), a framework for international cooperation in research, development demonstration and commercialization for the separation, capture, transportation, utilization and storage of carbon dioxide. The CSLF seeks to realize the promise of carbon capture utilization and storage (CCUS) over the coming decades, ensuring it to be commercially competitive and environmentally safe.

1. Purpose of the CSLF

To accelerate the research, development, demonstration, and commercial deployment of improved cost-effective technologies for the separation and capture of carbon dioxide for its transport and long-term safe storage or utilization; to make these technologies broadly available internationally; and to identify and address wider issues relating to CCUS. This could include promoting the appropriate technical, political, economic and regulatory environments for the research, development, demonstration, and commercial deployment of such technology.

2. Function of the CSLF

The CSLF seeks to:

2.1 Identify key obstacles to achieving improved technological capacity;

2.2 Identify potential areas of multilateral collaborations on carbon separation, capture, utilization, transport and storage technologies;

2.3 Foster collaborative research, development, and demonstration (RD&D) projects reflecting Members’ priorities;

2.4 Identify potential issues relating to the treatment of intellectual property;

2.5 Establish guidelines for the collaborations and reporting of their results;

2.6 Assess regularly the progress of collaborative RD&D projects and make recommendations on the direction of such projects;

2.7 Establish and regularly assess an inventory of the potential RD&D needs and gaps;

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2.8 Organize collaboration with the international stakeholder community, including industry, academia, financial institutions, government and non-government organizations; the CSLF is also intended to complement ongoing international cooperation;

2.9 Disseminate information and foster knowledge-sharing, in particular among members' demonstration projects;

2.10 Build the capacity of Members;

2.11 Conduct such other activities to advance achievement of the CSLF's purpose as the Members may determine;

2.12 Consult with and consider the views and needs of stakeholders in the activities of the CSLF;

2.13 Initiate and support international efforts to explain the value of CCUS, and address issues of public acceptance, legal and market frameworks and promote broad-based adoption of CCUS; and

2.14 Support international efforts to promote RD&D and capacity building projects in developing countries.

3. Organization of the CSLF

3.1 A Policy Group and a Technical Group oversee the management of the CSLF. Unless otherwise determined by consensus of the Members, each Member will make up to two appointments to the Policy Group and up to two appointments to the Technical Group.

3.2 The CSLF operates in a transparent manner. CSLF meetings are open to stakeholders who register for the meeting.

3.3 The Policy Group governs the overall framework and policies of the CSLF, periodically reviews the program of collaborative projects, and provides direction to the Secretariat. The Group should meet at least once a year, at times and places to be determined by its appointed representatives. All decisions of the Group will be made by consensus of the Members.

3.4 The Technical Group reports to the Policy Group. The Technical Group meets as often as necessary to review the progress of collaborative projects, identify promising directions for the research, and make recommendations to the Policy Group on needed actions.

3.5 The CSLF meets at such times and places as determined by the Policy Group. The Technical Group and Task Forces will meet at times that they decide in coordination with the Secretariat.

3.6 The principal coordinator of the CSLF's communications and activities is the CSLF Secretariat. The Secretariat: (1) organizes the meetings of the CSLF and its sub-groups, (2) arranges special activities such as teleconferences and workshops, (3) receives and forwards new membership requests to the Policy Group, (4)

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coordinates communications with regard to CSLF activities and their status, (5) acts as a clearing house of information for the CSLF, (6) maintains procedures for key functions that are approved by the Policy Group, and (7) performs such other tasks as the Policy Group directs. The focus of the Secretariat is administrative. The Secretariat does not act on matters of substance except as specifically instructed by the Policy Group.

3.7 The Secretariat may, as required, use the services of personnel employed by the Members and made available to the Secretariat. Unless otherwise provided in writing, such personnel are remunerated by their respective employers and will remain subject to their employers' conditions of employment.

3.8 The U.S. Department of Energy acts as the CSLF Secretariat unless otherwise decided by consensus of the Members.

3.9 Each Member individually determines the nature of its participation in the CSLF activities.

4 Membership

4.1 This Charter, which is administrative in nature, does not create any legally binding obligations between or among its Members. Each Member should conduct the activities contemplated by this Charter in accordance with the laws under which it operates and the international instruments to which its government is a party.

4.2 The CSLF is open to other national governmental entities and its membership will be decided by the Policy Group.

4.3 Technical and other experts from within and without CSLF Member organizations may participate in RD&D projects conducted under the auspices of the CSLF. These projects may be initiated either by the Policy Group or the Technical Group.

5 Funding

Unless otherwise determined by the Members, any costs arising from the activities contemplated by this Charter are to be borne by the Member that incurs them. Each Member's participation in CSLF activities is subject to the availability of funds, personnel and other resources.

6 Open Research and Intellectual Property

6.1 To the extent practicable, the RD&D fostered by the CSLF should be open and nonproprietary.

6.2 The protection and allocation of intellectual property, and the treatment of proprietary information, generated in RD&D collaborations under CSLF auspices should be defined by written implementing arrangements between the participants therein.

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7. Commencement, Modification, Withdrawal, and Discontinuation

7.1 Commencement and Modification

7.1.1 Activities under this Charter may commence on June 25, 2003. The Members may, by unanimous consent, discontinue activities under this Charter by written arrangement at any time.

7.1.2 This Charter may be modified in writing at any time by unanimous consent of all Members.

7.2 Withdrawal and Discontinuation

A Member may withdraw from membership in the CSLF by giving 90 days advance written notice to the Secretariat.

8. Counterparts

This Charter may be signed in counterpart.

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Carbon Sequestration Leadership Forum
www.cslforum.org

revision date: 07 October 2010

CARBON SEQUESTRATION LEADERSHIP FORUM
TERMS OF REFERENCE AND PROCEDURES

These Terms of Reference and Procedures provide the overall framework to implement the Charter of the Carbon Sequestration Leadership Forum (CSLF). They define the organization of the CSLF and provide the rules under which the CSLF will operate.

1. Organizational Responsibilities

1.1. Policy Group. The Policy Group will govern the overall framework and policies of the CSLF in line with Article 3.2 of the CSLF Charter. The Policy Group is responsible for carrying out the following functions of the CSLF as delineated in Article 2 of the CSLF Charter:

- Identify key legal, regulatory, financial, public perception, institutional-related or other issues associated with the achievement of improved technological capacity.
- Identify potential issues relating to the treatment of intellectual property.
- Establish guidelines for the collaborations and reporting of results.
- Assess regularly the progress of collaborative projects and following reports from the Technical Group make recommendations on the direction of such projects.
- Ensure that CSLF activities complement ongoing international cooperation in this area.
- Consider approaches to address issues associated with the above functions.

In order to implement Article 3.2 of the CSLF Charter, the Policy Group will:

- Review all projects for consistency with the CSLF Charter.
- Consider recommendations of the Technical Group for appropriate action.
- Annually review the overall program of the Policy and Technical Groups and each of their activities.
- Periodically review the Terms of Reference and Procedures.

The Chair of the Policy Group will provide information and guidance to the Technical Group on required tasks and initiatives to be undertaken based upon decisions of the Policy Group. The Chair of the Policy Group will also arrange for appropriate exchange of information between both the Policy Group and the Technical Group.

1.2. Technical Group. The Technical Group will report to the Policy Group and make recommendations to the Policy Group on needed actions in line with Article 3.3 of the CSLF Charter. The Technical Group is responsible for carrying out the following functions of the CSLF as delineated in Article 2 of the CSLF Charter:

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- Identify key technical, economic, environmental and other issues related to the achievement of improved technological capacity.
- Identify potential areas of multilateral collaboration on carbon capture, transport and storage technologies.
- Foster collaborative research, development, and demonstration (RD&D) projects reflecting Members' priorities.
- Assess regularly the progress of collaborative projects and make recommendations to the Policy Group on the direction of such projects.
- Establish and regularly assess an inventory of the potential areas of needed research.
- Facilitate technical collaboration with all sectors of the international research community, academia, industry, government and non-governmental organizations.
- Consider approaches to address issues associated with the above functions.

In order to implement Article 3.2 of the CSLF Charter, the Technical Group will:

- Recommend collaborative projects to the Policy Group.
- Set up and keep procedures to review the progress of collaborative projects.
- Follow the instructions and guidance of the Policy Group on required tasks and initiatives to be undertaken.

1.3. <u>Secretariat</u>. The Secretariat will carry out those activities enumerated in Section 3.5 of the CSLF Charter. The role of the Secretariat is administrative and the Secretariat acts on matters of substance as specifically instructed by the Policy Group. The Secretariat will review all Members material submitted for the CSLF web site and suggest modification where warranted. The Secretariat will also clearly identify the status and ownership of the materials.

2. Additions to Membership

2.1. <u>Application</u>.

Pursuant to Article 4 of the CSLF Charter, national governmental entities may apply for membership to the CSLF by writing to the Secretariat. A letter of application should be signed by the responsible Minister from the applicant country. In their application letter, prospective Members should:

1) demonstrate they are a significant producer or user of fossil fuels that have the potential for carbon capture;
2) describe their existing national vision and/or plan regarding carbon capture and storage (CCS) technologies;
3) describe an existing national commitment to invest resources on research, development and demonstration activities in CCS technologies;
4) describe their commitment to engage the private sector in the development and deployment of CCS technologies; and
5) describe specific projects or activities proposed for being undertaken within the frame of the CSLF.

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The Policy Group will address new member applications at the Policy Group Meetings.

2.2. Offer. If the Policy Group approves the application, membership will then be offered to the national governmental entity that submitted the application.

2.3. Acceptance. The applicant national governmental entity may accept the offer of membership by signing the Charter in Counterpart and delivering such signature to the embassy of the Secretariat. A notarized "true copy" of the signed document is acceptable in lieu of the original. The nominated national governmental entity to which an offer has been extended becomes a Member upon receipt by the Secretariat of the signed Charter.

3. CSLF Governance

3.1. Appointment of Members' Representatives. Members may make appointments and/or replacements to the Policy Group and Technical Group at any time pursuant to Article 3.1 of the CSLF Charter by notifying the Secretariat. The Secretariat will acknowledge such appointment to the Member and keep an up-to-date list of all Policy Group and Technical Group representatives on the CSLF web site.

3.2. Meetings.

(a) The Policy Group should meet at least once each year at a venue and date selected by a decision of the Members.

(b) Ministerial meetings will normally be held approximately every other year. Ministerial meetings will review the overall progress of CSLF collaboration, findings, and accomplishments on major carbon capture and storage issues and provide overall direction on priorities for future work.

(c) The Technical Group will meet as often as necessary and at least once each year at a considered time interval prior to the meeting of the Policy Group.

(d) Meetings of the Policy Group or Technical Group may be called by the respective Chairs of those Groups after consultation with the members.

(e) The Policy and Technical Groups may designate observers and resource persons to attend their respective meetings. CSLF Members may bring other individuals, as indicated in Article 3.1 of the CSLF Charter, to the Policy and Technical Group meetings with prior notice to the Secretariat. The Chair of the Technical Group and whomever else the Technical Group designates may be observers at the Policy Group meeting.

(f) The Secretariat will produce minutes for each of the meetings of the Policy Group and the Technical Group and provide such minutes to all the Members' representatives to the appropriate Group within thirty (30) days of the meeting. Any materials to be considered by Members of the Policy or Technical Groups will be made available to the Secretariat for distribution thirty (30) days prior to meetings.

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3.3. Organization of the Policy and Technical Groups

(a) The Policy Group and the Technical Group will each have a Chair and up to three Vice Chairs. The Chairs of the Policy and Technical Groups will be elected every three years.

1) At least 3 months before a CSLF decision is required on the election of a Chair or Vice Chair a note should be sent from the Secretariat to CSLF Members asking for nominations. The note should contain the following:

   > Nominations should be made by the heads of delegations. Nominations should be sent to the Secretariat. The closing date for nominations should be six weeks prior to the CSLF decision date.

2) Within one week after the closing date for nominations, the Secretariat should post on the CSLF website and email to Policy and Technical Group delegates as appropriate the names of Members nominated and identify the Members that nominated them.
3) As specified by Article 3.2 of the CSLF Charter, the election of Chair and Vice- Chairs will be made by consensus of the Members.
4) When possible, regional balance and emerging economy representation among the Chairs and Vice Chairs should be taken into consideration by Members.

(b) Task Forces of the Policy Group and Technical Group consisting of Members' representatives and/or other individuals may be organized to perform specific tasks as agreed by a decision of the representatives at a meeting of that Group. Meetings of Task Forces of the Policy or Technical Group will be set by those Task Forces.

(c) The Chairs of the Policy Group and the Technical Group will have the option of presiding over the Groups' meetings. Task force leaders will be appointed by a consensus of the Policy and Technical Groups on the basis of recommendations by individual Members. Overall direction of the Secretariat is the responsibility of the Chair of the Policy Group. The Chair of the Technical Group may give such direction to the Secretariat as is relevant to the operations of the Technical Group.

3.4. Decision Making. As specified by Article 3.2 of the CSLF Charter, all decisions will be made by consensus of the Members.

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4. CSLF Projects

4.1. Types of Collaborative Projects. Collaborative projects of any type consistent with Article 1 of the CSLF Charter may be recognized by the CSLF as described below. This specifically includes projects that are indicative of the following:

- Information exchange and networking,
- Planning and road-mapping,
- Facilitation of collaboration,
- Research and development,
- Demonstrations, or
- Other issues as indicated in Article 1 of the CSLF Charter.

4.2. Project Recognition. All projects proposed for recognition by the CSLF shall be evaluated via a CSLF Project Submission Form. The CSLF Project Submission Form shall request from project sponsors the type and quantity of information that will allow the project to be adequately evaluated by the CSLF.

A proposal for project recognition can be submitted by any CSLF delegate to the Technical Group and must contain a completed CSLF Project Submission Form. In order to formalize and document the relationship with the CSLF, the representatives of the project sponsors and the delegates of Members nominating a project must sign the CSLF Project Submission Form specifying that relationship before the project can be considered.

The Technical Group shall evaluate all projects proposed for recognition. Projects that meet all evaluation criteria shall be recommended to the Policy Group. A project becomes recognized by the CSLF following approval by the Policy Group.

4.3. Information Availability from Recognized Projects. Non-proprietary information from CSLF-recognized projects, including key project contacts, shall be made available to the CSLF by project sponsors. The Secretariat shall have the responsibility of maintaining this information on the CSLF website.

5. Interaction with Stakeholders

It is recognized that stakeholders, those organizations that are affected by and can affect the goals of the CSLF, form an essential component of CSLF activities. Accordingly, the CSLF will engage stakeholders paying due attention to equitable access, effectiveness and efficiency and will be open, visible, flexible and transparent. In addition, CSLF members will continue to build and communicate with their respective stakeholder networks.

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Carbon Sequestration Leadership Forum

www.cslforum.org

Active and Completed CSLF Recognized Projects

(as of February 2012)

1. **Alberta Enhanced Coal-Bed Methane Recovery Project** ***(Completed)***
   Nominators: Canada (lead), United States, and United Kingdom
   This pilot-scale project, located in Alberta, Canada, aimed at demonstrating, from both economic and environmental criteria, the overall feasibility of coal bed methane (CBM) production and simultaneous CO_2 storage in deep unmineable coal seams. Specific objectives of the project were to determine baseline production of CBM from coals; determine the effect of CO_2 injection and storage on CBM production; assess economics; and monitor and trace the path of CO_2 movement by geochemical and geophysical methods. All testing undertaken was successful, with one important conclusion being that flue gas injection appears to enhance methane production to a greater degree possible than with CO_2 while still sequestering CO_2, albeit in smaller quantities.
   Recognized by the CSLF at its Melbourne meeting, September 2004

2. **CANMET Energy Technology Centre (CETC) R&D Oxyfuel Combustion for CO_2 Capture**
   Nominators: Canada (lead) and United States
   This is a pilot-scale project, located in Ontario, Canada, that will demonstrate oxy-fuel combustion technology with CO_2 capture. The goal of the project is to develop energy-efficient integrated multi-pollutant control, waste management and CO_2 capture technologies for combustion-based applications and to provide information for the scale-up, design and operation of large-scale industrial and utility plants based on the oxy-fuel concept.
   Recognized by the CSLF at its Melbourne meeting, September 2004

3. **CASTOR** ***(Completed)***
   Nominators: European Commission (lead), France, and Norway
   This was a multifaceted project that had activities at various sites in Europe, in three main areas: strategy for CO_2 reduction, post-combustion capture, and CO_2 storage performance and risk assessment studies. The goal was to reduce the cost of post-combustion CO_2 capture and to develop and validate, in both public and private partnerships, all the innovative technologies needed to capture and store CO_2 in a reliable and safe way. The tests showed the reliability and efficiency of the post-combustion capture process.
   Recognized by the CSLF at its Melbourne meeting, September 2004

4. **CCS Bełchatów Project**
   Nominators: Poland (lead), European Commission, and United States
   This is a large-scale project, located in central Poland, which will demonstrate commercial-scale CO_2 capture, transport and storage at a new lignite-fired power plant unit. The project will demonstrate the full CCS value chain, including capture, transport, and safe geological storage of up to 1.8 million tonnes of CO_2 per year. Project components include identification of potential issues related to intellectual property,

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storage site selection, permitting, facilities and pipeline construction, and public engagement activities. Success of this project will expedite commercialization of CCS for large-scale fossil fuel power generation.
Recognized by the CSLF at its Warsaw meeting, October 2010

5. **CCS Rotterdam Project**
Nominators: Netherlands (lead) and Germany
This project will implement a large-scale "CO_2 Hub" for capture, transport, utilization, and storage of CO_2 in the Rotterdam metropolitan area. The project is part of the Rotterdam Climate Initiative (RCI), which has a goal of reducing Rotterdam's CO_2 emissions by 50% by 2025 (as compared to 1990 levels). A "CO_2 cluster approach" will be utilized, with various point sources (e.g., CO_2 captured from power plants) connected via a hub / manifold arrangement to multiple storage sites such as depleted gas fields under the North Sea. This will reduce the costs for capture, transport and storage compared to individual CCS chains. The project will also work toward developing a policy and enabling framework for CCS in the region.
Recognized by the CSLF at its London meeting, October 2009

6. **CGS Europe Project**
Nominators: Netherlands (lead) and Germany
This is a collaborative venture, involving 35 partners from participant countries in Europe, with extensive structured networking, knowledge transfer, and information exchange. A goal of the project is to create a durable network of experts in CO_2 geological storage and a centralized knowledge base which will provide an independent source of information for European and international stakeholders. The CGS Europe Project is intended to provide an information pathway toward large-scale implementation of CO_2 geological storage throughout Europe. This is intended to be a three-year project, starting in November 2011, and has received financial support from the European Commission's 7th Framework Programme (FP7).
Recognized by the CSLF at its Beijing meeting, September 2011

7. **China Coalbed Methane Technology/CO_2 Sequestration Project** ***(Completed)***
Nominators: Canada (lead), United States, and China
This pilot-scale project successfully demonstrated that coal seams in the anthracitic coals of Shanxi Province of China are permeable and stable enough to absorb CO_2 and enhance methane production, leading to a clean energy source for China. The project evaluated reservoir properties of selected coal seams of the Qinshui Basin of eastern China and carried out field testing at relatively low CO_2 injection rates. The project recommendation was to proceed to full scale pilot test at south Qinshui, as the prospect in other coal basins in China is good.
Recognized by the CSLF at its Berlin meeting, September 2005

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8. **CO_2 Capture Project – Phase 2** ***(Completed)***
   Nominators: United Kingdom (lead), Italy, Norway, and United States
   This pilot-scale project continued the development of new technologies to reduce the cost of CO_2 separation, capture, and geologic storage from combustion sources such as turbines, heaters and boilers. These technologies will be applicable to a large fraction of CO_2 sources around the world, including power plants and other industrial processes. The ultimate goal of the entire project is to reduce the cost of CO_2 capture from large fixed combustion sources by 20-30%, while also addressing critical issues such as storage site/project certification, well integrity and monitoring.
   Recognized by the CSLF at its Melbourne meeting, September 2004

9. **CO_2 Capture Project – Phase 3**
   Nominators: United Kingdom (lead) and United States
   This is a collaborative venture of seven partner companies (international oil and gas producers) plus the Electric Power Research Institute. The overall goals of the project are to increase technical and cost knowledge associated with CO_2 capture technologies, to reduce CO_2 capture costs by 20-30%, to quantify remaining assurance issues surrounding geological storage of CO_2, and to validate cost-effectiveness of monitoring technologies. The project is comprised of four areas: CO_2 Capture; Storage Monitoring & Verification; Policy & Incentives; and Communications. A fifth activity, in support of these four teams, is Economic Modeling. This third phase of the project will include at least two field demonstrations of CO_2 capture technologies and a series of monitoring field trials in order to obtain a clearer understanding of how to monitor CO_2 in the subsurface. Third phase activities began in 2009 and are expected to continue into 2013. Financial support is being provided by project consortium members.
   Recognized by the CSLF at its Beijing meeting, September 2011

10. **CO2CRC Otway Project**
    Nominators: Australia (lead) and United States
    This is a pilot-scale project, located in southwestern Victoria, Australia, that involves transport and injection of approximately 100,000 tons of CO_2 over a two year period into a depleted natural gas well. Besides the operational aspects of processing, transport and injection of a CO_2-containing gas stream, the project also includes development and testing of new and enhanced monitoring, and verification of storage (MMV) technologies, modeling of post-injection CO_2 behavior, and implementation of an outreach program for stakeholders and nearby communities. Data from the project will be used in developing a future regulatory regime for CO_2 capture and storage (CCS) in Australia.
    Recognized by the CSLF at its Paris meeting, March 2007

11. **CO_2 Field Lab Project**
    Nominators: Norway (lead), France, and United Kingdom
    This is a pilot-scale project, located at Svelvik, Norway, which will investigate CO_2 leakage characteristics in a well-controlled and well-characterized permeable geological formation. Relatively small amounts of CO_2 will be injected to obtain underground distribution data that resemble leakage at different depths. The resulting underground CO_2 distribution will resemble leakages and will be monitored with an extensive set of methods deployed by the project partners. The main objective is to assure and increase CO_2 storage safety by obtaining valuable knowledge about monitoring CO_2 migration and leakage. The outcomes from this project will help facilitate commercial deployment of CO_2 storage by providing the protocols for ensuring compliance with regulations, and

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will help assure the public about the safety of CO_2 storage by demonstrating the performance of monitoring systems.
Recognized by the CSLF at its Warsaw meeting, October 2010

12. CO_2 GeoNet
Nominators: European Commission (lead) and United Kingdom
This multifaceted project is focused on geologic storage options for CO_2 as a greenhouse gas mitigation option, and on assembling an authoritative body for Europe on geologic sequestration. Major objectives include formation of a partnership consisting, at first, of 13 key European research centers and other expert collaborators in the area of geological storage of CO_2, identification of knowledge gaps in the long-term geologic storage of CO_2, and formulation of new research projects and tools to eliminate these gaps. This project will result in re-alignment of European national research programs and prevention of site selection, injection operations, monitoring, verification, safety, environmental protection, and training standards.
Recognized by the CSLF at its Berlin meeting, September 2005

13. CO_2 Separation from Pressurized Gas Stream
Nominators: Japan (lead) and United States
This is a small-scale project that will evaluate processes and economics for CO_2 separation from pressurized gas streams. The project will evaluate primary promising new gas separation membranes, initially at atmospheric pressure. A subsequent stage of the project will improve the performance of the membranes for CO_2 removal from the fuel gas product of coal gasification and other gas streams under high pressure.
Recognized by the CSLF at its Melbourne meeting, September 2004

14. CO_2 STORE ***(Completed)***
Nominators: Norway (lead) and European Commission
This project, a follow-on to the Sleipner project, involved the monitoring of CO_2 migration (involving a seismic survey) in a saline formation beneath the North Sea and additional studies to gain further knowledge of geochemistry and dissolution processes. There were also several preliminary feasibility studies for additional geologic settings of future candidate project sites in Denmark, Germany, Norway, and the UK. The project was successful in developing sound scientific methodologies for the assessment, planning, and long-term monitoring of underground CO_2 storage, both onshore and offshore.
Recognized by the CSLF at its Melbourne meeting, September 2004

15. CO_2 Technology Centre Mongstad Project (formerly European CO_2 Technology Centre Mongstad Project)
Nominators: Norway (lead) and Netherlands
This is a large-scale project (100,000 tonnes per year CO_2 capacity) that will establish a facility for parallel testing of amine-based and chilled ammonia CO_2 capture technologies from two flue gas sources with different CO_2 contents. The goal of the project is to reduce cost and technical, environmental, and financial risks related to large scale CO_2 capture, while allowing evaluation of equipment, materials, process configurations, different capture solvents, and different operating conditions. The project will result in validation of process and engineering design for full-scale application and will provide insight into other aspects such as thermodynamics, kinetics, engineering, materials of construction, and health / safety / environmental (HSE).
Recognized by the CSLF at its London meeting, October 2009

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16. **Demonstration of an Oxyfuel Combustion System**
    Nominators: United Kingdom (lead) and France
    This project, located at Renfrew, Scotland, UK, will demonstrate oxyfuel technology on a full-scale 40-megawatt burner. The goal of the project is to gather sufficient data to establish the operational envelope of a full-scale oxyfuel burner and to determine the performance characteristics of the oxyfuel combustion process at such a scale and across a range of operating conditions. Data from the project will be used to develop advanced computer models of the oxyfuel combustion process, which will be utilized in the design of large oxyfuel boilers.
    Recognized by the CSLF at its London meeting, October 2009

17. **Dynamis** ***(Completed)***
    Nominators: European Commission (lead), and Norway
    This was the first phase of the multifaceted European Hypogen program, which will result in the construction and operation of an advanced commercial-scale power plant with hydrogen production and CO_2 management. The overall aim is for operation and validation of the power plant during the 2012-2015 timeframe. The Dynamis project assessed the various options for large-scale hydrogen production while focusing on the technological, economic, and societal issues.
    Recognized by the CSLF at its Cape Town meeting, April 2008

18. **ENCAP** ***(Completed)***
    Nominators: European Commission (lead), France, and Germany
    This multifaceted research project consisted of six sub-projects: Process and Power Systems, Pre-Combustion Decarbonization Technologies, O_2/ CO_2 Combustion (Oxy-fuel) Boiler Technologies, Chemical Looping Combustion (CLC), High-Temperature Oxygen Generation for Power Cycles, and Novel Pre-Combustion Capture Concepts. The goals were to develop promising pre-combustion CO_2 capture technologies (including O_2/ CO_2 combustion technologies) and propose the most competitive demonstration power plant technology, design, process scheme, and component choices. All sub-projects were successfully completed by March 2009.
    Recognized by the CSLF at its Berlin meeting, September 2005

19. **Fort Nelson Carbon Capture and Storage Project**
    Nominators: Canada (lead) and United States
    This is a large-scale project in northeastern British Columbia, Canada, which will permanently sequester approximately two million tonnes per year CO_2 emissions from a large natural gas-processing plant into deep saline formations of the Western Canadian Sedimentary Basin (WCSB). Goals of the project are to verify and validate the technical and economic feasibility of using brine-saturated carbonate formations for large-scale CO_2 injection and demonstrate that robust monitoring, verification, and accounting (MVA) of a brine-saturated CO_2 sequestration project can be conducted cost-effectively. The project will also develop appropriate tenure, regulations, and MVA technologies to support the implementation of future large-scale sour CO_2 injection into saline-filled deep carbonate reservoirs in the northeast British Columbia area of the WCSB.
    Recognized by the CSLF at its London meeting, October 2009

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20. Frio Project ***(Completed)***

Nominators: United States (lead) and Australia

This pilot-scale project demonstrated the process of CO_2 sequestration in an on-shore underground saline formation in Eastern Texas, USA. This location was ideal, as very large scale sequestration may be needed in the area to significantly offset anthropogenic CO_2 releases. The project involved injecting relatively small quantities of CO_2 into the formation and monitoring its movement for several years thereafter. The goals were to verify conceptual models of CO_2 sequestration in such geologic structures; demonstrate that no adverse health, safety or environmental effects will occur from this kind of sequestration; demonstrate field-test monitoring methods; and develop experience necessary for larger scale CO_2 injection experiments.

Recognized by the CSLF at its Melbourne meeting, September 2004

21. Geologic CO_2 Storage Assurance at In Salah, Algeria

Nominators: United Kingdom (lead) and Norway

This multifaceted project will develop the tools, technologies, techniques and management systems required to cost-effectively demonstrate, safe, secure, and verifiable CO_2 storage in conjunction with commercial natural gas production. The goals of the project are to develop a detailed dataset on the performance of CO_2 storage; provide a field-scale example on the verification and regulation of geologic storage systems; test technology options for the early detection of low-level seepage of CO_2 out of primary containment; evaluate monitoring options and develop guidelines for an appropriate and cost-effective, long-term monitoring methodology; and quantify the interaction of CO_2 re-injection and hydrocarbon production for long-term storage in oil and gas fields.

Recognized by the CSLF at its Berlin meeting, September 2005

22. Gorgon CO_2 Injection Project

Nominators: Australia (lead), Canada, and United States

This is a large-scale project that will store approximately 120 million tonnes of CO_2 in a water-bearing sandstone formation two kilometers below Barrow Island, off the northwest coast of Australia. The CO_2 stored by the project will be extracted from natural gas being produced from the nearby Gorgon Field and injected at approximately 3.5 to 4 million tonnes per year. There is an extensive integrated monitoring plan, and the objective of the project is to demonstrate the safe commercial-scale application of greenhouse gas storage technologies at a scale not previously attempted. The project has already progressed through its early development stages including site selection and appraisal, and is fully funded. Injection operations are expected to commence by the end of 2014.

Recognized by the CSLF at its Warsaw meeting, October 2010

23. IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project

Nominators: Canada and United States (leads) and Japan

This is a large-scale project that will utilize CO_2 for enhanced oil recovery (EOR) at a Canadian oil field. The goal of the project is to determine the performance and undertake a thorough risk assessment of CO_2 storage in conjunction with its use in enhanced oil recovery. The work program will encompass four major technical themes of the project: geological integrity; wellbore injection and integrity; storage monitoring methods; and risk assessment and storage mechanisms. Results from these technical themes, when integrated with policy research, will result in a Best Practices Manual for future CO_2 Enhanced Oil Recovery projects.

Recognized by the CSLF at its Melbourne meeting, September 2004

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24. ITC CO_2 Capture with Chemical Solvents Project

Nominators: Canada (lead) and United States

This is a pilot-scale project that will demonstrate CO_2 capture using chemical solvents. Supporting activities include bench and lab-scale units that will be used to optimize the entire process using improved solvents and contactors, develop fundamental knowledge of solvent stability, and minimize energy usage requirements. The goal of the project is to develop improved cost-effective technologies for separation and capture of CO_2 from flue gas.

Recognized by the CSLF at its Melbourne meeting, September 2004

25. Ketzin Test Site Project (formerly CO_2 SINK) ***(Completed)***

Nominators: European Commission (lead) and Germany

This is a pilot-scale project that tested and evaluated CO_2 capture and storage at an existing natural gas storage facility and in a deeper land-based saline formation. A key part of the project was monitoring the migration characteristics of the stored CO_2. The project was successful in advancing the understanding of the science and practical processes involved in underground storage of CO_2 and provided real case experience for use in development of future regulatory frameworks for geological storage of CO_2.

Recognized by the CSLF at its Melbourne meeting, September 2004

26. Lacq Integrated CCS Project

Nominators: France (lead) and Canada

This is an intermediate-scale project that will test and demonstrate an entire integrated CCS process, from emissions source to underground storage in a depleted gas field. The project will capture and store 60,000 tonnes per year of CO_2 for two years from an oxyfuel industrial boiler in the Lacq industrial complex in southwestern France. The goal is demonstrate the technical feasibility and reliability of the integrated process, including the oxyfuel boiler, at an intermediate scale before proceeding to a large-scale demonstration. The project will also include geological storage qualification methodologies, as well as monitoring and verification techniques, to prepare future larger-scale long term CO_2 storage projects.

Recognized by the CSLF at its London meeting, October 2009

27. Quest CCS Project

Nominators: Canada (lead), United Kingdom, and United States

This is a large-scale project, located at Fort Saskatchewan, Alberta, Canada, with integrated capture, transportation, storage, and monitoring, which will capture and store up to 1.2 million tonnes per year of CO_2 from an oil sands upgrading unit. The CO_2 will be transported via pipeline and stored in a deep saline aquifer in the Western Sedimentary Basin in Alberta, Canada. This is a fully integrated project, intended to significantly reduce the carbon footprint of the commercial oil sands upgrading facility while developing detailed cost data for projects of this nature. This will also be a large-scale deployment of CCS technologies and methodologies, including a comprehensive measurement, monitoring and verification (MMV) program.

Recognized by the CSLF at its Warsaw meeting, October 2010

28. Regional Carbon Sequestration Partnerships

Nominators: United States (lead) and Canada

This multifaceted project will identify and test the most promising opportunities to implement sequestration technologies in the United States and Canada. There are seven

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different regional partnerships, each with their own specific program plans, which will conduct field validation tests of specific sequestration technologies and infrastructure concepts; refine and implement (via field tests) appropriate measurement, monitoring and verification (MMV) protocols for sequestration projects; characterize the regions to determine the technical and economic storage capacities; implement and continue to research the regulatory compliance requirements for each type of sequestration technology; and identify commercially available sequestration technologies ready for large scale deployment.
Recognized by the CSLF at its Berlin meeting, September 2005

29. Regional Opportunities for CO_2 Capture and Storage in China ***(Completed)***
Nominators: United States (lead) and China
This project characterized the technical and economic potential of CO_2 capture and storage technologies in China. The goals were to compile key characteristics of large anthropogenic CO_2 sources (including power generation, iron and steel plants, cement kilns, petroleum and chemical refineries, etc.) as well as candidate geologic storage formations, and to develop estimates of geologic CO_2 storage capacities in China. The project found 2,300 gigatons of potential CO_2 storage capacity in onshore Chinese basins, significantly more than previous estimates. Another important finding is that the heavily developed coastal areas of the East and South Central regions appear to have less access to large quantities of onshore storage capacity than many of the inland regions. These findings present the possibility for China's continued economic growth with coal while safely and securely reducing CO_2 emissions to the atmosphere.
Recognized by the CSLF at its Berlin meeting, September 2005

30. Rotterdam Opslag en Afvang Demonstratieproject (ROAD)
Nominators: Netherlands (lead) and the European Commission
This is a large-scale integrated project, located near the city of Rotterdam, Netherlands, which includes CO_2 capture from a coal-fueled power plant, pipeline transportation of the CO_2, and offshore storage of the CO_2 in a depleted natural gas reservoir beneath the seabed of the North Sea (approximately 20 kilometers from the power plant). The goal of the project is to demonstrate the feasibility of a large-scale, integrated CCS project while addressing the various technical, legal, economic, organizational, and societal aspects of the project. ROAD will result in the capture and storage of approximately 1.1 million tonnes of CO_2 annually over a five year span starting in 2015. Subsequent commercial operation is anticipated, and there will be continuous knowledge sharing. This project has received financial support from the European Energy Programme for Recovery (EEPR), the Dutch Government, and the Global CCS Institute, and is a component of the Rotterdam Climate Initiative CO_2 Transportation Network.
Recognized by the CSLF at its Beijing meeting, September 2011

31. SaskPower Integrated CCS Demonstration Project at Boundary Dam Unit 3
Nominators: Canada (lead) and the United States
This is a large-scale project, located in the southeastern corner of Saskatchewan Province in Canada, which will be the first application of full stream CO_2 recovery from flue gas of a 139 megawatt coal-fueled power plant unit. A major goal is to demonstrate that a post-combustion CO_2 capture retrofit on a commercial power plant can achieve optimal integration with the thermodynamic power cycle and with power production at full commercial scale. The project will result in capture of approximately one million tonnes of CO_2 per year, which will be sold to oil producers for enhanced oil recovery (EOR) and injected into a deep saline aquifer. Commissioning of the reconfigured power plant unit

is expected by early 2014. The project has received financial support from the Government of Canada and the Saskatchewan Provincial Government, and SaskPower is investing additional funds for refurbishment of the power plant unit and installation of the CO_2 capture system.
Recognized by the CSLF at its Beijing meeting, September 2011

32. SECARB Early Test at Cranfield Project
Nominators: United States (lead) and Canada
This is a large-scale project, located near Natchez, Mississippi, USA, which involves transport, injection, and monitoring of approximately one million tonnes of CO_2 per year into a deep saline reservoir associated with a commercial enhanced oil recovery operation, but the focus of this project will be on the CO_2 storage and monitoring aspects. The project will promote the building of experience necessary for the validation and deployment of carbon sequestration technologies in the United States, and will increase technical competence and public confidence that large volumes of CO_2 can be safely injected and stored. Components of the project also include public outreach and education, site permitting, and implementation of an extensive data collection, modeling, and monitoring plan. This "early" test will set the stage for a subsequent large-scale integrated project that will involve post-combustion CO_2 capture, transportation via pipeline, and injection into a deep saline formation.
Recognized by the CSLF at its Warsaw meeting, October 2010

33. Zama Acid Gas EOR, CO_2 Sequestration, and Monitoring Project
Nominators: Canada (lead) and United States
This is a pilot-scale project that involves utilization of acid gas (approximately 70% CO_2 and 30% hydrogen sulfide) derived from natural gas extraction for enhanced oil recovery. Project objectives are to predict, monitor, and evaluate the fate of the injected acid gas; to determine the effect of hydrogen sulfide on CO_2 sequestration; and to develop a "best practices manual" for measurement, monitoring, and verification of storage (MMV) of the acid gas. Acid gas injection was initiated in December 2006 and will result in sequestration of about 25,000 tons (or 375 million cubic feet) of CO_2 per year.
Recognized by the CSLF at its Paris meeting, March 2007

34. Zero Emission Porto Tolle Project (ZEPT)
Nominators: Italy (lead) and European Commission
This is a large-scale project, located in northeastern Italy, which will demonstrate post-combustion CCS on 40% of the flue gas from one of the three 660 megawatt units of the existing Porto Tolle Power Plant (which is being converted from heavy oil fuel to coal). The goal of the project is to demonstrate industrial application of CO_2 capture and geological storage for the power sector at full commercial scale. The demonstration plant will be operated for an extended period (approx. 10 years) in order to fully demonstrate the technology on an industrial scale, clarify the real costs of CCS, and prove the retrofit option for high-efficiency coal fired units which will be built (or replaced) in the coming 10-15 years. Storage of approx. 1 million tonnes per year of CO_2 will take place in a deep saline aquifer beneath the seabed of the Adriatic Sea approx. 100 kilometers from the project site.
Recognized by the CSLF at its Beijing meeting, September 2011

Note: "Lead Nominator" in this usage indicates the CSLF Member which proposed the project.

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List of Meeting Registrants (as of 21 May 2012)

#	Title	First Name	Last Name	Organization	Country / Entity
1	Dr.	Richard	Aldous	CO2CRC	Australia
2	Dr.	Clinton	Foster	Geoscience Australia	Australia
3	Mr.	Habibur	Rahman	AED Bangladesh	Bangladesh
4	Dr.	Paulo Negrais	Seabra	Petrobras	Brazil
5	Dr.	Stefan	Bachu	Alberta Innovates - Technology Futures	Canada
6	Mr.	Len	Heckel	Shell in Canada	Canada
7	Mr.	Michael	Monea	Saskatchewan Power Corporation	Canada
8	Dr.	Ruimin	Gao	Research Institute of Shaanxi, Yanchang Petroleum Group Co., Ltd.	China
9	Dr.	Cailing	Hu	Euro-Asian Center for Environment and Education	China
10	Mr.	Shaojing	Jiang	Research Institute of Shaanxi, Yanchang Petroleum Group Co., Ltd.	China
11	Prof.	Mingyuan	Li	China University of Petroleum in Beijing	China
12	Prof.	Xiaochun	Li	Institute of Rock and Soil Mechanics, Chinese Academy of Sciences	China
13	Prof.	Bo	Peng	China Univ. of Petroleum	China
14	Mr.	Hong	Wang	Research Institute of Shaanxi Yanchang Petroleum (group) Co., Ltd.	China
15	Dr.	Xiuzhang	Wu	Shenhua Group Corporation	China
16	Mr.	Jiming	Zhang	China Shenhua Coal to Liquid and Chemical Company	China
17	Mr.	Yong	Zhang	China Shenhua Coal to Liquid and Chemical Company	China
18	Mr.	Ping	Zhong	The Administrative Centre for China's Agenda 21	China
19	Mr.	Richard	Lynch	CSLF Secretariat	CSLF Secretariat
20	Mr.	John	Panek	CSLF Secretariat	CSLF Secretariat
21	Mr.	Søren	Frederiksen	Danish Energy Agency	Denmark
22	Dr.	Estathios	Peteves	European Commission	European Commission
23	Dr.	Jeroen	Schuppers	European Commission	European Commission
24	Dr.	Didier	Bonijoly	BRGM	France
25	Dr.	François	Kalaydjian	Institut Français du Pétrole Energies Nouvelles	France
26	Mr.	Jacques	Monne	Total	France
27	Prof.	Jürgen-Friedrich	Hake	Forschungszentrum Jülich GmbH	Germany

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List of Meeting Registrants (as of 21 May 2012)

#	Title	First Name	Last Name	Organization	Country / Entity
28	Mr.	Daniel Kofi	Essien	Danish Development Research Network	Ghana
29	Mr.	Amir Mohammad	Eslami	Rahbord Energy Alborz Ltd.	Iran
30	Dr.	Giuseppe	Girardi	ENEL	Italy
31	Dr.	Sergio	Persoglia	OGS	Italy
32	Dr.	Ryo	Kubo	Research Institute of Innovative Technology for the Earth (RITE)	Japan
33	Dr.	Chong Kul	Ryu	KEPCO Research Institute	Korea
34	Dr.	Chang-Keun	Yi	Korea Institute of Energy Research	Korea
35	Dr.	Paul	Ramsak	Agentschap NL	Netherlands
36	Mr.	Hans	Schoenmakers	Rotterdam Opslag en Afvang Demonstratieproject (ROAD)	Netherlands
37	Mr.	Henrik	Andersen	Statoil	Norway
38	Dr.	Menno	Dillen	SINTEF	Norway
39	Prof.	Niels Peter	Christensen	Gassnova SF	Norway
40	Mr.	Lars Ingolf	Eide	Research Council of Norway	Norway
41	Mr.	Olav	Falk-Pedersen	CO_2 Technology Centre Mongstad	Norway
42	Mr.	Erik	Gjernes	Gassnova SF	Norway
43	Prof.	Arne	Graue	University of Bergen	Norway
44	Mr.	Bjørn-Erik	Haugan	Gassnova SF	Norway
45	Mr.	Hans Aksel	Haugen	Tel-Tek	Norway
46	Dr.	Eivind	Johannessen	Statoil	Norway
47	Mr.	Jostein Dahl	Karlsen	Ministry of Petroleum and Energy	Norway
48	Ms.	Anne Kristin	Kleiven	Research Council of Norway	Norway
49	Mr.	Claude R.	Olsen	Research Council of Norway	Norway
50	Mr.	Trygve	Riis	Research Council of Norway	Norway
51	Mr.	Gunnar	Sand	SINTEF / UNIS	Norway
52	Mr.	Muhammad Ismail	Shah	Gassnova SF	Norway
53	Ms.	Åse	Slagtern	Research Council of Norway	Norway
54	Dr.	Aage	Stangeland	Research Council of Norway	Norway

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List of Meeting Registrants (as of 21 May 2012)

#	Title	First Name	Last Name	Organization	Country / Entity
55	Prof.	Hallvard	Svendsen	NTNU	Norway
56	Prof.	Muhammad	Kashif	Nouveau Energy Management Services (Pvt) Ltd	Pakistan
57	Mrs.	Elzbieta	Wróblewska	Ministry of Economy	Poland
58	Dr.	Mikhail	Puchkov	Ministry of Education and Science	Russia
59	Mrs.	Naymya	Puchkova	International Information, Training and Consulting Centre	Russia
60	Dr.	Ahmed	Al-Eidan	Saudi Aramco	Saudi Arabia
61	Mr.	Abdullah	Al-Sarhan	Ministry of Petroleum and Mineral Resources	Saudi Arabia
62	Dr.	Ali	Al-Meshari	Ministry of Petroleum and Mineral Resources	Saudi Arabia
63	Prof.	Mohamed	Habib	KFUPM	Saudi Arabia
64	Mr.	Fred	Goede	Sasol Group Services (Pty) Ltd	South Africa
65	Prof.	Tony	Surridge	SANEDI	South Africa
66	Mr.	Mark	Crombie	BP Alternative Energy	United Kingdom
67	Prof.	Jon	Gibbins	U.K. CCS Research Centre	United Kingdom
68	Mr.	Declan	Murphy	The Ecology Foundation	United Kingdom
69	Mr.	Philip	Sharman	Evenlode Associates Ltd.	United Kingdom
70	Dr.	Vince	White	Air Products and Chemicals Inc.	United Kingdom
71	Mr.	Chris	Babel	Leonardo Technologies, Inc.	United States
72	Dr.	Grant	Bromhal	U.S. Department of Energy/NETL	United States
73	Dr.	Robert	Finley	IL State Geological Survey	United States
74	Mr.	Joseph	Giove	U.S. Department of Energy	United States
75	Mr.	Mike	Holmes	Energy & Environmental Research Center	United States
76	Mr.	Jeff	Jarrett	Leonardo Technologies, Inc.	United States
77	Mr.	Scott	McDonald	Archer Daniels Midland Company	United States
78	Mr.	Ed	Steadman	Energy & Environmental Research Center	United States