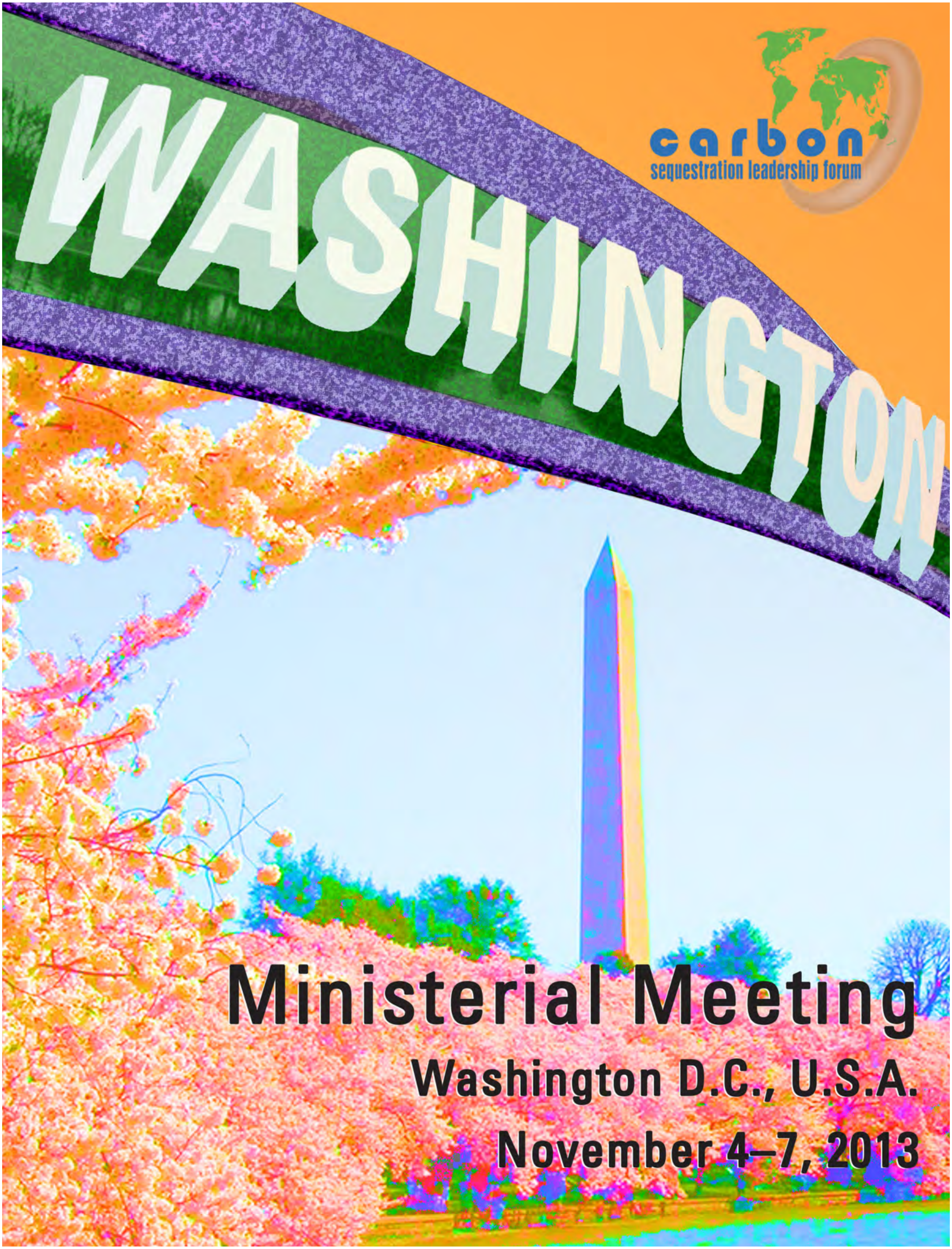

Ministerial Meeting

Washington D.C., U.S.A.

November 4–7, 2013

Carbon Sequestration Leadership Forum

www.cslforum.org

5th CSLF MINISTERIAL MEETING DOCUMENTS BOOK

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20. CSLF Charter
21. CSLF Terms of Reference and Procedures
22. Active and Completed CSLF Recognized Projects (as of October 2013)
23. CSLF Strategic Plan (October 2011 revision)
24. 2013 CSLF Technology Roadmap
25. Final Report by the CSLF Task Force on CCS Technology Opportunities and Gaps
26. Final Report by the CSLF Task Force on Technical Challenges in the Conversion of CO_2-EOR Projects to CO_2 Storage Projects
27. Final Phase II Report by the CSLF Task Force on CO_2 Utilization Options
28. 2013 Annual Report by the CSLF Task Force on Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2

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Carbon Sequestration Leadership Forum

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5th CSLF Ministerial Meeting
Washington, DC, USA
04-07 November 2013

	Monday November 4	Tuesday November 5	Wednesday November 6	Thursday November 7
Morning	Technical Group Task Forces Meetings	**Technical Group Meeting** Policy Group Task Forces Meetings	**Policy Group Meeting** **Stakeholders Meeting**	**Ministerial Meeting and Roundtable** (*open session*)
		Lunch	Lunch	Lunch Ministerial Lunch (*Ministers only*)
Afternoon	Technical Group Task Forces Meetings	**Technical Group Meeting** Ministerial Steering Committee Meeting (*closed meeting*) **Stakeholders Meeting**	**Policy Group Meeting**	**Ministerial Meeting and Roundtable** (*open session*) Ministerial Conference (*Ministers only*) Press Conference
Evening	Technical Group Reception	Opening Reception	Ministerial Meeting Reception	Closing Reception

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Task Force Meeting Schedule

Four Seasons Hotel, Smithson Room

	Monday, 4 Nov 2013	Tuesday, 5 Nov 2013
10:00 – 11:00am	Projects Interaction and Review Team (PIRT)	
11:00am – 12:00pm	Projects Interaction and Review Team (PIRT)	
12:00 – 1:00pm	Projects Interaction and Review Team (PIRT)	
1:00 – 2:00pm	Projects Interaction and Review Team (PIRT)	Capacity Building Task Force and Governing Council
2:00 – 3:00pm	Projects Interaction and Review Team (PIRT)	Capacity Building Task Force and Governing Council
3:00 – 4:00pm	Projects Interaction and Review Team (PIRT)	Ministerial Steering Committee (*closed*)
4:00 – 5:00pm	Projects Interaction and Review Team (PIRT)	Ministerial Steering Committee (*closed*)

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CARBON SEQUESTRATION LEADERSHIP FORUM MINISTERIAL MEETING
TENTATIVE SCHEDULE OF STAKEHOLDER SESSIONS AND DESCRIPTION

OCTOBER 30, 2013

Tuesday, November 5, 2013 – Stakeholder Roundtables

1:00 PM – 2:45 PM

A. Financial Roundtable – Why some projects reach final investment decisions and some do not.

- Role of incentives – CCS relative to other low/no carbon technologies.
- Achieving multiple revenue streams, CO_2 sales for enhanced oil recovery and other commercial uses of CO_2.
- The value of standardizing "costing methodologies".
- The outlook for commercial financing for CCS projects. Getting to full deployment.

International Chair: Bernard Frois, Director – *CEA France*
Host Vice-Chair: Andrew Paterson, Principal – *EBI/CCS Alliance*
Speakers:

- Shannon Angielski, Associate Director – *Coal Utilization Research Council*
- Dwight Cates, Director of Government Relations – *FLUOR*
- Pam Tomski, Senior Advisor, Policy and Regulatory – *Global CCS Institute*
- Martin Considine, Vice President, Btu Conversion – *Peabody Energy*
- Odin Knudsen, CEO – *Real Options International*
- Allan Baker, Managing Director, Global Head of Power – *Société Générale*
- Tim Bertels, Manager Global CCS Portfolio – *Shell*
- Chris Tynan, Director, Project Finance – *Summit Power*
- Graeme Sweeney, Chairman – *Zero Emissions Platform*

B. Communication Roundtable – Communicating the Value of Carbon, Capture & Storage.

- Case studies of projects that were cancelled due to public opposition.
- Why messaging is critical
- Coordinated communication strategies in other energy industry sector.
- Can global CCS stakeholders develop messages and identify messengers? Is this a role for stakeholders, governments or both?

International Chair: Stuart Neil, Senior Director, Communications – *World Energy Council*
Host Vice-Chair: Michael Moore, Executive Director - *North American Carbon Capture & Storage Association*
Speakers:

- Arthur Lee, Chevron Fellow and Principal Advisor – *Chevron*
- Angie Howard, President – *Howard-Johnson Associates*
- Bill Loveless, Host – *Platts Energy Week*
- Tim Wiwchar, Quest Business Opportunity Manager– *Shell*
- Llewellyn King, Host – *White House Chronicle*

2:45 PM – 3:15 PM **Break**

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3:15 PM – 5:00 PM

C. Regulatory Roundtable 1 – This will discuss both economic (utility commissions in regulated generation markets) and environmental regulation of capture, transport and storage.

- Role of various jurisdiction, i.e., national, provincial/state/local governments
- Case studies of handling long-term liability.
- Reducing release of CO_2 and other greenhouse gases in oil, gas, coal, cement, chemical, steel, etc., production.
- Regulating CO_2 storage in enhanced oil recovery
- CCS performance standards
- CCUS tax incentives

International Chair: Graeme Sweeney, Chairman – *Zero Emissions Platform*
Host Vice-Chair: Raj Barua, Executive Director – *National Regulatory Research Institute*
Speakers:

- Mike Fernandez, Executive Director – *Alberta Energy*
- Ann Weeks, Senior Counsel – *Clean Air Task Force*
- Fred Eames, Partner – *Hunton & Williams*; Counsel – *CCS Alliance*
- Dwight Cates, Director of Government Relations – *FLUOR*
- Pam Tomski, Senior Advisor, Policy and Regulatory – *Global CCS Institute*
- Tim Bertels, Manager Global CCS Portfolio – *Shell*
- Sarah Forbes, Senior Associate – *World Resources Institute*

D. Deploying a Demonstration Project in Developing Countries

- Need for CCS in non-OECD countries.
- How public-private partnership can enhance chances for project success.
- The role of the World Bank Group organizations, regional development banks and national development agencies.

International Chair: Edward Helminski, President – *ExchangeMonitor Publications and Forums*
Host Vice-Chair: Will Polen, Senior Director – *United States Energy Association*
Speakers:

- Steven Carpenter, Vice President – *Advanced Resources International*; Chair, *US Technical Advisory Group to ISO TC-265*
- Dennis Johnson, Head of Office of Technology, & Executive Director Process / Specialty Engineering – *FLUOR*
- Meade Harris, Senior Advisor, Europe and MENA – *Global CCS Institute*
- Dr. Robert F. Ichord, Jr., Ph.D., Deputy Assistant Secretary – *Bureau of Energy Resources, US Department of State*
- Yang Xiaoliang, Visiting Scholar – *World Resources Institute*
- Richard Zechter, Carbon Finance Unit – *World Bank*

5:00 PM – 6:00 PM **Opening Reception**

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Wednesday, November 6, 2013 – Continuation of Stakeholder Roundtable *

9:00 AM

E. Regulatory Roundtable 2 – This will discuss both economic (utility commissions in regulated generation markets) and environmental regulation of capture, transport and storage.

- Role of various jurisdiction, i.e., national, provincial/state/local governments
- Case studies of handling long-term liability.
- Reducing release of CO_2 and other greenhouse gases in oil, gas, coal, cement, chemical, steel, etc., production.
- Regulating CO_2 storage in enhanced oil recovery
- CCS performance standards
- CCUS tax incentives

International Chair: Raj Barua, Executive Director – *National Regulatory Research*
Host Vice-Chair: Sheila Hollis, Partner- *Duane Morris LLP*
Speakers:

- Jonas Helseth, Director – *Bellona Europa*
- Jeff Walker, Project Manager – *CSA Group*; *International Secretary to ISO TC-265*
- The Honorable David Boyd, Commissioner – *Minnesota Public Utilities Commission*
- Dr. George Peridas, Ph.D., Scientist – *Climate Center, Natural Resources Defense Council*

Wednesday, November 6, 2013 – Stakeholder Executive Addresses *

10:30 AM	Luke Warren, Chief Executive – *UKCCSA*
11:00 AM	Dr. Charles Soothill, Senior Vice President, Technology – *Alstom Power*
11:30 AM	Tim Bertels, Manager Global CCS Portfolio – *Royal Dutch Shell*
12:00 Noon	Graeme Sweeney, Chairman – *Zero Emissions Platform*
12:30 PM	**Buffet Lunch**

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DRAFT AGENDA
CSLF Technical Group Meeting
Four Seasons Hotel
Washington, D.C., USA
November 5, 2013

09:00-10:45 **Technical Group Meeting**
Salon A

1. **Welcome and Opening Statement**
   Trygve Riis, Technical Group Chair, Norway

2. **Introduction of Delegates**
   Delegates

3. **Adoption of Agenda**
   Trygve Riis, Technical Group Chair, Norway

4. **Review and Approval of Minutes from Rome Meeting** CSLF-T-2013-02
   Trygve Riis, Technical Group Chair, Norway

5. **Review of Rome Meeting Action Items**
   John Panek, CSLF Secretariat

6. **Report from Secretariat**
   - Secretariat Updates
   - Ministerial Meeting Preview
   - Technical Group Documents for Ministerial Meeting
   - CSLF Recognized Projects Report

   John Panek, CSLF Secretariat

7. **CCS in the USA**
   Mark Ackiewicz, United States Department of Energy

8. **Update from the IEA Greenhouse Gas R&D Programme**
   Tim Dixon, IEA GHG

10:45-11:00 **Refreshment Break**
Foyer outside Salon A

11:00-12:30 **Continuation of Meeting**

9. **Report from Projects Interaction and Review Team**
   Clinton Foster, PIRT Chair, Australia

10. **Approval of Projects Nominated for CSLF Recognition**
    - Midwest Regional Carbon Sequestration Partnership (MRCSP) Development Phase Project
      Neeraj Gupta, Battelle Institute, United States
    - Kemper County Energy Facility
      Kerry Bowers, The Southern Company, United States

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- Southeast Regional Carbon Sequestration Partnership (SECARB) Phase III Anthropogenic Test and Plant Barry CCS Demonstration
  Jerry Hill, Southern States Energy Board, United States

12:30-13:30 **Lunch**
Foyer outside Salon A

13:30-15:00 **Continuation of Meeting**

11. Report on Activities of the United Kingdom's CCS Cost Reduction Task Force CSLF-T-2013-04
Philip Sharman, United Kingdom

12. Report from 2013 CSLF Technology Roadmap Committee CSLF-P-2013-02
Trygve Riis, Technical Group Chair, Norway

13. Report from Technical Challenges for Conversion of CO_2 EOR to CCS Task Force CSLF-T-2013-05
Stefan Bachu, Task Force Chair, Canada

14. Report from CO_2 Utilization Options Task Force CSLF-T-2013-06
Mark Ackiewicz, Task Force Chair, United States

15. Report from Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2 Task Force CSLF-T-2013-07
Lars Ingolf Eide, Task Force Chair, Norway

15:00-15:15 **Refreshment Break**
Foyer outside Salon A

15:15-17:30 **Continuation of Meeting**

16. Report from Technology Opportunities and Gaps Task Force CSLF-T-2013-08
Richard Aldous, Task Force Chair, Australia

17. Report on Technical Group Recommendations and Messages to Policy Group CSLF-P-2013-03
Trygve Riis, Technical Group Chair, Norway
John Panek, CSLF Secretariat

18. Status of Activities / Discussion of the Need for New Technical Group Task Forces CSLF-T-2013-09
Trygve Riis, Technical Group Chair, Norway

19. New Business
Delegates

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

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

19:00-21:00 **Reception**
Salon B

* **Note:** This document is available only electronically. Please print it prior to the CSLF meeting if you need a hardcopy.

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Carbon Sequestration Leadership Forum

www.cslforum.org

CSLF-P-2013-01
Draft: 29 October 2013
Prepared by CSLF Secretariat

DRAFT AGENDA
CSLF Policy Group Meeting
Four Seasons Hotel
Washington, D.C., USA
November 6, 2013

08:00-12:00 **Registration**

09:00-10:45 **Policy Group Meeting**
Salon A

1. **Welcome and Opening Statement**
   Christopher Smith, Policy Group Chair, United States

2. **Introduction of Delegates**
   Delegates

3. **Adoption of Agenda**
   Christopher Smith, Policy Group Chair, United States

4. **Review and Approval of Minutes from Perth Meeting** — CSLF-P-2012-06
   Christopher Smith, Policy Group Chair, United States — CSLF-P/T-2012-03

5. **Review of Perth Meeting Action Items**
   Jarad Daniels, Director, CSLF Secretariat

6. **Report from CSLF Technical Group** — CSLF-P-2013-02
   Trygve Riis, Technical Group Chair, Norway — CSLF-P-2013-03

7. **Review and Approval of Proposed Projects**
   Trygve Riis, Technical Group Chair, Norway

8. **Report on Capacity Building**
   Tone Skogen, Capacity Building Governing Council Chair, Norway — CSLF-P-2013-04

10:45-11:00 **Refreshment Break**
Foyer outside Salon A

11:00-12:30 **Continuation of Meeting**

9. **Report on The World Bank's CCS Capacity Building Program**
   Richard Zechter, Carbon Finance Unit, The World Bank

10. **Report on Financing CCS**
    Bernard Frois, Financing CCS Task Force Chair, France

11. **Development of Policy Group Action Plan**
    [note: discussion to include 1) Enhanced Pilot Scale Test Network, 2) Subsurface Science Initiative, 3) Large Scale Deep Saline Initiative]
    Delegates

12:30-13:30 **Lunch**
Foyer outside Salon A

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13:30-15:00 **Continuation of Meeting**

11. Development of Policy Group Action Plan (Continued)
Delegates

12. Report on Risk and Liability
George Guthrie, Risk and Liability Task Force Co-Chair, United States

13. Report on CCS in the Academic Community
Klaus Lackner, CCUS Research Coordination Network, United States

15:00-15:15 **Refreshment Break**
Foyer outside Salon A

15:15-17:30 **Continuation of Meeting**

14. Possibilities for Offshore Carbon Storage
Ramón Treviño, University of Texas, United States

15. Stakeholders Roundtable
Stakeholders

16. Review of 2013 CSLF Ministerial Communiqué
Delegates

17. Election of Policy Group Vice Chairs CSLF-P-2013-05
Jarad Daniels, Director, CSLF Secretariat
Delegates

18. New Business
Delegates

19. Closing Remarks / Adjourn
Christopher Smith, Policy Group Chair, United States

19:00-21:00 **Reception**
Salon B

* **Note:** This document is available only electronically. Please print it prior to the CSLF meeting if you need a hardcopy.

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MINISTERIAL CONFERENCE

NOVEMBER 7, 2013

MORNING SESSION

Re-energizing Global Momentum for CCS, from Full-Scale Demonstration to Commercial Deployment

08:30-09:30 **Welcome / Ministerial Introductions**
CSLF Policy Group Chair

Host Country Address
Ernest Moniz, Secretary of Energy, United States

Opening Remarks Roundtable
Ministers

09:30-10:10 **Scene-Setting Presentations**
Moderator: Edward Davey, Minister of State for Energy and Climate Change, United Kingdom

- **"The Evolving Energy Picture and the Role of CCS"**
  Maria van der Hoeven, Executive Director, International Energy Agency (IEA)
- **"The Global Status of CCS"**
  Brad Page, CEO, Global Carbon Capture and Storage Institute (GCCSI)

10:10-10:35 **Stakeholder Perspectives**

- **Outcomes from CSLF Stakeholders Meetings**
  Presenter: *Barry Worthington, USEA*

10:35-10:50 **Refreshment Break**

10:50-12:20 **CEO Roundtable -** ***Topic*****: "Re-energizing Global Momentum for CCS: Lessons Learned from Large-Scale Projects – Actions to Move CCS Forward"**
Moderator: Ernest Moniz, Secretary of Energy, United States

- **Southern Company Kemper Project in the United States**:
  Tom Fanning, Chairman, President, & CEO, The Southern Company
- **SaskPower Boundary Dam Project in Canada:**
  Michael Monea, President of CCS Initiatives, SaskPower
- **Shell Quest Project in Canada, and Peterhead Project in the United Kingdom:**
  Michiel Kool, Executive Vice President of Safety, Environment, and Social Performance, Royal Dutch Shell
- **Uthmaniyah CO2-EOR Project in Saudi Arabia:**
  Ali Al-Meshari, Carbon Management Coordinator, Saudi Aramco
- **Statoil Sleipner Project in Norway**:
  Kai Bj. Lima, Vice President for CCS, Statoil
- **European Technology Platform for ZEP:**
  Graeme Sweeney, Chairman for Zero Emissions Platform (ZEP)

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MINISTERIAL CONFERENCE

NOVEMBER 7, 2013

AFTERNOON SESSION

Key Actions Needed for CCS Deployment Now and in the Near Future

12:20-13:50 **Participants Lunch - Ministers-only Lunch**

13:50-15:20 **CSLF Ministerial Discussion - *Topic*: Challenges and Key Actions Needed for CCS Deployment**
Personal Statements / Remarks from Ministers followed by several topical discussions on potential actions as identified in the Communiqué

15:20-15:50 **CLOSED SESSION - Ministerial Communiqué**

15:50-16:20 **Press Conference**

- **Statements provided by:**
  Ernest Moniz, Secretary of Energy, United States
  Other Ministers TBD

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Carbon Sequestration Leadership Forum

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CSLF-T-2013-02
Draft: 02 July 2013
Prepared by CSLF Secretariat

DRAFT

Minutes of the Technical Group Meeting

Rome, Italy
Wednesday, 17 April 2013

LIST OF ATTENDEES

Technical Group Delegates

Australia:	Christopher Consoli (Acting Vice Chair)
Canada:	Stefan Bachu (Vice Chair), Eddy Chui
China:	Risheng Guo, Jiutian Zhang
European Commission:	Jeroen Schuppers, Stathis Peteves
France:	Didier Bonijoly
Germany:	Jürgen-Friedrich Hake
Italy:	Giuseppe Girardi, Sergio Persoglia
Japan:	Ryozo Tanaka
Korea:	Chang-Keun Yi, Chong Kul Ryu
Netherlands:	Paul Ramsak
Norway:	Trygve Riis (Chair), Jostein Dahl Karlsen
Russia:	Georgy Ryabov
Saudi Arabia:	Ahmed Aleidan, Khalid Abuleif
South Africa:	Tony Surridge (Vice Chair)
United Kingdom:	Suk Yee Lam, Philip Sharman
United States:	Mark Ackiewicz, George Guthrie

Representatives of Allied Organizations

Global CCS Institute:	Angeline Kneppers
IEA GHG:	Tim Dixon

CSLF Secretariat

John Panek, Richard Lynch

Invited Speakers

Marcello Capra, Ministry of Economic Development, Italy
Francesca Cappelletti, Ministry of Economic Development, Italy
Salvatore Lombardi, Sapienza University of Rome, Italy
Ali Al-Meshari, Saudi Aramco, Saudi Arabia
Alvar Braathen, University Center in Svalbard (UNIS), Norway

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Observers

Australia:	Andrew Feitz
China:	Qi Li, Xiaochun Li
Chinese Taipei:	Chi-Wen Liao
Germany:	Martin Streibel
Norway:	Olav Hansen, Lars Ingolf Eide, Kei Ogata
Saudi Arabia:	Hamoud Alotaibi
United States:	Robert Finley, Sallie Greenberg, John Harju, Lee Spangler, Edward Steadman

1. Chairman's Welcome and Opening Remarks

Trygve Riis

The Chairman of the Technical Group, Trygve Riis, called the meeting to order and welcomed the delegates and observers to Rome.

Mr. Riis provided context for the meeting by mentioning that the Technical Group will be providing recommendations and messages to the Steering Committee for the upcoming CSLF Ministerial Meeting, which will take place in November 2013 in the United States. To that end, several items on the agenda for this meeting are relevant to the upcoming Ministerial.

2. Introduction of Delegates and Observers

Technical Group delegates and observers present for the session introduced themselves. Sixteen of the twenty-three CSLF Members were present at this meeting, including representatives from Australia, Canada, China, the European Commission, France, Germany, Italy, Japan, Korea, the Netherlands, Norway, Russia, Saudi Arabia, South Africa, the United Kingdom, and the United States. Observers representing Australia, China, Germany, Chinese Taipei, Norway, Saudi Arabia, and the United States were also present.

3. Adoption of Agenda

The Agenda was adopted with the small change that the presentation on Italian Law on CO_2 Storage would precede the presentation on CO_2 Storage Science Development and Application in Italy.

4. Approval of Minutes from Perth Meeting

The Technical Group minutes from the October 2012 meeting in Perth, Australia, were approved as final with no changes. After an inquiry, there was a clarification that Canada became a Technical Group Vice Chair as of the end of the Perth meeting.

5. Host Country Presentation

Marcello Capra, representing Italy's Ministry of Economic Development, welcomed meeting attendees to Rome, and described Italy's energy situation and carbon capture and storage (CCS) agenda. In Italy, there is currently an unfavorable energy mix that has resulted in high energy prices. More than 80% of primary energy (mainly oil and gas) is imported. Renewable energy capacity is increasing throughout Italy, which has resulted in an overcapacity of thermoelectricity power generation.

Marcello Capra

Dr. Capra stated that Italy's new National Energy Strategy is focused on clear objectives and is consistent with the need for growth. Emphasis is on more competitive energy sources in terms of cost, greater energy security, sustainable economic growth through development of the energy sector, and maintaining high environmental standards and quality of service. Priorities include fostering energy efficiency, promoting a competitive gas market, sustainably developing renewable energy sources, integration of Italy's electricity market with the European market, restructuring the refining industry / fuel distribution network, increasing domestic hydrocarbon production, and modernizing the energy sector's system of governance.

Concerning energy sector research and development for CCS, Dr. Capra stated that Italy's CCS agenda includes implementation of the European Directive on CO_2 storage, evaluation of the overall CO_2 storage capacity for the country, involvement in the European Union's framework program for CCS, and participation in international partnerships, including the CSLF.

6. Review of Action Items from Perth Meeting

John Panek provided a brief summary of the seven action items resulting from the Perth meeting. All have been completed.

7. Report from CSLF Secretariat

John Panek

John Panek gave a brief presentation that provided updates on the CSLF and some of its activities. The CSLF's application for liaison status with the International Organization for Standardization (ISO) Technical Committee on CO_2 Capture, Transportation and Geological Storage (ISO/TC 265) has been approved as a "Category A" organization, which is the most active status. Mr. Panek and Mark Ackiewicz have both agreed to serve as points of contact for the ISO and have expressed willingness to participate as necessary on behalf of the CSLF.

Concerning the CSLF website, Mr. Panek stated that a new "Technology Roadmap" section has been created that includes separate web page descriptions of CCS activities for 18 of the 23 CSLF Members. Paul Ramsak noted that the organizational chart shown on the CSLF website was out of date, and Mr. Panek replied that the website would be updated to fix that problem. The Secretariat was also requested to send emails to all CSLF delegations to request that they provide updates to their CCS activities descriptions.

Mr. Panek also gave a short update on the CSLF-recognized projects. There are now 27 active and 12 completed projects in the portfolio. The most recent projects to be completed are the Demonstration of an Oxyfuel Combustion Project, located in the United Kingdom, and the IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project, located in Canada. Ryozo Tanaka inquired if the Weyburn Project should no longer be classified as a CCS project. Mr. Panek replied that it is still an enhanced oil recovery (EOR) project and will continue long term, but the CO_2 monitoring part of the project is over. Tim Dixon offered to provide clarification at the next Technical Group meeting.

8. Italian Law on CO_2 Storage


Francesca Cappelletti

Francesca Cappelletti, representing Italy's Ministry of Economic Development, gave a short presentation that described the legal structure for regulation of CO_2 storage in Italy. Italy, as a member of the European Union, must comply with E.U. CCS directives, and to that end, an implementing decree was enacted in 2011. This decree adopted all parts of the E.U.'s directive, and included sections related to selection of storage sites, licensing, technical/economic requirements for being a storage site operator, CO_2 monitoring obligations, site closure/post-closure responsibilities, and public outreach requirements.

Dr. Cappelletti mentioned that working groups have been established to prepare additional implementing decrees concerning storage capacity evaluation, financial guarantees/tariffs, and public outreach. The working group on storage capacity will also have responsibility for developing criteria for storage site identification, and will include representatives from several research companies. The working group on communication will develop procedures for disseminating information about CCS to the public, which will include involvement of communities near proposed storage sites. The intention is to promote communication initiatives involving both the public and the private sector.

Dr. Cappelletti ended her presentation with a summary of Italy's National Energy Strategy as it relates to CCS. CCS is not yet cost-effective, but it will play an essential role in the long-term. Italy will therefore continue its research activities in CCS to prepare for that time.

9. CO_2 Storage Science Development and Application in Italy


Salvatore Lombardi

Salvatore Lombardi, representing the Sapienza University of Rome, gave a short presentation that described Italy's ongoing research, development and demonstration (RD&D) activities in CCS. Much work has gone into developing the CO_2 "baseline" for Italy at both the regional and local scale. This has included geochemical surveys over a wide range of geological scenarios such as volcanic areas, tectonic areas, and the Adriatic trough. There is a natural release of CO_2 occurring at some of these

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locations, which has made them into "natural laboratories" where technologies for CO_2 detection and measurement can be studied. Prof. Lombardi mentioned that there would be a field trip to one of these sites, Latera Caldera, on the final day of this four-day meeting.

Prof. Lombardi also stated that there are several industrial initiatives regarding CCS that are in progress in Italy, including the CSLF-recognized Zero Emission Porto Tolle (ZEPT) Project and a performance assessment of enhanced coalbed methane recovery in the Sulcis Basin on the island of Sardinia.

Some of the conclusions from this ongoing work are that Italy has a geologic storage capacity of about 12 gigatonnes, and no significant gas leakage has been found in areas of the country suitable for geologic storage. Prof. Lombardi mentioned that in developing the CO_2 baseline for Italy, CO_2 continuous monitoring stations have been installed in onshore and offshore locations. Data from these installations will increase the knowledge base on CO_2 storage for all of Europe.

10. Report from the CSLF Projects Interaction and Review Team (PIRT)


Christopher Consoli

The Acting PIRT Chair, Christopher Consoli, gave a presentation that summarized the previous day's PIRT meeting. There were several major outcomes from the meeting:

- Two projects were approved by the PIRT for Technical Group action: the Uthmaniyah CO_2-EOR Demonstration Project (nominated by Saudi Arabia and supported by the United States) and the Alberta Carbon Trunk Line Project (nominated by Canada and supported by the United States).
- Action on the UNIS CO_2 Lab Project (nominated by Norway and supported by the United States) was deferred, as there was uncertainty about project funding and the direction the project would take. Currently there are three scenarios: full CO_2 capture from the power plant; small-scale CO_2 capture involving development of a pilot plant; and no CO_2 capture, which would result in the project emphasizing its educational aspects. The PIRT agreed to reconsider this project once the scope becomes a bit clearer.
- There was consensus to revise the CSLF Project Submission Form. Agreement was reached to eliminate the request for projects sponsors to provide information about the relevance of the project to the overall aims of the CSLF and to CCS technology in general, and also to retitle the Gaps Analysis Checklist as the "CSLF Project Elements Checklist". Actions on other areas of the form were deferred due to their complexity and meeting time constraints. Revisions will be worked out via email exchange between PIRT members, and the current version of the Project Submission Form would continue to be used pending agreement on a complete revision of the Form.

- There was consensus that the PIRT would take on any activities related to the Technical Group Action Plan's "Best Practices Knowledge Sharing" action. This could include collaboration with the Global CCS Institute for a new "Knowledge Hub" website that would serve as a gateway to a broad range of information on CCS technologies and connect to other knowledge-sharing sites such as the European CCS Demonstration Project Network. However, due to the complexity of details and meeting time constraints, consideration of the Knowledge Hub proposal was deferred until the next PIRT meeting.

Ensuing discussion addressed the project approval process and, in general, what it means to be a CSLF-recognized project. Tony Surridge offered that duplication of technologies already used by other CSLF-recognized projects should not be a factor in the recognition process, since every project has at least subtle differences from any other. Philip Sharman suggested that there are three main schools of thought on what types of projects are desirable for the CSLF projects portfolio: (a) that projects proposed for CSLF recognition should address R&D gaps; (b) that knowledge sharing is the key, regardless of technology gaps; and (c) that many large-scale projects should be recognized, regardless of gaps and duplication, as the idea is to accelerate commercialization of CCS. However, there was no agreement on which of these should be the main consideration. In the end, there was consensus that the PIRT should re-examine the CSLF project approval process, including the Project Submission Form, and report back to the Technical Group.

Dr. Consoli then raised the point that any re-consideration of the project approval process, as well as the question on what it means to be a CSLF-recognized project, relates to PIRT governance. To that end, Dr. Consoli suggested that this would seem to be a good time to re-evaluate the PIRT's Terms of Reference document, and stated that PIRT governance would be an agenda item at its next meeting.

11. Approval of Projects Nominated for CSLF Recognition

<u>Uthmaniyah CO_2-EOR Demonstration Project</u> (nominated by Saudi Arabia and the United States)


Ali Al-Meshari

Ali Al-Meshari, Overall Carbon Management Coordinator of Carbon Strategy for Saudi Aramco, gave a presentation about the Uthmaniyah CO_2-EOR Project. This large-scale project, located in the Eastern Province of Saudi Arabia, will capture and store approximately 800,000 tonnes of CO_2 per year from a natural gas production and processing facility, and will include pipeline transportation of approximately 70 kilometers to the injection site (a small flooded area in the Uthmaniyah Field). The objectives of the project are determination of incremental oil recovery (beyond water flooding), estimation of sequestered CO_2, addressing the risks and uncertainties involved (including migration of CO_2 within the reservoir), and identifying operational concerns. Specific CO_2 monitoring objectives include developing a clear assessment of the CO_2 potential (for both EOR and overall storage) and testing new technologies for CO_2 monitoring. Construction of the capture facility and the pipeline is underway. The project duration is expected to be 4-5 years total, starting in 2013/2014.

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After brief discussion, there was consensus by the Technical Group to recommend to the Policy Group that the Uthmaniyah CO_2-EOR Demonstration Project receive CSLF recognition.

Stefan Bachu

Alberta Carbon Trunk Line Project (nominated by Canada and United States)

Stefan Bachu, representing project sponsor Enhance Energy Inc., gave a presentation about the Alberta Carbon Trunk Line (ACTL) Project. This large-scale fully-integrated project will collect CO_2 from two industrial sources (a fertilizer plant and an oil sands upgrading facility) in Canada's Province of Alberta industrial heartland and transport it via a 240-kilometer pipeline to depleted hydrocarbon reservoirs in central Alberta for utilization and storage in EOR projects. The pipeline is designed for a capacity of 14.6 million tonnes CO_2 per year although it is being initially licensed at 5.5 million tonnes per year. The pipeline route is expected to stimulate EOR development in Alberta and may eventually lead to a broad CO_2 pipeline network throughout central and southern Alberta. Pipeline right-of-way clearing began in February 2013 with commissioning expected in 2014 and start of operations in 2015. When in full operation, this will be the world's largest CCS project in terms of capacity.

After brief discussion, there was consensus by the Technical Group to recommend to the Policy Group that the Alberta Carbon Trunk Line Project receive CSLF recognition.

Alvar Braathen

UNIS CO_2 Lab (nominated by Norway and United States)

Alvar Braathen, Professor of Arctic Geology at the University Centre in Svalbard (UNIS), gave a presentation about the UNIS CO_2 Lab Project. This research-oriented project is located near Longyearbyen, Norway, in the Svalbard Archipelago (78°N latitude) and is intended to identify challenges for CCS and study CO_2 storage in an unconventional reservoir under difficult arctic conditions. The project includes research on storability of CO_2 at Svalbard, including injection tests, geologic analyses, and studies on cap rock integrity, as well as design of collegiate-level courses on CO_2 storage and other educational outreach.

As described above, the PIRT will reconsider this project at a later date. Prof. Braathen stated that this project would most likely be re-presented at the next PIRT meeting, once the scope and funding questions are settled.

12. Update on 2013 CSLF Technology Roadmap

Trygve Riis provided a brief status update on the 2013 CSLF Technology Roadmap (TRM). A draft-in-progress of the 2013 TRM was sent to Technical Group delegates in mid-March, and comments have been received from several CSLF delegations on this draft. All comments have been reviewed by the TRM Committee (which consists of the Technical Group Chair, Vice Chairs, Task Force Chairs, and the CSLF Secretariat). Most

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of these comments will be incorporated into the next version of the TRM. Mr. Riis mentioned that a few of the comments received were policy-related and would need to be addressed outside the TRM.

Concerning the process for completion of the TRM, Mr. Riis stated that the next version of the TRM would be sent by the Secretariat to Technical Group delegates by early May, and that comments on the draft would be needed no later than the end of May. Each CSLF delegation will be requested to provide a single coordinated set of comments, should it have any. The plan is for the final version of the TRM to be sent to the Secretariat by the end of June.

Ensuing discussion centered on messages and recommendations from the TRM going forward into the upcoming Ministerial meeting. John Panek stated that the TRM Committee will assemble messages coming out of the TRM into a much shorter document, and that the Task Force Chairs will be asked to provide input as well. Lars Ingolf Eide, the TRM's editor, stated that the R&D recommendations contained in this shorter document will be at a fairly high level and will not single out specific technologies or projects. However, there will be some definite actions that will be recommended. Mr. Panek mentioned that regional differences will be acknowledged and that one of the strengths of the document will be in pointing out there will be several perspectives in addressing CCS-related issues.

Mr. Panek commended Norway's efforts on the TRM and stated that good work is being done.

13. Report from Technical Challenges for Conversion of CO_2-EOR to CCS Task Force

Stefan Bachu

The Task Force Chair, Stefan Bachu, gave a brief update on the task force and its activities. The task force mandate is to review, compile and report on technical challenges that may constitute a barrier to the broad use of CO_2 for EOR and to the conversion of CO_2-EOR operations to CCS operations. Economic and policy barriers would be outside the scope of the task force. Dr. Bachu stated that the task force has nearly completed its report, which will identify these technical challenges and also any regulatory issues that involve technical aspects. The report will also highlight the commonalities and differences between CO_2-EOR and CCS, and the main message will be that there are no technological barriers to convert a CO_2-EOR project into a CCS project.

Sections of the report not yet finalized are the Summary and Conclusions, which will include recommendations, and the Executive Summary. Dr. Bachu mentioned that a final draft of the task force report will be sent by the Secretariat to Technical Group delegates at the beginning of June, and that comments on the draft would be needed no later than the beginning of August. Each CSLF delegation will be requested to provide a single coordinated set of comments, should it have any. The report will be finished in mid September, well in advance of the upcoming CSLF Ministerial meeting.

14. Report from CO_2 Utilization Options Task Force


Mark Ackiewicz

The Task Force Chair, Mark Ackiewicz, gave a brief summary of the task force and its activities. The task force is focused on all forms of CO_2 utilization except CO_2-EOR, and the mission is to identify/study the most economically promising CO_2 utilization options that have the potential to yield a meaningful, net reduction of CO_2 emissions, or facilitate the development and/or deployment of other CCS technologies. Mr. Ackiewicz stated that the task force's Phase 1 Report was completed last year. This report summarized existing information regarding CO_2 utilization options and discussed the state of each relevant technology and application. The objective of the Phase 2 Report is to provide a more thorough discussion of the most attractive CO_2 utilization options based upon economic promise and CO_2 reduction potential. The Phase 2 report will also review the current and future economic viability, potential for co-production, and RD&D needs.

Mr. Ackiewicz mentioned that there are still a few sections of the Phase 2 Report that are not yet complete, but it is on track for being finished in time for the upcoming CSLF Ministerial meeting. A final draft of the task force report will be sent by the Secretariat to Technical Group delegates in late June, and that comments on the draft would be needed no later than the middle of August. Each CSLF delegation will be requested to provide a single coordinated set of comments, should it have any.

15. Report from Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2 Task Force


Lars Ingolf Eide

The Task Force Chair, Lars Ingolf Eide, gave a brief update on the task force and its activities. The task force mandate is to perform initial identification and review of standards for storage and monitoring of injected CO_2. The application of such standards should inform CO_2 crediting mechanisms, but economic and policy issues are outside the scope of the task force.

Mr. Eide stated that the current work plan includes identification and review of existing standards for geological CO_2 storage and monitoring (on an annual basis); identification of shortcomings and/or weaknesses in standards/guidelines; communication of findings to the ISO/TC 265; producing 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; and following the work of other organizations related to CO_2 storage. The task force completed its first annual report in the 4th quarter of 2012 and is on track to finish its 2013 report in time for the upcoming CSLF Ministerial meeting. At that time a decision will be made on continuation or closure of the task force, as well as any future deliverables. A final draft of the task force report will be sent by the Secretariat to Technical Group delegates by about mid July, and that comments on the draft would be needed no later than the end of August. Each CSLF delegation will be requested to provide a single coordinated set of comments, should it have any.

Mr. Eide stated that there are currently more than twenty best practices manuals that have been assessed by the task force, and that this number will increase as time goes on. Mr. Eide also mentioned that eventually, task force findings could be made available via a web-based knowledge hub.

16. Report from CO_2 Technology Opportunities and Gaps Task Force


Christopher Consoli

The Acting Task Force Chair, Christopher Consoli, gave a brief update on the task force and its activities. The task force mandate is to identify and monitor key CCS technology gaps and related issues, to determine the effectiveness of ongoing CCS RD&D for addressing these gaps, and to recommend any RD&D that would address CCS gaps and other issues. In that regard, the task force is preparing a report that will be finalized in time for the upcoming CSLF Ministerial meeting.

Dr. Consoli stated that the three main sections of the report (capture, transport, and storage) are now essentially complete. Input is still needed for two additional sections, on biomass and oxyfiring. Collection, collation and analysis of data will continue into May, and a final draft of the task force report is expected to be ready for distribution by the Secretariat to Technical Group delegates in July, and that comments on the draft would be needed before the end of August. Each CSLF delegation will be requested to provide a single coordinated set of comments, should it have any.

Ensuing discussion focused on ways of obtaining additional data for the report. Philip Sharman noted that both Alstom and Doosan are developing oxyfiring technology, and could be sources of useful information.

17. Report on Activities of the United Kingdom's CCS Cost Reduction Task Force


Philip Sharman

At the Perth Technical Group in October 2012, activity had been deferred on the "Energy Penalty Reduction" action of the Technical Group Action Plan pending review of an interim report from the United Kingdom's Cost Reduction Task Force. This task force was established in March 2012 by the U.K.'s Department of Energy and Climate Change (DECC) to advise U.K. government and industry on the potential for reducing the costs of CCS, so that CCS power projects are financeable and competitive with other low-carbon technologies in the early 2020s.

Philip Sharman gave a presentation that summarized the conclusions from this report. The main conclusion was that U.K. gas and coal power stations equipped with CCS have clear potential to be cost competitive with other forms of low-carbon power generation. This is possible if there is investment in large, shared pipelines and also large CO_2 storage clusters, supplying multiple CO_2 sites. There must also be investment in large power stations with progressive improvements in CO_2 capture capability, a reduction in capital costs from the initial first-generation series of CCS demonstrations (achievable in part through lowered risk, which would improve investor confidence), and exploitation of potential synergies with CO_2-EOR opportunities in North Sea oil fields.

Ensuing discussion revisited the option for forming a Technical Group task force on "Energy Penalty Reduction". Mr. Sharman stated that the final report from this task force would be available soon, and would include a full set of proposed actions on how to take its recommendations forward. In the end, there was consensus to further defer any activity by the Technical Group in this area, pending review of the task force's final report. The U.K. delegation was requested to provide a copy of the final version of the DECC Energy Penalty Reduction Task Force report to the Secretariat, once it is complete, for the Secretariat to distribute it to the Technical Group delegates.

18. Status of Activities / Discussion of the Need for New Technical Group Task Forces

Trygve Riis proposed that it might be time for the Technical Group to consider new actions beyond those described in the Action Plan. John Panek added that it might also be appropriate for the Technical Group to re-evaluate and update the Action Plan itself. After ensuing discussion, there was consensus for the Technical Group Executive Committee to start this process. The Secretariat was asked to do a short progress report on the Technical Group Action Plan activities.

During the discussion, Tony Surridge offered that the South African Center for Carbon Capture & Storage (SACCCS) had recently completed a study, using CSLF Capacity Building funds, to examine impacts of CCS on South African national priorities beyond climate change (e.g., sustainable development, improved local infrastructure, job creation and protection, poverty alleviation, and social uplift), and that the final report would be issued soon. Dr. Surridge was asked to make the report available to the CSLF.

19. Update from the IEA Greenhouse Gas R&D Programme

Tim Dixon

Tim Dixon gave a presentation about the IEA GHG and its ongoing collaboration with the CSLF. Based on an agreement made back in 2008, the Technical Group is offered the opportunity to propose studies to be undertaken by the IEA GHG. These, along with proposals from IEA GHG Executive Committee (ExCo) members, go through a selection process at semiannual ExCo meetings. So far there have been three IEA GHG studies that originated from the CSLF Technical Group: "Development of Storage Coefficients for CO_2 Storage in Deep Saline Formations" (March 2010), "Geological Storage of CO_2 in Basalts" (September 2011), and "Potential Implications of Gas Production from Shales and Coal for CO_2 Geological Storage" (to be published later in 2013). The next deadline for proposal outlines is the beginning of June.

Mr. Dixon also provided details about several recent and ongoing studies of interest to the CSLF, including a one on "Interaction of CO_2 with Subsurface Resources". This policy-oriented study reviewed seven existing case studies and provided a checklist of potential interactions, impacts, and management options. Mr. Dixon stated that there will be several upcoming IEA GHG Network Meetings and Conferences in 2013 and 2014. This includes the GHGT-12 conference, which will be held in the United States in 2014.

20. New Business

Didier Bonijoly reported that some of the Technical Group delegates in Europe had received a letter from Chris Davies, Member of the European Parliament, concerning an upcoming report about "Developing and Applying Carbon Capture and Storage Technology in Europe". In his letter, Mr. Davies encouraged contributions from all with an interest in CCS. Dr. Bonijoly suggested that the CSLF Technical Group could consider providing information contained in the draft TRM about technology deployment. Ensuing discussion did not result in consensus. Jürgen-Friedrich Hake questioned if it would be advisable to distribute the TRM to outsiders before the CSLF Policy Group would even get to see it, while Philip Sharman suggested that the E.U. communication was a genuine request for input and that not to respond would send a negative signal. Khalid Abuleif suggested that there should be a Technical Group response of some kind, but Stefan Bachu stated that the CSLF itself had not received this request, only certain delegates, and also that it would set a bad precedent to release a draft document before comments on it have been received from the CSLF delegations. In the end, Trygve Riis stated that he would respond to the E.U. communication outside his official capacity as Technical Group Chair, and would provide names of the European Technical Group delegates who are willing to support this work. Also, Jeroen Schuppers agreed to provide the address for the E.C.'s related Clean Coal Technologies & CCS website.

The delegation from Korea confirmed its intention to host the 2014 CSLF Technical Group meeting. Chang-Keun Yi stated that the meeting would be held in either April or May, excluding Easter week, and that additional information would be provided at the CSLF Ministerial meeting in November.

21. Review of Consensuses Reached and Action Items

Consensus was reached on the following:

- The Uthmaniyah CO_2-EOR Demonstration Project and the Alberta Carbon Trunk Line Project are recommended by the Technical Group to the Policy Group for CSLF recognition.
- The Technical Group will defer consideration of the UNIS Field Lab Project pending resolution of uncertainties about the project's scope and funding.
- The Technical Group will further defer addressing the Action Plan on "Energy Penalty Reduction" pending review of the final report by the United Kingdom's Cost Reduction Task Force on this topic.
- Korea will host the 2014 Technical Group meeting. Dates and venue will be announced at the CSLF Ministerial meeting in November.

Action items from the meeting are as follows:

Item	Lead	Action
1	Technical Group Chair	Provide the Technical Group's recommendation to the Policy Group that the Uthmaniyah CO_2-EOR Demonstration Project and the Alberta Carbon Trunk Line Project be recognized by the CSLF.

Item	Lead	Action
2	PIRT	Re-examine the CSLF project approval process, including the Project Submission Form.
3	Secretariat	Send the draft Technology Roadmap to CSLF delegations for comments.
4	Each Technical Group Delegation	Provide a single coordinated set of comments on the draft Technology Roadmap by the end of May.
5	Each Technical Group Delegation	Provide a single coordinated set of comments for each of the four task force draft reports in August.
6	Technology Roadmap Committee	Incorporate comments from CSLF delegations and prepare draft final version of Technology Roadmap by beginning of July.
7	Technical Group Executive Committee	Re-evaluate and propose updates to Technical Group Action Plan.
8	United Kingdom	Provide a copy of the final version of the DECC Energy Penalty Reduction Task Force report to the Secretariat.
9	Secretariat	Send the DECC Energy Penalty Reduction Task Force report to Technical Group delegates.
10	Secretariat	Prepare progress report on Technical Group Action Plan activities.
11	European Commission	Provide address for the E.C.'s Clean Coal Technologies & CCS website.
12	South Africa	Provide copy of SACCCS final report concerning impacts of CCS on South African national priorities beyond climate change to the CSLF.
13	Secretariat	Send emails to all CSLF delegations to request they provide updates to their country-specific CCS activities pages on the CSLF website.
14	IEA GHG	Provide clarification of the status of the IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project at the next Technical Group meeting.
15	Secretariat	Update CSLF website as needed.

22. Closing Remarks / Adjourn

Trygve Riis thanked the delegates, observers, and Secretariat for their hard work and active participation in the meeting, and expressed his appreciation to the Italian Government and especially to Giuseppe Girardi of ENEA for hosting the meeting. Mr. Riis reminded attendees of the next day's CO_2 Monitoring Interactive Workshop, and adjourned the meeting.

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Carbon Sequestration Leadership Forum
www.cslforum.org
CSLF-T-2013-04
04 October 2013

TECHNICAL GROUP

Summary Findings from the United Kingdom's CCS Cost Reduction Task Force

Background

At the April 2013 CSLF Technical Group Meeting in Rome, the Technical Group deferred any activity on the "Energy Penalty Reduction" Action in its Action Plan, pending review of the final report from the United Kingdom's CCS Cost Reduction Task Force. A copy of the final report was provided to Technical Group delegates by the CSLF Secretariat in May 2013. This paper is a summary of conclusions and key next steps proposed by the task force.

Action Requested

The Technical Group is requested to review the findings of the United Kingdom's CCS Cost Reduction Task Force.

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Key Next Steps to Support the Large Scale Development of Power and Industrial Carbon Capture and Storage (CCS): the findings of the UK CCS Cost Reduction Taskforce

In recognition of the importance of cost reduction for the development and widespread deployment of CCS, the UK Government established an industry-led CCS Cost Reduction Task Force (CRTF). The Task Force was created in March 2012 with the objective of publishing a report to advise Government and industry on reducing the cost of CCS so that projects are financeable and competitive with other low carbon technologies in the early 2020s.

While initiated in the UK, membership was drawn from a broad spectrum of UK and international organisations, such that key findings may be applicable elsewhere.

Key conclusion

The Cost Reduction Task Force presented their Final Report in May 2013. The primary conclusion of the Task Force was that UK gas and coal power stations equipped with carbon capture, transport and storage have **clear potential to be cost competitive with other forms of low-carbon power generation**, **delivering electricity at a levelised cost approaching £100/MWh ($160/MWh) by the early 2020s**, and at a cost significantly below that soon thereafter.

This conclusion was based on a comprehensive analysis of potential savings across the full chain of CCS, as well as wider cost savings such as from reducing the cost of capital or incorporating new revenue streams such as from CO_2-based Enhanced Oil Recovery (EOR).

Opportunities for cost reduction

Their analysis highlighted five areas where significant cost reductions could be achieved:

1. investment in large CO2 storage clusters, supplying multiple CO2 sites;
2. investment in large, shared pipelines, with high use;
3. investment in large power stations with progressive improvements in CO2 capture capability that should be available in the early 2020s;
4. a reduction in the cost of project capital through a set of measures to reduce risk and improve investor confidence in UK CCS projects; and
5. exploiting potential synergies with CO_2-based EOR.

An indication of the relative significance of each of these factors (for the UK) is given in the graph below. The analysis assumes that early CCS projects will have higher costs because of their smaller size; relatively short lifetime if retrofitted onto existing power plants; single point-to-point full chain configuration; engineering prudence and risk averse commercial and financing arrangements. These early projects are represented by the first column, with costs in the range of £150-200/MWh ($240-320/MWh). The subsequent columns illustrate potential costs of follow-on projects, taking into account the cost reductions achievable.

The greatest savings have been identified in the areas of transport and storage, improved financeability and improved design and performance. In addition, the Task Force estimated a

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potential additional EOR benefit in the range of £5-12/MWh ($8-20/MWh) for gas CCS, and £10-26/MWh ($16-24/MWh) for coal CCS, which would be in addition to the reductions identified on the graph.

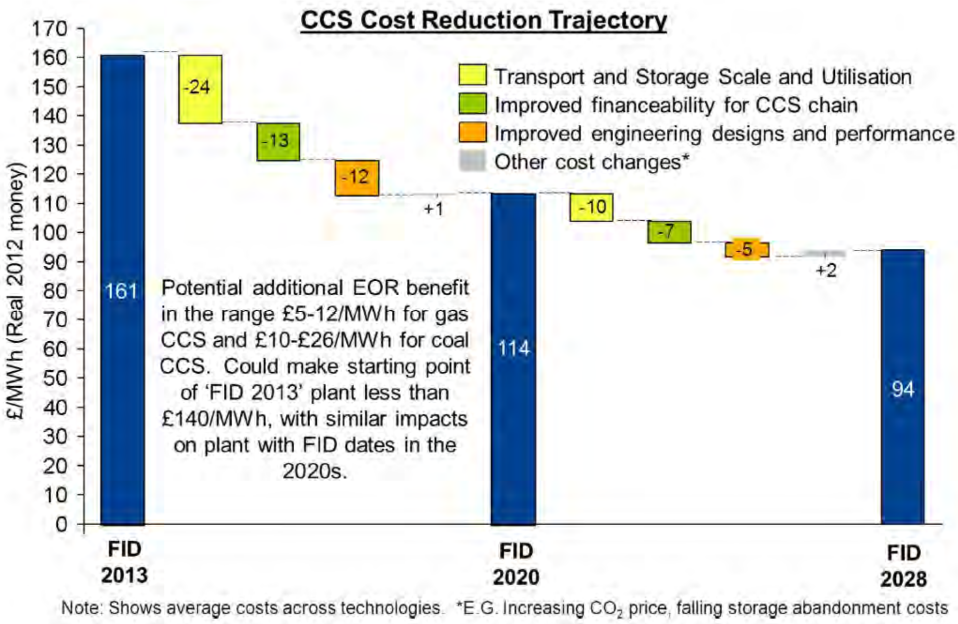

Figure 1: Waterfall Graph - key components of potential cost reduction across the CCS chain

To note, cost savings for a range of different technology configurations were analysed by the Task Force but average cost levels across technologies are used here to simplify messages. Full details of the analysis undertaken are available in the Task Force's report.

In addition to identifying the opportunities for cost reduction, the Task Force also looked at how these cost savings could be achieved.

CCS landscape

The Task Force highlighted the importance of a wider 'landscape' that is favourable to the development of CCS projects. They propose that cost reductions can only take place if a conducive landscape engenders the transition from the early projects to one where CCS is viewed as conventional. The key characteristics of such a landscape include:

1. Credible long term Government policy commitment to CCS - including a suitable regulatory structure and financial and policy framework to foster development of CCS.
2. Successful demonstration of full chain CCS projects at scale - including a commitment to knowledge sharing from projects in the UK and globally.
3. Continued engagement with the financial community - so that they understand the technology and can appropriately assess risk, as well as to ensure their needs are factored into policy development.

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The landscape alone will not, by itself, guarantee that costs of CCS projects can be reduced. However, the Task Force believe it will enable a wide range of cost reducing actions to be pursued. Their analysis then examined what are the most important of these actions for encouraging deployment and securing cost reductions.

Key next steps to support large scale development of CCS

While the UK Government is taking forward a comprehensive Commercialisation Programme to build the first full-chain CCS plants in the UK, the Task Force examined the key next steps needed to support *subsequent* large scale development of CCS. As with the cost savings identified, these are UK specific but are likely to be applicable elsewhere too.

Seven key steps were identified to allow the follow-on and future CCS projects to be developed in a way that delivers the identified cost reductions. These were:

1. Ensure optimal CCS transport and storage network configuration – identifying options for transport and storage system configurations that take into account likely future developments and minimise long run costs.
2. Incentivise CO2 EOR to limit emissions and maximise hydrocarbon production
3. Ensure funding mechanisms are fit-for-purpose – funding instruments should be suitable for widespread use in coal and gas CCS projects.
4. Create bankable contracts - focus on how to construct contracts that will be needed to make follow-on projects bankable.
5. Create a vision for development of CCS Projects from follow-on projects through to widespread adoption with the aim of encouraging prospective developers of CCS projects.
6. Promote characterisation of CO_2 storage locations to maximise benefit from storage resource - the aim is to reduce the 'exploration risk' premium, thereby making storage sites bankable both commercially and technically.
7. Create policy and financing regimes for CCS from industrial CO_2 sources.

In addition to these Key Next Steps, the Task Force identified a further 26 supporting steps which should be taken in order to mitigate investor and operational risks and underpin successful development of future CCS projects. Details of these, and the full analysis undertaken by the Task Force, is set out in the **CCS Cost Reduction Task Force Final Report** available from the UK Government Website:

https://www.gov.uk/government/policy-advisory-groups/ccs-cost-reduction-task-force

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CSLF-T-2013-05
04 October 2013

TECHNICAL GROUP

Summary of the Report by the CSLF Task Force on Technical Challenges in the Transition from CO_2-EOR to CCS

Background

At the September 2011 CSLF Ministerial Meeting in Beijing, the Technical Group approved a new multi-year Action Plan to identify priorities and provide a structure and framework for conducting Technical Group efforts through 2016. To that end, a task force (led by Canada) was formed to address the "Technical Challenges for Conversion of CO_2-EOR to CCS" Action in the Plan. The task force mandate was to review, compile and report on technical challenges that may constitute a barrier to the broad use of CO_2 for EOR and to the conversion of CO_2-EOR operations to CCS operations. The final report of the task force has been issued. This paper is a summary of the findings of the task force.

Action Requested

The Technical Group is requested to review the summary of findings from the Technical Challenges for Conversion of CO_2-EOR to CCS Task Force.

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Technical Challenges in the Conversion of CO_2-EOR Projects to CO_2 Storage Projects

Summary of the Report by the CSLF Task Force on Technical Challenges in the Transition from CO_2-EOR to CCS

Forty years of experience and more than 120 CO_2-EOR operations currently active in the world indicate that there is sufficient operational and regulatory experience for this technology to be considered as being mature, with an associated storage rate of 90-95 % of the purchased CO_2. Application of CO_2-EOR for CO_2 storage has a number of advantages:

1) It enables CCS technology improvement and cost reduction;
2) It improves the business case for CCS demonstration and early movers;
3) It supports the development of CO_2 transportation networks;
4) It may provide significant CO_2 storage capacity in the short-to-medium-term, particularly if residual oil zones (ROZ) are produced;
5) It enables knowledge transfer, bridging the experience gap and building and sustaining a skilled CCS workforce; and
6) It helps gaining public and policy-makers acceptance.

The current number of CO_2-EOR operations in the world is negligible compared with the number of oil pools in the world, and **the main reason CO_2-EOR is not applied on larger scale is the unavailability of high-purity CO_2 in the amounts and at the cost needed for this technology to be deployed on a large scale**. The potential for CO_2 storage and incremental oil recovery through CO_2-EOR is significant, particularly if residual oil zones (ROZ) and hybrid CO_2-EOR/CCS operations are considered. Besides the main impediment in the adoption and deployment of this technology mentioned above, **the absence of infrastructure to both capture the CO_2 and transport it from CO_2 sources to oil fields suitable for CO_2-EOR is also a key reason for the lack of large scale deployment of CO_2-EOR**.

There are a number of commonalities between CO_2-EOR and pure CO_2 storage operations, both at the operational and regulatory levels, which create a good basis for transitioning from CO_2-EOR to CO_2 storage in oil fields. However, currently there are a significant number of differences between the two types of operations that can be grouped in seven broad categories:

1) Operational, including CO_2 purity and quality;
2) Objectives and economics;
3) Supply and demand;
4) Legal and regulatory;
5) Assurance of well integrity;
6) Long term CO_2 monitoring requirements; and
7) Industry's experience.

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There are no specific technological barriers or challenges *per se* in transitioning and converting a pure CO_2-EOR operation into a CO_2 storage operation. The main differences between the two types of operations stem from legal, regulatory and economic differences between the two. While the legal and regulatory framework for CO_2-EOR, where it is practiced, it is well established, the legal and regulatory framework for CO_2 storage is being refined and is still evolving. Nevertheless, it is clear that CO_2 storage operations will likely require more monitoring and reporting 1) of a wider range of parameters, 2) outside the oil reservoir itself, and 3) on a wider area, and for a longer period of time than oil production. Because of this, pure CO_2 storage will impose additional costs on the operator. A challenge for CO_2-EOR operations which may, in the future, convert to CO_2 storage operations is the lack of baseline data for monitoring, besides wellhead and production monitoring, for which there is a wealth of data.

In order to facilitate the transition of a pure CO_2-EOR operation to CO_2 storage, operators and policy makers have to address a series of legal, regulatory and economic issues in the absence of which this transition can not take place. These should include:

1. Clarification of the policy and regulatory framework for CO_2 storage in oil reservoirs, including incidental and transitioned storage CO_2-EOR operations. This framework should take into account the significant differences between CO_2 storage in deep saline aquifers, which has been the focus of regulatory efforts to date, and CO_2 storage in oil and gas reservoirs, with particular attention to the special case of CO_2-EOR operations.
2. Clarification if CO_2-EOR operations transitioning to CO_2 storage operations should be tenured and permitted under mineral/oil & gas legislation or under CO_2 storage legislation.
3. Clarification of any long-term liability for CO_2 storage in CO_2-EOR operations that have transitioned to CO_2 storage, notwithstanding the CO_2 stored during the previous phase of pure CO_2-EOR.
4. Clarification of the monitoring and well status requirements for oil and gas reservoirs, particularly for CO_2-EOR, including baseline conditions for CO_2 storage.
5. Addressing the issue of jurisdictional responsibility for pure CO_2 storage in oil and gas reservoirs, both in regard to national-subnational jurisdiction in federal countries, and to organizational jurisdiction (environment versus development ministries/departments).
6. Examination of the need to assist with the economics, particularly the cost of CO_2 and the infrastructure to bring anthropogenic CO_2 to oil fields.

The Policy Group should take note of these issues and establish ways to address them within CSLF, and make appropriate recommendations to the governments of its members.

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Carbon Sequestration Leadership Forum
www.cslforum.org
CSLF-T-2013-06
04 October 2013

TECHNICAL GROUP

Summary of the Report by the CSLF Task Force on CO_2 Utilization Options

Background

At the September 2011 CSLF Ministerial Meeting in Beijing, the Technical Group approved a new multi-year Action Plan to identify priorities and provide a structure and framework for conducting Technical Group efforts through 2016. To that end, a task force (led by the United States) was formed to address the "CO_2 Utilization Options" Action in the Plan. The task force mandate was to identify/study the most economically promising CO_2 utilization options that have the potential to yield a meaningful, net reduction of CO_2 emissions, or facilitate the development and/or deployment of other CCS technologies. The final Phase 2 report of the task force has been issued. This paper is a summary of the findings of the task force's Phase 2 report.

Action Requested

The Technical Group is requested to review the summary of findings from the CO_2 Utilization Options Task Force.

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Carbon Sequestration Leadership Forum

www.cslforum.org

Utilization Options of CO_2

Summary of the Phase 2 Report by the CSLF Task Force on Utilization Options of CO_2

The Phase 2 Report on CO_2 Utilization Options provides a more thorough discussion of the most attractive CO_2 utilization options based upon economic promise and CO_2 reduction potential. This report looks at the current and future economic viability, potential for co-production, and Research, Development and Demonstration (RD&D) needs of these options. The CO_2 Utilization Task Force members selected the following options for further investigation: enhanced gas recovery (CO_2-EGR), shale gas recovery, shale oil recovery, urea production, algal routes to fuels, utilization in greenhouses, aggregate and secondary construction material production, and CO_2-assisted geothermal systems. This work did not include Enhanced Oil Recovery, which is addressed by a separate CSLF Task Force.

As identified in the Phase 1 report, market potential for many of the utilization options is limited (i.e., small, and/or 'niche'), with some exceptions (e.g., enhanced oil recovery – not a subject of this report – or the conversion of CO_2 to fuels or chemicals). However, when taken cumulatively, the sum of these options can provide a number of technological mechanisms to utilize CO_2 in a manner that has potential to provide economic benefits for fossil fuel fired power plants or industrial processes. As such, they may well be a means of supporting the early deployment of carbon capture and storage (CCS) in certain circumstances and accelerating deployment.

One of the key observations from this report is that the potential uses of CO_2 are broad. CO_2 has the potential to be used in the extraction of other energy resources, as a working fluid, and as a chemical feedstock. These applications have some market potential, although the technology maturity varies widely. Some applications, such as urea production, already have an existing global market, while other less mature options, such as algae to fuels have the potential for significant markets and require additional RD&D to address technical challenges and to validate the utilization of CO_2 as an option, reduce the cost and improve the efficiency.

There are a wide range of CO_2 utilization options available, which can serve as an additional mechanism for deployment and commercialization of CCS by providing an economic return for the capture and utilization of CO_2. The results offer several recommendations that can assist with the continued development and deployment of non-EOR CO_2 utilization options in this context.

1. For commercially and technologically mature options such as urea production and utilization in greenhouses, efforts should be on demonstration projects. For urea production, the focus should be on the use of non-traditional feedstocks (such as coal) or 'polygeneration' concepts (such as those based on integrated gasification combined cycle (IGCC) concepts) which can help facilitate CCS deployment by diversifying the product mix and providing a mechanism for return on investment. For utilization in

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greenhouses, new and integrated concepts that can couple surplus and demand for CO_2 as well as energy, thus optimizing the whole energy and economic system, would be valuable.

2. Efforts that are focused on hydrocarbon recovery, such as CO_2 for enhanced gas recovery (via methane displacement), or CO_2 utilization as a fracturing fluid, should focus on field tests to validate existing technologies and capabilities, and to understand the dynamics of CO_2 interactions in the reservoir. R&D efforts on CO_2 as a fracturing fluid should focus on the development of viscosity enhancers that can improve efficiency and optimize the process. Issues such as wellbore construction, monitoring and simulations should leverage those tools and technologies that currently exist in industry or are under development through existing CCS R&D efforts.
3. For algal routes to fuels and aggregate/secondary construction materials (SCM) production, the primary focus should be on R&D activities that address the key techno-economic challenges previously identified for these particular utilization options. Independent tests to verify the performance (less energy requirements with CO_2 utilization to produce SCM and building materials) of these products compared to technical requirements and standards should be conducted. Support of small, pilot-scale tests of first generation technologies and designs could help provide initial data on engineering and process challenges of these options.
4. For CO_2-assisted geothermal systems, more R&D and studies are necessary to address the subsurface impacts of utilizing CO_2 in this application. Additionally, small pilot-scale tests could provide some initial data on actual operational impacts and key engineering challenges that need to be addressed.
5. Finally, more detailed technical, economic, and environmental analyses should be conducted to better quantify the potential impacts and economic potential of these technologies and to clarify how R&D could potentially expand the market for these utilization options (e.g., in enhanced gas recovery) and improve the economic and environmental performance of the system. A holistic approach, not only taking a one-dimensional technocratic perspective, is important.

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Carbon Sequestration Leadership Forum
www.cslforum.org
CSLF-T-2013-07
04 October 2013

TECHNICAL GROUP

Summary of the Report by the CSLF Task Force on Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2

Background

At the September 2011 CSLF Ministerial Meeting in Beijing, the Technical Group approved a new multi-year Action Plan to identify priorities and provide a structure and framework for conducting Technical Group efforts through 2016. To that end, a task force (led by Norway) was formed to address the "Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2" Action in the Plan. The task force mandate was to perform initial identification and review of best practices and standards for storage and monitoring of injected CO_2. The 2013 annual report of the task force has been issued. This paper is a summary of the findings of the task force's 2013 report.

Action Requested

The Technical Group is requested to review the summary of findings from the Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2 Task Force.

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Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2

Summary of the Initial Compilation of Standards, Best Practices and Guidelines for CO_2 Storage and Monitoring

Task Force 6 (TF6) of the Carbon Sequestration Leadership Forum (CSLF) Technical Group has prepared an overview of standards, best practices and guidelines for storage and monitoring of CO_2 in geological formations. The report gives an initial compilation of BPMs and similar documents that have been issued before August 2013 with:

1. Date, publisher and title and link to a web site from which the document can be downloaded
2. Brief description of content
3. High level assessment of scope and content
4. Appendices that list regulations, monitoring tools in projects, risk assessment BPMs, storage atlases, BPMs on storage capacity, BPMs on regulatory issues and community engagement and BPMs related to CO_2 pipelines.

The initial compilation shows that:

- Site selection, monitoring and verification and risk assessment are well covered by several existing documents
- By September 2013, only one standard on CO_2 storage has been identified, the Canadian CSA Z741-12. It is also the document that appears to cover most topics related to storage and monitoring CO_2 in geological formations
- There is a need to
  - identify the applicability of the documents to various stakeholders
  - identify shortcomings of the various documents

It is recommended that:
- Applicability and shortcomings are identified
- The results are communicated to ISO TC265 (ISO committee for development of a set of CCS standards)
- A web solution for annual updates should be established, e.g. by the CSLF Projects Interaction and Review Team (PIRT).

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Carbon Sequestration Leadership Forum
www.cslforum.org
CSLF-T-2013-08
04 October 2013

TECHNICAL GROUP

Summary of the Report by the CSLF Task Force on CCS Technology Opportunities and Gaps

Background

At the September 2011 CSLF Ministerial Meeting in Beijing, the Technical Group approved a new multi-year Action Plan to identify priorities and provide a structure and framework for conducting Technical Group efforts through 2016. To that end, a task force (led by Australia) was formed to address the "CCS Technology Opportunities and Gaps" Action in the Plan. The task force mandate was to identify and monitor key CCS technology gaps and related issues, to determine the effectiveness of ongoing CCS RD&D for addressing these gaps, and to recommend any RD&D that would address CCS gaps and other issues. The final report of the task force has been issued. This paper is a summary of the findings of the task force's report.

Action Requested

The Technical Group is requested to review the summary of findings from the CCS Technology Opportunities and Gaps Task Force.

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Summary of the Final Report of the CCS Technology Opportunities and Gaps Task Force

- At a high level there are no major technology gaps or impediments to CCS; the technology is available and can be effectively deployed.
- The focus of the technology development is now on driving down costs and securing more efficient operational, monitoring and regulatory outcomes.
- Current commercially available capture technologies will evolve by building more projects. This typical "learning by doing" phenomenon is common with many technologies and is already happening in CCS.
- For the next generation of capture technologies, that promise much lower costs, more attention needed. Investment in the early stages of development has been significant with a number of promising emerging technologies. However with little or no market for CCS (e.g., CO_2 price or emissions reduction mandate) the market pull for this next crop of technologies is weak. Getting next generation lower cost technologies into large scale pilots and demonstration is important and requires governments to act to ensure that much lower costs of capture are available for deployment by 2030 and beyond.
- Technologies for capturing CO_2 from natural gas combustion are a priority, as low cost shale gas will encourage more gas combustion as the need to reduce emissions increases.
- Pipeline transporting of CO2 is a mature technology, but more experience is need in planning and designing large scale transport hubs managing a diverse supply of CO_2 with different impurity concentrations. Large scale transport of CO_2 by ship offers promise and needs to be demonstrated as scale.
- On storage, the significant body of knowledge from the oil and gas industry combined with what is now 10-15 years of R&D on the behaviour of CO_2 in deep rock formations underpins a strong consensus that safe CO_2 storage is possible today
- The Lead times from initiating exploration through to approvals and construction will often be 10-15 years. The rate at which exploration is incentivised to start will have a profound impact on the degree to which CCS can contribute to reaching 2050 global reduction targets. This will increase the ability to deploy CCS more rapidly and will in turn affect the rate of technology improvement. There is a strong recommendation to start or incentivize more exploration for storage.
- Monitoring, measurement verification (MMV) for stored CO_2 continues to progress well. Low cost continuous high resolution subsurface monitoring is being refined and may be valuable in some situations. An important new front is developing MMV technologies and strategies for MMV on storage in offshore environments.
- It is recommended that Governments continue to look to support and incentivise international technology collaboration and researcher exchange to spark faster developments and the diffusion of new CCS technology.

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CSLF-T-2013-09
04 October 2013

TECHNICAL GROUP

Action Plan Update

Background

At the September 2011 CSLF Ministerial Meeting in Beijing, the Technical Group approved a new multi-year Action Plan to identify priorities and provide a structure and framework for conducting Technical Group efforts through 2016. Twelve individual actions were identified, and Task Forces were formed to address four of these twelve actions. At the 2013 Technical Group Meeting in Rome, the Secretariat was asked to prepare the following update on the status of the Action Plan.

Action Requested

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

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CSLF Technical Group Action Plan Update

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.

Status: Technology Opportunities and Gaps Task Force (*led by Australia*) active since June 2012. **Final Report issued.**

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.

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

Status: Activity assigned to Projects Interaction and Review Team (*led by Australia*).

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.

Status: United Kingdom (DECC) final report in this area sent to Technical Group delegates on 23 May 2013. **Possible activity in this area to be addressed at Technical Group meeting.**

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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.

Status: Clean Energy Ministerial / IEA report issued. **Possible activity in this area to be addressed at Technical Group meeting.**

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.

Status: No activity yet.

Action Plan 6: Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2

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

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

Status: Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2 Task Force (*led by Norway*) active since June 2012. Reports for Years 2012 and 2013 issued. **Continuation of Task Force an option.**

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.

Status: Technical Challenges for Conversion of CO_2-EOR to CCS Task Force (*led by Canada*) active since June 2012. **Final Report issued.**

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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.

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

Status: **Deferred** pending review of IEA GHG report in this area.

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.

Status: No activity yet.

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.

Status: **Canceled.** Policy Group task force formed to investigate this area.

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.

Status: No activity yet.

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.

Status: CO_2 Utilization Options Task Force (*led by United States*) active since June 2012. **Final report issued.**

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Carbon Sequestration Leadership Forum

www.cslforum.org

CSLF-P-2012-06
Draft: 31 December 2012

POLICY GROUP

Revised Draft
Minutes of the CSLF Policy Group Meeting

Perth, Australia
25 October 2012

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-P-2012-06
Draft: 31 December 2012

MINUTES OF THE CSLF POLICY GROUP MEETING
PERTH, AUSTRALIA
25 OCTOBER 2012

Note by the Secretariat

Background

The Policy Group of the Carbon Sequestration Leadership Forum held a business meeting on 25 October 2012, in Perth, Australia. Initial draft minutes of this meeting have been compiled by the CSLF Secretariat and were circulated to the Policy 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

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

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-P/T-2012-03
Revised Draft: 31 December 2012
Prepared by CSLF Secretariat

REVISED DRAFT
Minutes of the Policy Group Meeting

Perth, Australia
Thursday, October 25, 2012

LIST OF ATTENDEES

Policy Group Delegates

Chair:	Barbara McKee (United States)
Australia:	Ann Boon, Margaret Sewell
Canada:	Eddy Chui
China:	Sizhen Peng, Jiutian Zhang
France:	Bernard Frois
Japan:	Koji Hachiyama, Kei Miyaji
Norway:	Tone Skogen
Saudi Arabia:	Hamoud Al-Otaibi
South Africa:	Faizel Mulla, Gina Downes
United Kingdom:	Jonathan Hood
United States:	James Wood

CSLF Secretariat

Jeffrey Price, Adam Wong

Observers

Australia:	Maureen Clifford (CarbonNet Project); Asha Titus (University of Newcastle); Zoe Naden (Dept. of Resources, Energy and Tourism); Clement Yoong (Coal Innovation NSW)
India:	Preeti Malhotra (Alstom)
Netherlands:	Bill Spence (Shell)
Chinese Taipei:	Shih-Ming Chuang, Ren-Chen Wang (Industrial Technology Research Institute)
United States:	Victoria Osborne (Striker Communications); Barry Worthington (U.S. Energy Association)
Global CCS Institute:	Barry Jones
International Energy Agency:	Juho Lipponen

PROCEEDINGS

1. Opening Statement

Barbara McKee, Deputy Assistant Secretary of Energy for the United States, said that Charles McConnell, the Chair of the Policy Group, had asked her to read a message from him to the Policy Group. In that message, Mr. McConnell extended his regrets that he could not attend the meeting in Perth and said that Ms. McKee would serve in his place as Chair of the Policy Group. In the letter Mr. McConnell also raised the concern that the world was not on track to meet the agreed-upon goal at least 20 diverse, fully-integrated, industrial-scale projects by 2020, noted the importance of moving from Carbon Capture and Storage (CCS) to Carbon Capture Utilization and Storage (CCUS), and asked the CSLF to address the fundamental question of how international collaboration could be redefined and restructured through the CSLF to meet that goal.

Ms. McKee thanked Australia for its hospitality in hosting this meeting in Perth and noted that this was the second time Australia has hosted a CSLF meeting. She also thanked the delegates and stakeholders participating in this meeting, many of whom had to travel long distances to attend. She reviewed the major decisions of the CSLF Ministerial last year in Beijing. These major decisions were that the term of the CSLF was extended indefinitely from 2013 when it was originally to expire; the mission of the CSLF was expanded to include commercialization; and the scope was broadened from CCS to CCUS.

Ms. McKee said the ultimate goal of the CSLF must be the real-world application of CCUS technologies. Economic barriers have been particularly daunting and simply storing CO_2 in a saline formation – where the main considerations are cost and risk – does not yet provide a compelling incentive for industry to invest in these technologies. CCUS offers an approach that can take us much closer to the finish line because it provides a viable stream of revenue to cover much of those costs. Noting that many countries do not have opportunities for EOR, she said that those countries will benefit because CCUS will accelerate the development at scale of the technologies and procedures needed to capture and store CO_2.

2. Australia Host Country Welcome

Margaret Sewell, Head of Clean Energy and Environment Division, Australia Department of Resources, Energy and Tourism, welcomed the delegates to Perth. She thanked the Australian organizing team and the CSLF Secretariat for their work on the meeting and stated that Australia places a high importance on international collaboration. Ms. Sewell then described the policy drivers for CCS in Australia and explained why CCS was important to Australia. She said that a carbon price of A$23 per tonne was introduced in July 2012 and will become flexible in 2015. This price will be linked to the European Union's emissions trading scheme. The goal is to encourage investment in CCS and other low-carbon technologies. Australia has a heavy reliance on fossil fuels and is the world's largest net exporter of coal and, for these reasons, Australia has many projects for both CO_2 capture and storage, some of which she described.

Ms. Sewell also conveyed the following message from Hon. Martin Ferguson AM MP, Minister for Resources and Energy and Minister for Tourism: "I wish you a successful meeting, and encourage you to exchange ideas and discuss practical ways to accelerate the development and deployment of CCS."

3. Introduction of Delegates

Chairman McKee asked delegates and observers to introduce themselves, which they all did.

4. Adoption of Agenda

The Agenda was approved without change.

5. Review and Approval of Minutes from Beijing Meeting

The draft of the Minutes of the previous Policy Group Meeting, held in Beijing, China in September 2011 had been circulated for comment to the Policy Group prior to the meeting. The final draft, which incorporated comments received, had been posted on the CSLF website. The Minutes were approved without further change.

6. Review of Beijing Meeting Action Items

Jeffrey Price of the CSLF Secretariat reviewed the status of the Action Items from the Policy Group Meeting in Beijing. Two action items related to raising further money for capacity building, but currently-available funds have not yet been fund committed so fundraising has not been started. Action items for the Communications and Public Outreach and CCUS in the Academic Community Task Forces are underway. The edits to the Strategic Plan have been completed.

Task Force Reports

7. Report on Capacity Building

Tone Skogen, Norway, Chair of the Capacity Building Governing Council, gave a presentation on CSLF capacity building activities. She said that the CSLF Capacity Building Fund was established at the CSLF Ministerial in London in October 2009. Contributions from Australia, Canada, Norway and the United Kingdom to the CSLF Capacity Building Fund total US $2,965,143.75. The CSLF Capacity Building Governing Council was established to assure that the Fund is spent wisely and appropriately. Although the Fund is open to all CSLF Members, the expectation is that the financial contributions should focus on emerging economy CSLF Members. A total of US $2,016,950 has been committed to 12 projects in 4 countries. These include 3 projects in Brazil, 5 projects in China, 2 projects in South Africa and 2 projects in Mexico. A total of US $250,000 has also been ring-fenced for a possible project in India. US $514,812 remains available for further projects. Submissions for those remaining funds will be invited by the Governing Council. The Governing Council is also keen to make sure that lessons learned from activities are shared with the largest possible group of interested stakeholders.

Sizhen Peng of China thanked the Capacity Building Governing Council for its support of China's CCUS activities, including the Chinese CCUS website (www.ccus.china.org.cn), a legal and regulatory workshop and a knowledge-sharing workshop. These have had a very significant impact in China where there is considerable interest. He said that participants from other CSLF countries had been invited to the workshops and he wanted to encourage their participation. Juho Lipponen of the International Energy Agency (IEA) noted that participation by other CSLF Members added moral support that was itself important. The

Chair said that the Secretariat would be pleased to work with China to obtain participation from other CSLF Members in future workshops.

Gina Downes of South Africa also thanked the Governing Council for its generous support. Workshops held in 2011 provided a base upon which the South African Center for Carbon Capture and Storage could build. Subsequent to the workshops, an extensive work program was developed and the workshops enabled industrial representatives to come on board with that program.

Asked whether the Governing Council should try to raise additions funds, Ms. Skogen responded that further fundraising should be put on hold for the time being since substantial funds were still available from the original contributions to the Fund. After seeing the response to the call for submissions next year, the Governing Council would determine whether additional funds are needed. China suggested that industrial firms be invited to contribute to the Fund. The Governing Council will take this under consideration.

8. **Report from Financing CCS Task Force**

Bernard Frois of France, Chair of the Task Force, gave a presentation on the Task Force's activities. Mr. Frois stated that the Task Force had held two roundtables on financing. The first roundtable was held in Paris in January 2012 on the topic of "What will it take to turn ambition into reality." The second roundtable was held in Washington in September 2012 on the topic of "Lessons from first movers in CCUS." The Paris workshop had about 50 participants including many from banks. The banks indicated that they are ready to finance large-scale projects provided that the projects have solid business plans. Mr. Frois also stated that one conclusion was that polygeneration plants were the most viable approach, but the situation was different in Europe and the U.S. The Washington roundtable consisted of presentations from several first movers. These projects are proceeding based on their economics, not due to climate regulation. Enhanced Oil Recovery (EOR) was seen as having value for both the project and the production of significant amounts of oil. This could be valuable in the United States, the Middle East and China. His conclusion was that large-scale CCUS is possible, but today only polygeneration with EOR would create adequate revenues.

Barbara McKee noted that considerable knowledge had been gained through the workshops and asked how the Task Force planned to convey this knowledge to a wider audience. The response was that the Chair of the Task Force wanted feedback from Policy Group about what the Policy Group wanted. Delegates were then invited by the Chair of the Policy Group to provide that feedback. In response, delegates stated that messages on financing could be developed for Ministers, but cautioned that situations vary widely, particularly as it relates to the potential for EOR. Delegates from Australia, Norway, South Africa, and the United Kingdom stated that many countries did not have opportunities for EOR which was central to the successful financing approach described by the Chair of the Task Force. They emphasized that national circumstances differ and "one size does not fit all."

Potential messages on financing that should be given to the Ministers were discussed. Norway emphasized that conditions vary in different parts of the world and, in particular, the ZEP initiative in Europe had concluded that the long-term path to a business case was not present without public funding. Other delegates echoed this message. Australia noted that

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the Clean Energy Ministerial (CEM) may be addressing financing in the messages it presents to its Ministers at its April 2013 Ministerial. The Task Force Chair was requested and agreed to have a dialog with CEM about building on the CEM's work and coordinating messages.

9. **Policy Roundtable: Advancing CCUS in a Time of Challenge**

James Wood, United States Delegate, moderated this roundtable discussion, which consisted of his presentation and two other presentations in the morning followed by an open discussion after lunch. He began the Roundtable by describing the extensive work on CCUS of the US Department of Energy, including the National Energy Technology Laboratory. He discussed the Department's major demonstration projects, emphasizing the commercial and financial aspects of the projects. Costs of these projects are being shared by companies that see commercial opportunities in those projects. He also described the global drivers for CCUS including the rapidly increasing needs for energy, rising coal demand and how carbon capture can meet climate goals.

Mr. Wood emphasized how the drivers have changed since 2009 and how this change created a need for CO_2 utilization and, in particular, for EOR, which has a very large potential to increase oil production and to create jobs. He said that EOR is not a business case, but rather an implementation method for moving some projects forward. He noted that several projects in the United States were moving forward without EOR, notably FutureGen and ADM. The focus of work on CCUS should be on reducing the costs of capture and addressing related challenges such as the energy penalty and scale. Work is proceeding in many R&D areas to develop and improve technologies to reduce capture costs.

Juho Lipponen of the IEA described what he saw as the four fundamentals of CCS, what CCS could accomplish, and what should now be the focus of further work. The four fundamentals were: (1) demand for energy and corresponding CO_2 emissions are increasing; (2) fossil fuels are indisputably part of the global energy mix; (3) global energy use will continue to grow; and (4) CO_2 emissions must be cut by 50% by 2050. CCS could play a very significant role in reducing CO_2 emissions, not as a substitute for other low-carbon energy technologies, but in addition to them. One unique advantage of CCS is that it can be applied in industrial sectors where no other solutions are feasible. While the investment required in CCS is large, US $3.6 trillion, an additional investment of US $3.1 trillion would be required to meet the same emissions reduction goals in the electricity sector without CCS. Clear, long-term policy objectives are required to deploy CCS. Specifically, governments should assess the role CCS could play in their countries; it is critical that demonstration projects continue; appropriate policy mechanisms beyond capital subsidies should be considered; and the CCS story should be told in a positive way.

Barry Jones of the Global CCS Institute presented the findings of the Institute's new report, "The Global Status of CCS: 2012," which was released on October 10. This report describes progress since 2011. It has several key messages, notably that action is needed now to ensure that CCS can play a vital role in tackling climate change and progress must be accelerated. That acceleration depends on collaboration and knowledge sharing. The report presents an analysis of Large Scale Integrated Projects (LSIPs) and shows that 74 such projects are currently underway throughout the world, but most are at a relatively early stage of development. More policy support is required, both internationally and nationally. While various barriers must be overcome, analyses by the Institute show that CCS can be competitive with other low- or no-carbon alternatives.

10. Policy Roundtable: Advancing CCUS in a Time of Challenge (Continued)

The discussion moderated by James Wood continued after lunch. At the beginning of the discussion, Mr. Wood reiterated and commented upon a number of points he drew from the prior discussion:

- While one size does not fit all, experience has shown that more rapid progress is made when a business case can be made for a project, as it will attract private equity investment.
- It is important to encourage diverse projects, both large and small, because they all involve regulators, political decision makers and the public and make them more comfortable with the technology.
- EOR is not a business case because the value of CO_2 is insufficient to cover the cost of capture. There are many possible business cases to make products from fossil fuels, including electricity, while capturing and storing or utilizing the CO_2.
- The capture cost of CO_2 is too high. The focus of the CSLF and its Members should be reducing the cost of capture.

The ensuing discussion focused in several related areas. Points made in this discussion by various speakers are summarized below organized by topic. Many of these have implications to CSLF activities.

Advancing CCUS Technology and Demonstration Projects

Enough projects must be built globally by 2020 to reduce costs, but challenges are still substantial and adequate progress is not being made. Many projects are in the final stages of development but are awaiting financing. Nearly all proposed projects are receiving or expecting government financial incentives but different methods are being used to provide those incentives. Some, such as tax credits, do not involve direct government expenditures. A level playing field with other low-carbon technologies is needed.

The types of projects and incentives needed depend on project location since circumstances vary regionally. For this reason, a regional approach may be useful. EOR contributes in some regions while other utilization methods or storage may contribute elsewhere.

First-generation projects demonstrate the integration of various project components at scale but are not optimized. A second generation of plants is needed to begin the optimization process. Due to tight government budgets, these second-generation plants are likely to be modifications of the first generation rather than totally new plants.

Different business cases may be made for different uses of fossil fuels that capture CO_2. Each business case will need to have adequate revenue streams to go forward. CCUS is not a single technology applied in a single industry but rather a range of technologies applied in a wide range of industries with different situations.

Messages to Ministers and Others

The CSLF should create messages for Ministers and others, including the public and political leaders that re-energize interest in CCS/CCUS. It is important to convey the message to political decision makers and to the public that CCUS is about clean energy. The CSLF should seek ways to re-energize the political process and focus political decision makers on the short term. We cannot delay advancing CCS/CCUS technology; we are far from meeting the goal set in the CSLF/IEA recommendations to the G8 in 2007. We need to show that CCS/CCUS has progressed, the technology is ready to go and it can contribute. If the CSLF wants to be relevant it should give guidance for actions for the short run, that is, by 2020. Importantly, it was felt that the CSLF should be the organization to involve Ministers in the discussion so the Ministers can make commitments.

Need for a Short-Term Roadmap

The CSLF must develop and advocate for roadmaps that have a time horizon no later than 2020. Short-term actions are required both to commercialize the technology in a timely manner and to gain meaningful political commitments. Roadmaps can be valuable as a guide to action but depend on how much importance governments attached to them.

The long-term vision for CCUS is that it should eventually become part of the global low-carbon portfolio, but care should be taken that the long-term vision does not detract from the practical achievement of short-term goals. The IEA is revisiting its CCS Roadmap and one idea is a strong section on what must be done in this decade. The CSLF should have both a short-term and long-term view. In the short-term it is important to have several projects realized and in the long-term to develop business cases.

Coordination with CEM and IEA

At least two related Ministerial meetings will be held in 2013 in which messages about CCUS can be delivered to Ministers. These messages can be coordinated for maximum impact. The CCUS Action Group of the CEM will make recommendations to the CEM Ministerial in April 2013. Similarly, the IEA Ministers will meet in 2013 shortly after the CSLF Ministers. These Ministerials provide opportunities to reinforce CSLF messages, but it is important to avoid duplication. As an Action Item, the CSLF should coordinate messages to Ministers with the CEM and IEA and should coordinate with the IEA on roadmaps.

11. Election of Policy Group Chair

The Chair stated that term of the Policy Group Chair is three years and it was now time for a new election. Vice Chairs will be elected next year. She asked the Vice Chair from China, Sizhen Peng, to chair the election procedure. He reviewed the rules for elections of the Chairs and Vice Chairs and stated that the Secretariat has received nominations from Australia, China, Japan, Mexico, and Norway of the United States to be Chair and that the Members have been notified of this nomination. The United States was elected by consensus. After the election, Barbara McKee thanked the delegates for re-electing the United States.

12. Review of 2013 CSLF Ministerial Concept Paper

The Chair stated that the Draft Concept Paper for the Ministerial, which will be held next year in Houston, Texas, USA, was a first draft and would evolve over time in response to comments. Jeffrey Price of the Secretariat presented a brief overview of the Draft Concept Paper covering one section at a time. Delegates were then asked for comments and suggestions on each section of the draft.

General Theme

The general theme of the Ministerial was proposed as "The Business Case for CCUS – Carbon Utilization to Meet Energy Sustainability for Economic Development and to Fight Poverty."

Norway expressed a concern about how poverty fit into the theme when the objective of CCS/CCUS is to combat climate change and was not convinced that this topic should be in the theme.

Australia thanked the Secretariat for the first draft of the Concept Paper as a starting point for discussion and said that this was one of the best Policy Group discussions. Australia also noted that the Policy Group had earlier concluded that an agenda was needed to re-energize the political process and a short-term roadmap would help to make CCS/CCUS a priority again for Ministers. Discussions of these issues could be incorporated into the Ministerial agenda. Australia also said that a high-level theme should indicate that utilization is possible in some, but not all, countries and that financial issues remain to be resolved.

The Chair summarized the prior discussion by saying that we had heard that "one size does not fit all;" we must re-energize the political process; and a short-term roadmap is required. She said that the Technical Group would be directed to develop a roadmap that would lead to accomplishments by 2020.

Key Issues

A number of issues for discussion at the Ministerial were proposed in the Draft Concept Paper. Many of these relate to the political will to make commitments to CCS/CCSUS. A number of comments were made on these suggested issues.

Australia expressed concern that the issues as written blurred the distinction between CCS and CCUS and it is important to make the distinction.

The United Kingdom stated that the need for a level playing field for CCUS as a low-carbon technology could be explored further.

France expressed the opinion that what was needed was not a list of issues but rather to focus on a few concrete things that we want to happen.

China stated that the purpose of utilization is to help remove the obstacles of cost and safety in the short term so that we could have CCS in the long term.

South Africa suggested that rather than phrasing the key issues as "willingness to" which implies dragging people along, the issues should be phrased more positively as "showing leadership in." South Africa also mentioned bottlenecks in the CCS value chain identified in a study by the Global CCS Institute as an area where not enough was being done.

Norway stated that we should be careful not to make EOR the only focus.

South Africa asked how countries that did not have the option of EOR could attract investment to CCS. Responding to South Africa, Barry Jones of the Global CCS Institute reiterated that "one size does not fit all" in terms of attracting investment because there are very different national circumstances. A discussion of what is needed to attract investment should account for those varying national circumstances. Juho Lipponen of the IEA added that, where utilization is not an option, government incentives may be necessary to create the final part of the incentive. He added that the challenges are particularly great for a developing country such as South Africa.

The United States commented that EOR would not attract investment by itself because the cost of capture is so much higher than the potential revenues from EOR, but governments, whether EOR is possible or not, can provide incentives such as tax benefits on a time-limited basis. The benefits that accrue to governments are jobs, the beneficial use (if any) of the CO_2, and the involvement of political policy makers, regulators and the public who will be able to see that projects are safe and produce benefits.

Expected Outcomes

Expected outcomes included reaffirmations of prior Ministerial statements and potential new agreements.

Norway stated that it was not happy with the statement that CCUS is needed to make fossil fuels sustainable and preferred to remove this statement as an outcome. The United Kingdom concurred and suggested not including the word "sustainable." Norway and several other delegated agreed. Juho Lipponen of the IEA commented that sustainability was a large concept that combined aspects of economics, supply security and the environment and it can be taken to mean different things. As an alternative, Norway suggested using terminology such as CCS being needed to "move to a low carbon future."

Norway suggested that the expected outcome of "reducing poverty" be changed instead to "access to energy."

Australia voiced concern over statements of "commitments" for governments, stating that Ministers would find it difficult to make such commitments in current budgetary situations.

Japan stated that outreach was important and should be included as one of the actions in the expected outcomes.

South Africa stated that CO_2-EOR should not be promoted as "the key component" of a CCUS strategy, but rather as "one of the components."

The United States stated that rather than saying "governments should create the business case," it should be recognized that what governments actually can do is promote an atmosphere in which business cases can develop. There are regions where there is no utilization possible with EOR and we should keep the door open and not be restrictive.

Role of Stakeholders

Barry Worthington, as Acting Chair of the Stakeholders Group, reported on the Stakeholders Meeting held the previous day. He said that the participation of stakeholders in the

Ministerial and proposed topics were discussed. The stakeholders would like to have representation on the Ministerial Steering Committee. Stakeholders also discussed reinvigorating and renewing stakeholder participation, particularly by regional officials, NGOs and academics. Stakeholders, particularly corporations, would also like to have the option of sponsoring activities and welcomed the opportunity of participating in the Technology Showcase. A full-day stakeholders' session was seen as desirable with a report on the session being given to the Ministers. Stakeholders also expressed gratitude that they were welcomed as observers and asked to be included in the entire Ministerial, recognizing that government-to-government and government-only meetings would be closed.

Site and Date for the Ministerial

Barry Worthington, as Executive Director of the United States Energy Association, which is responsible for the logistical arrangements for the 2013 Ministerial, discussed the possible sites and dates for the Ministerial, which is to be held in Houston, Texas, USA. He noted that virtually every major energy company in the world has a Houston office and this creates opportunities for Ministers. The three best hotels in Houston have been identified and these hotels have been asked to provide availability information from mid-September through the third week in November, 2013. Appropriate venues for social functions are also being explored.

Mr. Worthington asked delegates for dates within the time frame under consideration that they would not want to have a Ministerial, such as conflicts with other Ministerial meetings. In response, Juho Lipponen said that the IEA Ministerial will be held on November 19 and 20, 2013.

Procedure for Redrafting the Concept Paper

The procedure for redrafting the Concept Paper was discussed. It was agreed that:

1. Delegates would provide further comments in writing to the Secretariat as soon as possible. These comments may be in track changes or other formats. The comments may also include ideas for new concepts, themes or additions.
2. The Secretariat will take these comments and revise the draft Concept Paper by the second week of January 2013.
3. Delegates will have an opportunity to comment on this revised draft.
4. The Steering Committee would then take up planning for the Ministerial using the Revised Draft Concept Paper.

Juho Lipponen of the IEA also stated that he found the draft difficult to navigate and would provide a suggested format for the redraft. Australia also called attention to the terminology in the definition of CCUS and how it related to CCS, stating that the distinction between the two needs to be clearer.

The Chair also noted that Canada had offered to host a Policy Group meeting if it is needed to prepare for the Ministerial.

13. Selection of 2013 Ministerial Steering Committee

The Chair stated that a Steering Committee is needed to plan the 2013 Ministerial and asked delegates for volunteers for the Ministerial Steering Committee. The United States will chair the Committee. Canada and France agreed to serve, as did the Global CCS Institute and the International Energy Agency. Australia said that it could participate if it could participate in meetings by videoconference. The Chair said that she wanted Members that had hosted prior Ministerial to participate in the planning so that the CSLF could benefit from their experience. China, Norway Saudi Arabia, South Africa, and the United Kingdom will consult with their capitals on whether to serve on the Steering Committee.

14. New Business

The Chair asked delegates if there was any new business. There was none.

15. Closing Remarks/Adjourn

The Chair thanked the delegates and the Policy Group Task Forces for their hard work. She said that we need to re-energize and re-invigorate the CSLF and said that the discussion had brought out much that had to be considered and she looked forward to making the upcoming Ministerial the best we have had.

The meeting was then adjourned.

ACTION ITEMS FROM THE POLICY GROUP MEETING

Item	Lead	Action
1	Secretariat, China	Work together to inform participants from other countries that they can participate in future workshops in China
2	Capacity Building Governing Council	Consider how to invite business enterprises to contribute to CSLF capacity-building activities
3	Capacity Building Governing Council	Issue a request for submissions for capacity building projects to be undertaken by the CSLF
4	Capacity Building Governing Council	Consider whether to raise additional contributions to the CSLF Capacity Building Fund after receiving the response to the request for submissions
5	Capacity Building Governing Council and Task Force	Consider ways to more widely share knowledge and information developed for CSLF capacity-building activities
6	International Energy Agency, Secretariat	Work together to have CSLF Members participate in the IEA’s CCS Legal-Regulatory activities
7	CSLF Secretariat	Conduct a dialog with CEM and IEA to coordinate messages to Ministers in respective Ministerial meetings
8	France	Have a dialog with CEM to see how we can coordinate with their activities
9	Technical Group	Develop a CCS/CCUS Roadmap with short-term (by 2020) results

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Item	Lead	Action
10	Ministerial Steering Committee	Develop ways to re-energize the political process for CCS/CCUS
11	Policy Group Delegates	Send comments on the current draft of the Ministerial Concept Paper to the Secretariat as soon as possible
12	International Energy Agency	Provide the Secretariat with a formatting idea for the revised Ministerial Concept Paper
13	Secretariat	Revise Ministerial Concept Paper by second week of 2013
14	China, Norway, Saudi Arabia, South Africa, United Kingdom	Consider whether to take part in the Ministerial Steering Committee and inform the Secretariat
15	Ministerial Steering Committee	Plan the Ministerial Concept based on input from the Concept Paper and Member comments
16	Policy Group Delegates	Inform the Secretariat of possible dates between mid-September and November 2013 that may conflict with a Ministerial
17	U.S. Energy Association	Identify possible dates for the Ministerial

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Carbon Sequestration Leadership Forum

CSLF-P/T-2012-03
Draft: 31 December 2012

www.cslforum.org

POLICY GROUP
TECHNICAL GROUP

Revised Draft
Minutes of the Joint CSLF Policy and Technical Group Meeting

Perth, Australia
26 October 2012

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CSLF-P/T-2012-03
Draft: 31 December 2012

MINUTES OF THE JOINT CSLF POLICY AND TECHNICAL GROUP MEETING
PERTH, AUSTRALIA
26 OCTOBER 2012

Note by the Secretariat

Background

The Policy and Technical Group of the Carbon Sequestration Leadership Forum held a joint meeting on 26 October 2012, in Perth, Australia. Initial draft minutes of this meeting have been compiled by the CSLF Secretariat and were circulated to the Policy Group and 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

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

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-P/T-2012-03
Revised Draft: 31 December 2012
Prepared by CSLF Secretariat

REVISED DRAFT
Minutes of the Joint Meeting of the Policy and Technical Groups

Perth, Australia
Friday, October 26, 2012

LIST OF ATTENDEES

Policy Group Delegates

Chair:	Barbara McKee (United States)
Australia:	Ann Boon, Margaret Sewell
China:	Sizhen Peng, Jiutian Zhang
France:	Bernard Frois
Japan:	Koji Hachiyama, Kei Miyaji
Norway:	Tone Skogen
Saudi Arabia:	Hamoud Al-Otaibi
South Africa:	Faizel Mulla, Gina Downes
United Kingdom:	Jonathan Hood
United States:	James Wood

Technical Group Delegates

Chair:	Trygve Riis (Norway)
Australia:	Clinton Foster, Richard Aldous
Canada:	Stefan Bachu, Eddie Chui
China:	Qi Li, Jiutian Zhang
European Commission:	Jeroen Schuppers
France:	Didier Bonijoly
Germany	Torsten Ketelsen
Italy:	Giuseppe Girardi
Japan:	Ryozo Tanaka
Netherlands:	Paul Ramsak
Norway:	Jostein Dahl Karlsen
Saudi Arabia	Ahmed Aleidan
South Africa:	Tony Surridge
United Kingdom:	Philip Sharman
United States:	GeorgeGuthrie, Darren Mollot

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CSLF Secretariat

Richard Lynch, John Panek, Jeffrey Price, Adam Wong

Observers

Australia:	Wayne Calder (Dept. of Resources, Energy and Tourism); Maureen Clifford (CarbonNet Project); David Cooling (Alcoa of Australia, Ltd.); Asha Titus (University of Newcastle); Dominique Van Gent (Western Australia Dept. of Mines and Petroleum); Zoe Naden (Dept. of Resources, Energy and Tourism); John Nayton (Nayton Communications); Claire Richards (Dept. of Resources, Energy and Tourism); Clement Yoong (Coal Innovation NSW)
India:	Preeti Malhotra (Alstom)
Netherlands:	Bill Spence (Shell)
Chinese Taipei:	Chi-Nen Liao, Shih-Ming Chuang, Shoung Ouyang, Ren-Chen Wang (Industrial Technology Research Institute)
United States:	Arthur Lee (Chevron); Victoria Osborne (Striker Communications); Barry Worthington (U.S. Energy Association)
Global CCS Institute:	Barry Jones
International Energy Agency:	Juho Lipponen

PROCEEDINGS

1. Opening Remarks

Barbara McKee opened the meeting and thanked the Australia Department of Resources, Energy and Tourism for hosting the Annual Meeting , the Western Australian Department of Mines and Petroleum for hosting the dinner the previous evening and the Gorgon Project for hosting the Opening Reception. She then reviewed the agenda of the Joint Meeting and stated that she understood that several new projects were being submitted for CSLF recognition.

Delegates were asked to briefly introduce themselves, which they did.

2. Adoption of Agenda

The Agenda was approved without change.

3. Review and Approval of Minutes from Beijing Meeting

The draft of the Minutes of the previous Policy Group Meeting, held in Beijing, China in September 2011, had been circulated for comment to the Policy Group prior to the meeting. The final draft, which incorporated comments received, had been posted on the CSLF website. The Minutes were approved without further change.

4. Review of Beijing Action Items

Jeffrey Price of the CSLF Secretariat went through the status of the Action Items. He stated that all of the action items were either completed or underway. One Action Item for the

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Communications and Public Outreach Task Force would be accomplished by a roundtable later in the meeting.

5. Report from the Policy Group

Barbara McKee presented the report on the Policy Group meeting. The meeting consisted of task force reports, a policy roundtable on the topic of "Advancing CCUS in a Time of Challenge," election of a Policy Group Chair, review of the 2013 CSLF Ministerial Concept Paper and selection of the Ministerial Steering Committee.

The Capacity Building Governing Council reported that twelve projects had been funded by the US $2.965 million CSLF Capacity Building Fund in four countries (Brazil, China, Mexico and South Africa). US $514,812 is available for further projects. The Financing Task Force held two workshops over the last year. The theme of the first workshop, held in Paris in January 2012, was "What will it take to turn ambition into reality?" and the theme of the second, held in Washington in September 2012, was "Lessons from first movers in CCUS." Key messages from these workshops were that electricity prices alone are insufficient to cover costs and no one financing approach fits all projects.

The Policy Roundtable featured several presentations and a discussion. Several key points emerged from the discussion: country circumstances vary; one size does not fit all; EOR is not a business model but a mechanism to cover some costs; and it is vital to re-energize political and public support. Most importantly for this meeting, a request was made to the Technical Group for a Roadmap achievable in the near term (i.e., by 2020).

The United State was re-elected Policy Group Chair for the next 3 years.

There was a lively discussion with many comments on the Draft Concept Paper for the 2013 Ministerial. The key issue discussed most extensively was how the potential for utilization of CO_2 differs among countries. Members were requested to provide input as soon as possible to the Secretariat, which will draft a revision by January 2013. The revision will guide the work of a Steering Committee for the Ministerial. The discussion emphasized that a Roadmap with short-term goals was of absolute importance.

6. Report from the Technical Group

Trygve Riis, Technical Group Chair, Norway, presented the report from the Technical Group which discussed both the June 2012 Technical Group meeting in Bergen, Norway and the meeting the previous day in Perth.

The meeting in Bergen recommended three projects for CSLF recommendation, considered the Phase II report of the Risk Assessment Task Force and received reports from four new task forces. The continuation of the work of the Risk Assessment Task Force is to be taken up by the Risk and Liability Task Force. The meeting in Bergen also included a workshop on CO_2 capture and a visit to the CSLF-recognized CO_2 Technology Centre Mongstad, which is the world's largest CO_2 capture test facility.

Mr. Riis also reported on the Technical Group meeting in Perth. The four new task forces are making good progress and three new Technical Action Plans are being addressed. Norway was re-elected Technical Group Chair and Australia, Canada and South Africa were elected Vice Chairs. Two projects proposed for CSLF recognition were discussed and approved for recommendation to the Policy Group. It was also decided that work on the Technology Roadmap will continue under the guidance of a Steering Committee chaired by the Technical Group Chair. The Norway Ministry of Petroleum and Energy is funding an consultant who will work on the Roadmap.

Responding to the request from the Policy Group for a short-term roadmap, Mr. Riis said that it would be possible to have clear short-term recommendations, targets and goals for the Ministers. The Technical Group would also be willing to say that, if it is done the right way, CO_2 storage is safe.

The Technical Group also had a robust discussion of the Ministerial Concept Paper. The Technical Group's opinions on the Concept Paper were that:

- The term "fighting poverty" is not a credible part of the title.
- We need to be careful mixing up the terms CCS and CCUS. There are different conceptions of how these terms relate to each other. Which, for example, is a subset of the other? This needs to be clarified.
- CO_2-EOR is an important bridge to CCS but is not applicable to all countries. An exclusive emphasis on EOR may be a disincentive for some Ministers to participate.
- References to activities of the Technical Group are missing from the Concept Paper.
- CO_2 is seen as the main issue, not EOR, which is seen as a bridging technology.
- It was unclear whether the term "business case" should be in the title.
- Geologic storage is safe with proper operation.

France suggested that the Technical and Policy Groups should have a dialog with each other on messages to the Ministers. This suggestion was taken up as an Action Item.

7. Review and Approval of Proposed Projects

Trygve Riis gave a presentation on the projects that the Technical Group was recommending to the Policy Group for recognition by the CSLF. Five projects were recommended:

- Illinois Basin – Decatur Project,
- Illinois Industrial Carbon Capture and Storage Project,
- Air Products CO_2 Capture from Hydrogen Facility Project,
- South West Hub Geosequestration Project, and
- CarbonNet Project.

Mr. Riis noted that these projects were much larger and more expensive than previous CSLF-recognized projects and were being recommended at an earlier stage of development than those previous projects. Therefore there may be a somewhat higher risk that these projects may not be completed, but the recommended projects do have substantial government commitments. He said that these projects would add value to the CSLF portfolio of projects. According to the Secretariat the CSLF currently has recognized 34 projects, 23 of which are active and 11 of which have been completed.

All of the projects recommended were approved.

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8. Report from the Task Force on Risk and Liability

George Guthrie, Co-chair, presented the report of this new Task Force and then asked for discussion. He noted that the Task Force is a joint Task Force of the Technical and Policy Groups and the workshop was held to improve the understanding of the relationship between geologic risk and potential financial liabilities.

The workshop was jointly sponsored by the CSLF, Global CCS Institute, and the IEA and was held at the IEA's offices in Paris on 10–11 July 2012. Participants included 62 representatives from governments, industry, academia/research, multilateral institutions, law firms, financial institutions, NGOs and consulting firms. The workshop had five sessions (geologic risks, industry perspective, economics of liability, government and policy responses, and "How safe is safe enough?") A report on the workshop is posted on the CSLF website. Several recommendations based on the workshop were made in the report:

- Take all opportunities to highlight that risks of storing CO_2 can be managed.
- Conduct another workshop on risk and liability in the Asia-Pacific region.
- Continue and expand capacity building for regulatory institutions.
- Consider the role of international or national standards for geologic storage of CO_2.
- Conduct dialog with the insurance industry about coverage for geologic storage.
- Consider ways to enhance and support public outreach on geologic storage.
- Conduct further RD&D to resolve remaining geologic storage uncertainties.

Bernard Frois, Co-chair, said that the workshop was a mixed bag and that we heard different things with each session. We could do better by having the Technical Group and the Policy Group interact more on risk and liability. He thought that the report on the workshop was too long and did not have any useful messages. He agreed to write a short executive summary that would be sharp and crisp and have useful messages.

Stefan Bachu of Canada stated that he attended the workshop and thought that two key messages came out of the workshop and the report, which should be conveyed to the Ministers:

1. CO_2 storage is safe if properly done and this must be conveyed to the public.
2. Most risks associated with storage can be dealt with by industry but industry cannot address undefined or unlimited liabilities.

George Guthrie, in response to comments from China and South Africa, noted that the Task Force addressed geologic storage and not risks of capture because the Technical Group's Risk Assessment Task Force concluded that industry already had ways to deal with risks related to CO_2 capture and transportation. Also, as was discussed in the workshop, legal frameworks vary widely by country. He also stated that the next steps for the Task Force would be to consider another workshop in the Asia-Pacific Region and to work with the stakeholders group to help craft a statement of safety that can be presented to the Ministers.

9. Update on the Nagaoka CO_2 Storage Project

Koji Hachiyama, Director, Global Environmental Partnership, Ministry of Economy, Trade and Industry, Japan, gave a presentation on this project. This presentation consisted of an overview of the project, a discussion of the well-based CO_2 monitoring at the injection site and a description of the site safety assessments conducted after two large earthquakes. The project injected 10,400 tons of CO_2 into a sandstone formation from 2003 to 2005 and consisted of an injection well and several observation wells. Several different types of monitoring were used and these showed that the CO_2 was held in place by several different trapping mechanisms. The project experienced two large earthquakes, the first during injection and the second after injection ceased. No movement or leakage of injected CO_2 was detected after either earthquake and none of the facilities used for the test were damaged. This confirms the safety of CO_2 storage in the Nagaoka Project. They are currently trying to communicate what this shows about the safety of CCS to the public in Japan, which is very concerned about earthquakes.

10. New Business

There was no new business.

11. Advancing CO_2 Utilization: A Policy and Technical Roundtable

Trygve Riis, Technical Group Chair, Norway, moderated this roundtable discussion on several different options for CO_2 utilization. He said that while EOR is the best-known type of utilization, there are other aspects of utilization that also will be discussed.

Stefan Bachu, Alberta Innovates–Technology Futures, Canada, spoke on the technical aspects of advancing CO_2 utilization. He stated that there are three broad categories of potential uses for CO_2: resource recovery (mostly EOR, but also other types of energy recovery), non-consumptive uses such as desalinization, and consumptive uses such as production of building materials. Of these, CO_2-EOR is the only mature technology and has the most potential. CO_2-EOR differs from CO_2 storage. There may be technical issues with transitioning relating to how CO_2 storage and EOR are implemented and regulated, for example, monitoring and reporting requirements. There are also many policy issues in transitioning from CO_2-EOR to CO_2 storage such as jurisdictional issues, long-term liability regulatory frameworks and credits for stored CO_2.

Darren Mollot, United States Department of Energy, described the work of the CSLF's CO_2 Utilization Task Force. He said that the purpose of the Task Force is to study the most economically promising CO_2 utilization options with the potential for a net reduction of CO_2 emissions. The final Phase I report of this Task Force was completed in October 2012. It identified numerous uses of CO_2. Some of these uses are for hydrocarbon recovery; others are non-consumptive use of CO_2 and still others are consumptive uses. A tentative list of eight promising CO_2 pathways was identified in each category. The next step for the Task Force will be to develop a Phase II report which will provide a more thorough discussion and analysis of the most attractive options identified.

David Cooling of Alcoa of Australia Ltd., Australia described the Residue Carbon Capture Project which is an example of CO_2 utilization. This project was visited in the site tour the previous day. The production of aluminum from bauxite creates a highly caustic wet mud which must be dried and disposed of, which is a very capital and labor–intensive process. Treating the mud with CO_2 makes it less caustic and enables it to be dried more easily, thus opening opportunities for reuse and allowing it to be spread on the ground as a biologically active soil. This provides a permanent sink for the CO_2. CO_2 for this project is available from the nearby Kwinana Carbon Capture Plant. CO_2 adds value to Alcoa of Australia Ltd. Potential future developments include use of CO_2 from other sources and new uses of the process.

Sizhen Peng of the Administrative Centre for Agenda 21, Ministry of Science and Technology, China said there are many different potential approaches to CO_2 utilization other than CO_2-EOR. He said CCUS should help with sustainable development. CCUS should serve as an important tool to match urgent and important energy and resource needs. He gave several examples of CO_2 utilization in China such as the production of liquid minerals or solving water resource issues. For example, water could be extracted when CO_2 is injected in areas with water shortages.

Ahmed Al-Eidan, Saudi Aramco, Saudi Arabia, spoke about the relationship between CCS and CCUS. He said that CCUS can be a bridge to CCS. It has to have the components of safe storage, an anthropogenic source should be used, and it should have a monitoring program and closure. There are still areas to improve on CO_2-EOR, particularly in the residual oil zone and injection of carbonated water. Technologies for CO_2 geologic storage and EOR can complement each other.

A discussion followed the presentations. Mr. Riis noted that CO_2 is recycled in EOR and this makes it much more complicated to convince people that EOR is safe storage. He asked how it would be possible to show that it is safe storage. The response was that if wells used for EOR are properly sealed, CO_2 already there will stay in place. Ultimately, most of the injected CO_2 will stays in the ground. It was also pointed out that if CO_2 storage has no value, oil producers will emphasize EOR, not storage.

Mr. Riis asked whether other methods of using CO_2 for hydrocarbon production are near-term. Stefan Bachu responded that there are differences between EOR and enhanced gas recovery. In oil production, most of the original oil in place wil be left after primary recovery, meaning that most of the oil remains to be produced by enhanced oil recovery. By contrast, 80 to 90 percent of gas in a reservoir is typically produced and this usually makes it uneconomic to recover the rest. Enhanced Coal Bed Methane Recovery pilots have been scientifically successful but not economic. Using CO_2 for shale gas and oil production is very new.

Mr. Riis asked whether non-consumptive uses could contribute. The response was that there may be opportunities to use the same CO_2 twice and thus eliminate the need to generate CO_2 for the second use. There are also exotic options such as algae, but they are probably some time off.

Consumptive uses such as the production of new minerals were seen as too expensive due to the extensive materials handling and high energy use. These processes would only work if done as part of another process.

12. Roundtable: Outreach on Critical Issues

James Wood moderated this roundtable discussion. Opening the roundtable, Mr. Wood defined public outreach as making an effort to understand, anticipate and address public perceptions of and concerns about CO_2 storage. It is very difficult to reach the public when the public has limited technical literacy. Public outreach faces several key challenges. These include timing, uncertainty, fear of the unknown and independent verification of responsible behavior. He noted that the US Regional Carbon Sequestration Partnerships has prepared a best practices manual on public outreach for carbon storage projects. Outreach efforts should identify key stakeholders early and understanding their concerns at an emotional level is necessary in order to develop and implement an effective communications strategy. Key messages must be tailored to their concerns and communicated by an established "face" of the project. He also described how the Hydrogen Energy California (HECA) Project did effective public outreach by demonstrating that it was producing local benefits.

Victoria Osborne of Striker Communications, a United States public relations firm, raised the question of whether a communications process for CCUS can be developed in a proactive way. She said that this would require an updated definition of public relations as a strategic communications process that builds mutually beneficial relationships, but there are many roadblocks to such a process. It is often not true that more information leads to greater acceptance; the public and the media want stories, not facts. She also raised questions about the effectiveness of the websites of CCUS organizations such as the CSLF and the Global CCS Institute, noting that they attract far less traffic than do the websites of major Environmental NGOs. Public relations efforts draw on passion, resources and time. Different communicators have these to different extents. Bloggers, for example, have much passion and time, but few resources, while NGOs have much passion and resources, but not much time. An effective communications campaign by CCUS advocates would require a balance of passion, time and resources as well as a good story.

Dominique Van Gent of the Western Australia Department of Mines and Petroleum described the lessons learned from the community consultation process for the Southwest Hub Project, an integrated CO_2 project in which CO_2 is permanently stored in red mud from aluminum production. The community consultation strategy, developed in 2010, consists of numerous discussions with community groups about each activity in the project, but each activity must be part of the total project. One of the key lessons is that language—the exact words used—are important. In particular, avoid technical language, which is not understood. The involvement of the local community, both local companies and schools, helps to develop good community relationships. It is as important to listen as it is to talk and also make yourself available to answer questions. Avoid surprises to the community and local government. Acceptance comes when the community's questions are answered in a way that is understood.

Bill Spence, Shell, Netherlands, spoke on Shell's experience with community outreach. He contrasted the approach Shell used at the early CCS project at Barendrecht in the Netherlands and the lessons learned in that project, with the approach used later for the Quest project in Alberta, Canada. The project at Barendrecht was abandoned due to the opposition of the local community. The developers of that project did not understand that community's concerns. There is a need to listen.

John Nayton of Nayton Communications, Australia discussed problems with communications. He saw a major problem being a difference in personality types between executives and general public stakeholders, citing differences in personalities as measured by the Myers-Briggs psychological test of those two groups. He said that what matters to executives in making judgments is science, evidence, processes, problem-solving, experience and facts. By contrast, most stakeholders make judgments based on considerations such as

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credibly, accountability, transparency, confidence, oversight and integrity. Delivering "facts" is inadequate to communicate to stakeholders. Effective communications is about earning trust and credibility, ensuring that those who are accountable, not public relations people, do the communications, and build long-term relationships. Stakeholders want to be considered and to be treated with respect.

At the conclusion of the presentation James Wood suggested that feedback be gathered on how the CSLF projects itself on its website in order to see how it can be improved.

13. Closing Remarks and Adjourn

Barbara McKee asked if there were any conflicts with November 4 through 8, 2013 for the CSLF meeting next year with the Ministers meeting on November 7. No concerns were expressed and so planning will go forward with those dates.

Margaret Sewell noted that we talked about re-energizing the interest in CCS and that the Ministerial will be an opportunity to accomplish that by having the Ministers make strong statements, particularly about safety of storage.

Chair McKee thanked the delegates and observers for their hard work and participation over the last three days and said that much had been accomplished. She also thanked the Australian hosts for their hospitality and the members of the Secretariat who worked hard on this meeting and supported CSLF task forces. She also said that the United States very much appreciates the opportunity to continue to chair the Policy Group. Finally, she encouraged all the participants to continue their efforts to make CCUS a commercial reality throughout the world.

ACTION ITEMS FROM THE JOINT MEETING OF THE POLICY AND TECHNICAL GROUPS

Item	Lead	Action
1	Technical Group	Create a roadmap with clear and concise messages for Ministers and others for what must be achieved by 2020
2	Technical Group Chair	Serve on the Steering Committee for the next Ministerial
3	Technical and Policy Groups	Conduct a dialog over the next several months to discuss issues and messages for the Ministers
4	France	Write a short executive summary of the Paris Workshop on Risk and Liability
6	Task Force on Communication and Public Outreach	Review the CSLF website to make it more attractive for a wider audience
7	Secretariat and Ministerial Steering Committee	Plan for the CSLF meetings next year on November 4 through 8, 2013, with the Ministerial being on November 7
8	Ministerial Steering Committee	Develop a statement for the Ministers to make at the Ministerial that CCS/CCUS will be safe

Carbon Sequestration Leadership Forum
www.cslforum.org
CSLF-P-2013-02
17 October 2013

POLICY GROUP

Key Messages and Recommendations from the 2013 CSLF Technology Roadmap

Background

The CSLF Technical Group Executive Committee has overseen a complete and major rewrite of the CSLF Technology Roadmap. This new version of the Roadmap contains several key recommendations for advancing carbon capture and storage (CCS) technologies towards the year 2020 and beyond. Additionally, the Roadmap includes eight key messages concerning CCS and its utilization as a climate change mitigation option.

This paper summarizes the messages and key recommendations from the Roadmap.

Action Requested

The Policy Group is requested to review the key messages and recommendations from the 2013 CSLF Technology Roadmap.

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Key Messages and Recommendations from the 2013 CSLF Technology Roadmap

Prepared by the CSLF Technical Group Executive Committee

Key messages from the Technology Roadmap

- First generation CO_2 capture technology for power generation applications is available today (albeit expensive).
- CO_2 transport is an established technology.
- CO_2 storage is safe provided that proper planning; operating, closure and post-closure procedures are developed and followed. However, sites display a wide variety of geology and other *in situ* conditions.
- Data collection for site characterization, qualification and permitting currently requires a long lead-time (3-10 years) mostly before an investment decision on detailed design work and then construction for a large new capture facility.
- There are no technical challenges per se in converting CO_2-EOR operations to CCS, although issues like availability of high quality CO_2 at an economic cost, infrastructure for transporting CO_2 to oil fields; and legal, regulatory and long-term liability must be addressed for this to happen.
- There is a broad array of non-EOR CO_2 utilization options that, when taken cumulatively, could provide a mechanism to utilize CO_2 in an economic manner. These options are at various levels of technological and market maturity
- Need for plain language communication to allay any public fears and concerns that may arise from transport and geological storage of CO_2.

Key Recommendations from the 2013 Technology Roadmap

Towards 2020 nations should work together to ensure that CCS remains a viable GHG mitigation option, building upon the global progress to date through:

International Collaboration

- Establish international networks of laboratories (like the European Carbon Dioxide Capture and Storage Laboratory Infrastructure, ECCSEL) and test centres and comprehensive RD&D programmes.
- Establish international collaborative R&D programmes that facilitate the demonstration of safe long term CO_2 storage.
- Address the different priorities, technical developments and needs of developed and developing countries.

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Demonstration Projects

- Implement large-scale demonstration projects in power generation in a sufficient number to gain experience with 1st generation CO_2 capture technologies and their integration into the power plant;
- Encourage and support the first demonstration plants for CO_2 capture in other industries than the power sector and gas processing and reforming, particularly in the cement and iron and steel industries.
- Develop sizeable pilot-scale projects for CO_2 storage that can provide greater understanding of the storage medium, establish networks of such projects to share the knowledge and experience for various geological and environmental settings, jurisdictions and regions of the world, including monitoring programmes.

Common Standards, Specifications and Best Practices

- Agree on common standards or best practices for establishing CO_2 storage capacity in geological formations.
- Develop common specifications for impurities in the CO_2 stream for the transport and storage of CO_2.
- Develop internationally agreed common standards or best practices for the screening, and selection of CO_2 storage sites in order to reduce lead-time and have the sites ready for permitting between 2020 and 2025, including CO_2-enhanced oil recovery (CO_2-EOR) sites.

Regional networks and opportunities for CCS

- Design large-scale, regional CO_2 transport networks and infrastructure that integrate CO_2 capture from power generation as well as other industries, CO_2 transport and storage
- Conduct regional (nationally as well as internationally) impact assessments of large-scale CCS implementation as part of an energy mix with renewables and fossil fuels.
- Map regional opportunities for CO_2 utilization and start implementing projects.

CO2 Utilization Options

- Continue R&D and small-scale testing of promising non-EOR CO_2 utilization options.

Towards 2030 nations should work together to:

- Move 2nd generation CO_2 capture technologies for power generation and industrial applications through demonstration to commercialisation, with possible targets of 30% reduction of energy penalty, normalized capital cost, and normalized operational and maintenance (O&M) costs compared to 2013 costs for 1st generation technologies
- Implement large-scale regional CO_2 transport networks and infrastructure, nationally as well as internationally.
- Demonstrate safe, large-scale CO_2 storage and monitoring
- Qualify regional, and potentially cross-border, clusters of CO_2 storage reservoirs with sufficient capacity.
- Ensure sufficient resource capacity for a large-scale CCS industry, by starting widespread exploration as soon as possible, because of the long lead times.
- Scale-up and demonstrate non-EOR CO_2 utilization options.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-P-2013-03
16 October 2013

POLICY GROUP

Key Messages and Recommendations from the CSLF Technical Group

Background

At the September 2011 CSLF Ministerial Meeting in Beijing, the Technical Group approved a new multi-year Action Plan to identify priorities and provide a structure and framework for conducting Technical Group efforts through 2016. Twelve individual actions were identified, and Task Forces were formed to address four of these twelve actions. This paper is a summary of key messages and recommendations from the following three Technical Group Task Forces:

- Technology Opportunities and Gaps Task Force
- Technical Challenges for Conversion of CO_2-EOR to CCS Task Force
- CO_2 Utilization Options Task Force

Action Requested

The Policy Group is requested to review the messages and recommendations from the Technical Group.

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Carbon Sequestration Leadership Forum
www.cslforum.org
CSLF-P-2013-03
16 October 2013

Key Messages and Recommendations from the CSLF Technical Group

Prepared by the CSLF Technical Group Executive Committee

CCS Technology Opportunities and Gaps

- At a high level there are no major technology gaps or impediments to large-scale CCS deployment; the technology is available and can be effectively deployed.
- The focus of the technology development is now on driving down costs, improving operational and monitoring performance, and contributing to better regulatory frameworks for CCS.
- Current commercially available capture technologies will evolve by implementing more projects. This typical "learning by doing" phenomenon is common with many technologies and is already happening in CCS.
- For the next generation of capture technologies, that promise much lower costs than those currently available, more attention is needed. Investment in the early stages of development has been significant with a number of promising emerging technologies. However, with little or no market for CCS (e.g., CO_2 price or emissions reduction mandate), the market pull for this next crop of technologies is weak. Getting next-generation lower-cost technologies into large scale pilots and demonstration operations is important and requires governments to act to ensure that CO_2 capture at much lower costs is available for deployment by 2030 and beyond.
- Technologies for capturing CO_2 from natural gas combustion should be a priority, as low-cost shale gas will encourage more gas combustion driven both by market costs and by an increasing need to reduce CO_2 emissions.
- Pipeline transporting of CO_2 is a mature technology, but more experience is need in planning and designing large scale transport hubs managing a diverse supply of CO_2 with different impurity concentrations. Large scale transport of CO_2 by ship offers promise and needs to be demonstrated as scale.
- On storage, the significant body of knowledge from the oil and gas industry combined with what is now 10-15 years of R&D on the behaviour of CO_2 in deep rock formations underpins a strong consensus that safe CO_2 storage is possible today.
- The lead times from initiating exploration through to approvals and construction of storage sites will often be 10-15 years. The rate at which exploration is incentivised to start will have a profound impact on the degree to which CCS can contribute to reaching 2050 global CO_2 reduction targets. This will increase the ability to deploy CCS more rapidly and will in turn affect the rate of technology improvement. There is a strong recommendation to start or incentivize more exploration for storage.

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- Monitoring, measurement verification (MMV) for stored CO_2 continues to progress well. Low cost, continuous, high-resolution subsurface monitoring is being refined and may be valuable in some situations. An important new front is developing MMV technologies and strategies for MMV for storage in offshore environments.
- It is recommended that Governments continue to look to support and incentivise international technology collaboration and researcher exchange to spark faster developments and the diffusion of new CCS technologies, particularly in the fields of capture and monitoring.

Converting CO_2-EOR Operations to CCS

- Enhanced Oil Recovery (EOR) is the most near-term utilization option that has broad commercial deployment opportunities.
- There is sufficient operational and regulatory experience for this technology to be considered as being mature, with an associated CO_2 storage rate of the purchased CO_2 greater than 90%.
- The main reason CO_2-EOR is not applied on a large scale outside west Texas in the United States is the unavailability of high-purity CO_2 in the amounts and at the cost needed for this technology to be deployed on a large scale.
- The absence of infrastructure to both capture the CO_2 and transport it from CO_2 sources to oil fields suitable for CO_2-EOR is also a key reason for the lack of large scale deployment of CO_2-EOR.
- There are a number of commonalities between CO_2-EOR and pure CO_2 storage operations, both at the operational and regulatory levels, which create a good basis for transitioning from CO_2-EOR to CO_2 storage in oil fields.
- There are no specific technological barriers or challenges *per se* in transitioning and converting a pure CO_2-EOR operation into a CO_2 storage operation. The main differences between the two types of operations stem from legal, regulatory and economic differences between the two.
- A challenge for CO_2-EOR operations which may, in the future, convert to CO_2 storage operations is the lack of baseline data for monitoring.
- In order to facilitate the transition of a pure CO_2-EOR operation to CO_2 storage, operators and policy makers have to address a series of legal, regulatory and economic issues in the absence of which this transition can not take place. These should include:
  1. Clarification of the policy and regulatory framework for CO_2 storage in oil reservoirs, including incidental and transitioned storage CO_2-EOR operations.
  2. Clarification if CO_2-EOR operations transitioning to CO_2 storage operations should be tenured and permitted under mineral/oil & gas legislation or under CO_2 storage legislation.
  3. Clarification of any long-term liability for CO_2 storage in CO_2-EOR operations that have transitioned to CO_2 storage, notwithstanding the CO_2 stored during the previous phase of pure CO_2-EOR.

4. Clarification of the monitoring and well status requirements for oil and gas reservoirs, particularly for CO_2-EOR, including baseline conditions for CO_2 storage.
5. Addressing the issue of jurisdictional responsibility for pure CO_2 storage in oil and gas reservoirs, both in regard to national-subnational jurisdiction in federal countries, and to organizational jurisdiction (environment versus development ministries/departments).

CO_2 Utilization Options

- Besides utilization in CO_2-EOR operations, there is a wide range of CO_2 utilization options available which can serve as a mechanism for deployment and commercialization of carbon capture and storage (CCS) by providing an economic return for the capture and utilization of CO_2.
- Non-EOR CO_2 utilization options are at varying degrees of commercial readiness and technical maturity.
- For commercially and technologically mature options such as urea production and utilization in greenhouses, efforts should be on demonstration projects and on the use of non-traditional feedstocks (such as coal) or 'polygeneration' concepts (such as those based on integrated gasification combined cycle (IGCC) concepts). This can help facilitate CCS deployment by diversifying the product mix and providing a mechanism for return on investment.
- Efforts that are focused on hydrocarbon recovery other than EOR, such as CO_2 for enhanced gas recovery (via methane displacement) or CO_2 utilization as a fracturing fluid, should focus on field tests to validate existing technologies and capabilities, and to understand the dynamics of CO_2 interactions in the reservoir.
- Efforts that are in early R&D or pilot-scale stages, such as algal routes to fuels, aggregate/secondary construction materials (SCM) production, and enhanced geothermal systems, should focus on: addressing key techno-economic challenges; independent tests to verify the performance (e.g., less energy requirements with CO_2 utilization to produce SCM and building materials) of these products compared to technical requirements and standards; and support of small, pilot-scale tests of first generation technologies and designs that could help provide initial data on engineering and process challenges of these options.
- More detailed technical, economic, and environmental analyses should be conducted to better quantify the potential impacts and economic potential of CO_2 utilization technologies and to clarify how R&D could potentially expand the market for these utilization options (e.g., in enhanced gas recovery) and improve the economic and environmental performance of the system.

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Carbon Sequestration Leadership Forum
www.cslforum.org
CSLF-P-2013-04
28 October 2013

POLICY GROUP

CSLF Capacity Building Program Progress Report

Background

The CSLF Capacity Building Program was approved by the CSLF Policy Group and endorsed by Ministers in 2009. The Program strives to assist all CSLF Members to develop the information, tools, skills, expertise, and institutions required to implement carbon capture and storage (CCS) demonstrations and then move rapidly into commercial operation.

This document is a status update of the CSLF Capacity Building Program.

Action Requested

The Policy Group is requested to review the Progress Report from the Capacity Building Governing Council.

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CSLF Capacity Building Program Progress Report

Report by the CSLF Capacity Building Governing Council

CSLF Capacity Building Program

The CSLF Capacity Building Program was approved by the CSLF Policy Group and endorsed by Ministers in 2009. The Program strives to assist all CSLF Members to develop the information, tools, skills, expertise, and institutions required to implement carbon capture and storage (CCS) demonstrations and then move rapidly into commercial operation.

The Program Plan further defines four program initiatives:

- Disseminate practical information
- Build capacity in emerging economies
- Assist government and regulatory agencies
- Build academic and research institutions for CCS

Each of the capacity building projects undertaken by the CSLF, as described below, addresses one or more of these program initiatives.

Governance of the CSLF Capacity Building Fund

The CSLF Capacity Building Fund Governing Council is composed of representatives of significant donors. The Governing Council oversees financial aspects of the Capacity Building Program. The Governing Council began its operation by developing a Terms of Reference for its operation and for governance of the CSLF Capacity Building Fund.

The Governing Council also developed a procedure for soliciting and evaluating requests for capacity building projects using criteria established by the Capacity Building Task Force. This procedure was implemented from 2010 to 2013 in coordination with the Capacity Building Task Force by soliciting and evaluating requests from emerging economy CSLF Members.

Collaborations

The CSLF is collaborating with the Global Carbon Capture and Storage Institute in the management of its Capacity Building Program and is coordinating its activities with CCS capacity building activities of the World Bank. Various other industrial and academic institutions in Member countries are taking part in CSLF capacity building projects.

Capacity Building Projects

To date, a total of 13 capacity building projects in four countries have been approved and either have been, or will be, conducted by the CSLF. While projects may be held in a

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specific country, workshops and other events are open to participants from all CSLF Members.

Approved projects include:

Brazil

- Training Program in carbon capture applied to mineral coal combustion and gasification process - This program is building and developing a knowledge base in the process of carbon capture in Brazil through a training program applied to mineral coal combustion and gasification process. The program brings foreign skilled personnel to instruct local human resources and allows Brazilian researchers to participate in practical trainings at the United States Department of Energy (US-DOE) – National Energy Technology Laboratory (NETL) or institutions with recognized expertise. This project has three courses divided over two and a half years.
- Develop a training program in the process of CCS in the offshore environment - This program was for professionals from the oil industry, research institutions, universities and stakeholders in general and was critical to the sustainable development of Brazil's petroleum industry.
- Develop a knowledge base on environmental impact assessment and CO_2 monitoring technologies - This knowledge base will be used for the development of CCS projects in South America by bringing skilled personal to instruct local human resources and advise on the appropriate technology and instrumentation necessary for a specific project. The first course, a basic one, was held in July 2012 and was titled "Understanding Carbon Capture and Storage."
- CO_2 Storage in the Clean Development Mechanism – Opportunities in Portuguese Language Countries – From September 19-20, 2013, a workshop was held in Lisbon, Portugal that helped to disseminate knowledge about CCS technology among the Community of Portuguese Language Countries (CPLP) members. The workshop allowed participants to discuss business and investment opportunities, and promoted cooperation between companies and institutions capable of intervening in the activities necessary to implement energy and industrial projects integrated with CCS in CPLP countries.

China

- Develop website on Carbon Capture Utilization and Storage Technologies - This project established the first website focusing on CCS technologies and its development in China. The aims were to serve as a platform to share information and knowledge on technology advancements and good practices, and to educate the public. The website was also translated into English.
- Workshop on experience sharing among CCS demonstration and pilot projects - This workshop was held in July 2012 in Beijing, China. It focused on CCS experience sharing in China and served as a platform of exchange and discussion within China and internationally. Participants were representatives of government departments, academia, industrial stakeholders, and NGOs.
- Workshop on legal and regulatory issues for CCS technology development – This workshop was held in October 2012 in Beijing, China, and introduced the role of regulatory and enabling environments for CCS development, experiences of developed countries, and how China may move forward. Participants were representatives of government departments, academia, industrial stakeholders, and NGOs.
- Exploring CCUS Legal and Regulatory Framework in China - This project aims to explore the CCUS legal and regulatory issues in China through an empirical perspective.

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The project also plans to raise awareness among relevant stakeholder groups, with an aim to promote the establishment of such a regulatory framework and to facilitate the implementation of future CCUS demonstration projects in China.

- Roadmap: CCUS Financing in China - This project aims to address CCUS challenges by formulating the financial roadmap for CCUS development and demonstration in China and spreading information to key stakeholders.

Mexico

- Introduce CCS into academic programs - This project was held in March 2012 and educated professors and graduate students on carbon capture, utilization and storage through two workshops. The first workshop focused on "CO_2 Geological Storage and Enhanced Oil Recovery," while the second workshop was on "CO_2 Capture." The project also sent two individuals from Mexico to attend the Greenhouse Gas Control Technologies (GHGT)-11 Conference in November 2012 in Kyoto, Japan.
- Internships on CCS - This proposal will link qualified Mexican personnel to international projects with similar background, objectives, and operations to demonstration projects around the world. Mexico is interested in CO_2 monitoring strategies and techniques and one form of obtaining such experience is via this proposed internship. The first intern will undertake the internship in Australia at the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) in Australia.

South Africa

- Conduct workshops and conferences during South Africa's CCS week - Two workshops were held in October 2011 to disseminate information on CCS to relevant stakeholders.
- Impacts of CCS on South African national priorities beyond climate change - The aim of this study was to improve the understanding of how CCS impacts South Africa's national priority issues beyond CO_2 mitigation and climate change, such as sustainable development, improved local infrastructure, job creation and protection, poverty alleviation, and social upliftment.

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CSLF-P-2013-05
02 October 2013

POLICY GROUP

Election of Policy Group Vice Chairs

Background

As stated in Section 3.3 (a) of the CSLF Terms of Reference and Procedures, CSLF Chairs and Vice Chairs will be elected every three years. The previous election of the Policy Group Vice Chairs was at the Warsaw meeting in October 2010, so the next election is scheduled for the Policy Group Meeting on November 6, 2013 in Washington, D.C., USA.

Action Requested

The Policy Group is requested to hold an election to select three Vice Chairs whose term will run through November 2016.

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Election of Policy Group Vice Chairs

At its meeting in Paris in 2007, the Policy Group reached consensus on the following procedures for election of all CSLF Chairs and Vice Chairs:

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.*

On 26 June 2013, the Secretariat sent an e-mail to CSLF Policy Group delegates, informing them of the upcoming election of the Policy Group Vice Chairs and that nominations must be received by the Secretariat no later than six weeks prior to the meeting (i.e., by 26 September 2013).

The following nomination was received by the Secretariat:

China has nominated China, Saudi Arabia, and the United Kingdom for Policy Group Vice Chairs.

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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
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. Secretariat. 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. Application.

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.

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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Active and Completed CSLF Recognized Projects

(as of October 2013)

1. **Air Products CO_2 Capture from Hydrogen Facility Project**
   Nominators: United States (lead), Netherlands, and United Kingdom
   This is a large-scale commercial project, located in eastern Texas in the United States, which will demonstrate a state-of-the-art system to concentrate CO_2 from two steam methane reformer (SMR) hydrogen production plants, and purify the CO_2 to make it suitable for sequestration by injection into an oil reservoir as part of an ongoing CO_2 Enhanced Oil Recovery (EOR) project. The commercial goal of the project is to recover and purify approximately 1 million tonnes per year of CO_2 for pipeline transport to Texas oilfields for use in EOR. The technical goal is to capture at least 75% of the CO_2 from a treated industrial gas stream that would otherwise be emitted to the atmosphere. A financial goal is to demonstrate real-world CO_2 capture economics.
   Recognized by the CSLF at its Perth meeting, October 2012

2. **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

3. **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

4. **CarbonNet Project**
   Nominators: Australia (lead) and United States
   This is a large-scale project that will implement a large-scale multi-user CO_2 capture, transport, and storage network in southeastern Australia in the Latrobe Valley. Multiple

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industrial and utility point sources of CO_2 will be connected via a pipeline to a site site where the CO_2 can be stored in saline aquifers in the offshore Gippsland Basin. The project initially plans to sequester approximately 1 to 5 million tonnes of CO_2 per year, with the potential to increase capacity significantly over time. The project will also include reservoir characterization and, once storage is underway, measurement, monitoring and verification (MMV) technologies.
Recognized by the CSLF at its Perth meeting, October 2012

5. **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

6. **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

7. **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

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8. 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

9. 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

10. 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

11. 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

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12. 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 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

13. 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

14. 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

15. 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

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16. 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

17. Demonstration of an Oxyfuel Combustion System *(Completed)*

Nominators: United Kingdom (lead) and France

This project, located at Renfrew, Scotland, UK, demonstrated oxyfuel technology on a full-scale 40-megawatt burner. The goal of the project was 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 is being 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

18. 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

19. 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

20. 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

21. 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

22. 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

23. 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

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24. IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project *(Completed)*

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

25. Illinois Basin – Decatur Project

Nominators: United States (lead) and United Kingdom

This is a large-scale research project that will geologically store up to 1 million metric tons of CO_2 over a 3-year period. The CO_2 is being captured from the fermentation process used to produce ethanol at an industrial corn processing complex in Decatur, Illinois, in the United States. After three years, the injection well will be sealed and the reservoir monitored using geophysical techniques. Monitoring, verification, and accounting (MVA) efforts include tracking the CO_2 in the subsurface, monitoring the performance of the reservoir seal, and continuous checking of soil, air, and groundwater both during and after injection. The project focus is on demonstration of CCS project development, operation, and implementation while demonstrating CCS technology and reservoir quality.

Recognized by the CSLF at its Perth meeting, October 2012

26. Illinois Industrial Carbon Capture and Storage Project

Nominators: United States (lead) and France

This is a large-scale commercial project that will collect up to 3,000 tonnes per day of CO_2 for deep geologic storage. The CO_2 is being captured from the fermentation process used to produce ethanol at an industrial corn processing complex in Decatur, Illinois, in the United States. The goals of the project are to design, construct, and operate a new CO_2 collection, compression, and dehydration facility capable of delivering up to 2,000 tonnes of CO_2 per day to the injection site; to integrate the new facility with an existing 1,000 tonnes of CO_2 per day compression and dehydration facility to achieve a total CO_2 injection capacity of 3,000 tonnes per day (or one million tonnes annually); to implement deep subsurface and near-surface MVA of the stored CO_2; and to develop and conduct an integrated community outreach, training, and education initiative.

Recognized by the CSLF at its Perth meeting, October 2012

27. 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

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28. 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

29. 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

30. 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

31. 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 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

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32. 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

33. 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

34. 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

35. 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

36. South West Hub Geosequestration Project
Nominators: Australia (lead), United States, and Canada
This is a large-scale project that will implement a large-scale "CO_2 Hub" for multi-user capture, transport, utilization, and storage of CO_2 in southwestern Australia near the city of Perth. Several industrial and utility point sources of CO_2 will be connected via a pipeline to a site for safe geologic storage deep underground in the Triassic Lesueur Sandstone Formation. The project initially plans to sequester 2.4 million tonnes of CO_2 per year and has the potential for capturing approximately 6.5 million tonnes of CO_2 per year. The project will also include reservoir characterization and, once storage is underway, MMV technologies.
Recognized by the CSLF at its Perth meeting, October 2012

37. 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

38. 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

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

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Carbon Sequestration Leadership Forum

www.cslforum.org

CSLF Strategic Plan

Second Update

2011-2016

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1. INTRODUCTION

This is the Second Update of the CSLF Strategic Plan. The CSLF Strategic Plan was initially prepared in 2004 and was updated in 2009. The 2009 update set out a strategy to carry the CSLF through June 2013, when the CSLF Charter was then set to expire. In preparation for the expected extension of the term of the CSLF beyond 2013 at the 2011 Ministerial in Beijing, this Second Update to the Strategic Plan provides a strategy for the CSLF through 2016, three years beyond the original expiration date of the CSLF Charter.

One additional major change to the Charter that will affect the strategy and activities of the CSLF is anticipated at the Beijing Ministerial: the focus of the CSLF is expected to be broadened from Carbon Capture and Storage (CCS) to Carbon Capture, Utilization and Storage (CCUS). This broadening recognizes that beneficial reuse is another potentially viable option for captured carbon dioxide (CO_2). Beneficial reuse includes a range of applications for CO_2, including Enhanced Oil Recovery (EOR, already envisioned in CCS), chemical and food production, as well as other uses. In some cases of these applications – many EOR projects, for example – captured CO_2 would be a replacement for natural sources of CO_2.

The technical, economic and institutional landscape for CCUS has changed since 2009 and this also needs to be reflected in the new strategy. Considerable progress has been made on the technology and practice of CCS and the world stands ready to build and operate many industrial-scale, fully-integrated CCS projects, potentially exceeding the 20 projects by 2020 called for by the CSLF and International Energy Agency in 2007. On the other hand, the economic downturn in many countries, the large investments required, and a continuing lack of public understanding have presented major hurdles to these projects and a number of them have been cancelled. A major challenge facing the CCUS community is to bring enough diverse industrial-scale integrated projects into operation with adequate information sharing to ensure that CCUS becomes widely commercial on a global scale by 2020. This will put a premium on international collaboration through the CSLF and other collaborative mechanisms.

Objective of this Update to the Strategic Plan

The objective of this Second Update to the CSLF Strategic Plan is to lay the groundwork for effective international collaboration through the CSLF on those activities necessary for CCUS to become widely commercial in both industrialized and developing countries. The Strategic Plan Second Update builds on the ongoing activities and demonstrated capabilities of the CSLF, takes into account the current global situation of CCUS, and is aligned with other international collaborations on CCUS.

Organization of this Update

The next section describes the framework under which this Update is being developed, including external and internal factors affecting the CSLF and defines the overall strategy. The sections following that describe the strategies and action plans of the three major organizational components of the CSLF: the Policy Group, Technical Group and Secretariat.

2. STRATEGIC FRAMEWORK AND STRATEGY

The development of a strategic plan for the CSLF requires understanding the objectives of the CSLF and how the external environment affects achievement of those objectives. It also requires understanding the organizational structure and strategic position of the CSLF. The strategic position consists of the current status of activities, as well as the strengths and weaknesses of the CSLF, its opportunities and threats, and its relationships to other organizations with similar goals. The strategy to achieve the objectives must then take into account the internal and external factors and take best advantage of the strategic position of the CSLF.

CSLF Objectives

The purpose of the CSLF, as stated in its Charter is:

- ✓ "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 carbon capture and storage.

This could include promoting the appropriate technical, political, economic and regulatory environments for the research, development, demonstration and commercial deployment of such technology."

External Environment

The major driver for CCUS is the need to reduce greenhouse gas emissions and, in particular, CO_2 emissions, coupled with the needs of Member countries for continued economic stability and growth, as well as energy security. The widespread global use of fossil fuels is projected to continue in large industrial and power generation facilities for decades to come. The broad abundance and low cost of fossil fuels, as well as the immaturity and high cost of alternatives, make large-scale switching from fossil fuels difficult in the near term. The use of fossil fuels must become more efficient and less carbon intensive. For many large fossil fuel power generation and industrial facilities, CCUS is the only method to substantially reduce CO_2 emissions.

The Potential Role of CCUS

The potential global role that CCUS could play in emission reduction was shown in a recent study by the International Energy Agency (IEA), the results of which are shown in Figure 1. This study projects that CCS in the power and industrial sectors is needed to achieve 19 percent of the emission reduction required to keep CO_2 concentrations in the atmosphere below 450 parts per million. This is the level above which the Intergovernmental Panel on Climate Change (IPCC) concluded average temperatures would rise by 2^{o}C, causing serious climate impacts. According to more recent analyses by the IEA, however, the "Prospect of limiting the global increase in temperature to 2ºC is getting bleaker" as increases in CO_2

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emissions and atmospheric concentrations continue to rise to record levels. [1] All this makes the need for rapid deployment of CCUS increasingly vital.

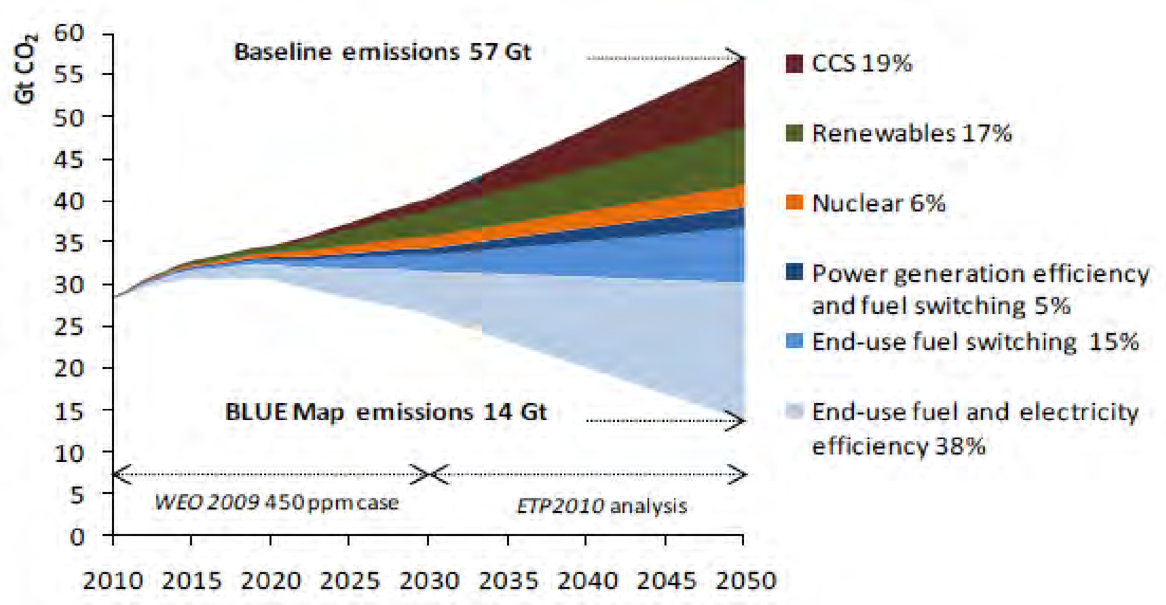

Figure 1. CO_2 Emission Reduction by Type in an Emission Reduction Scenario

Source: International Energy Agency, "Energy Technology Perspectives 2010: Scenarios and Strategies to 2050," Paris: OECD/IEA 2010.

Utilization of CO_2 (the expected new area under the CSLF Charter), especially for EOR, would improve the economics of projects. CO_2 drive EOR is a well-established practice in some regions and has a broader potential worldwide. At the same time, other utilization applications have been relatively unexplored.

Trends since the 2009 Update

Three trends evident in 2009 have continued to influence the potential for CCUS and the work of the CSLF: continued progress on CCUS, economic challenges and still-unresolved international discussions.

Progress on CCUS technology is accelerating. Interest in CCUS technology has grown and the research community working on it continues to expand. The scope of CCUS research, development and demonstration activities has vastly increased throughout the world. The next step towards development and deployment of CCUS is to develop fully-integrated industrial scale demonstration projects. Many fully-integrated industrial scale demonstration and commercial facilities are now under development.

Economic challenges continue in North America and Europe and may reduce the financial resources available for capital-intensive activities such as CCUS, and the costs of major projects have been escalating. On the other hand, CCUS projects have been part of economic stimulus packages in some countries. The challenge of financing is particularly difficult in developing countries.

[1] http://www.iea.org/index_info.asp?id=1959, accessed June 5, 2011.

International discussions are continuing through the United Nations Framework Commission for Climate Change (UNFCCC) on the arrangements to the second commitment period to the Kyoto Protocol. The status of CCS as a domestic mitigation policy is well accepted, but the debate continues over the use of CCS in the Clean Development Mechanism (CDM).

Barriers to CCUS

While great progress has been made, significant barriers to CCUS remain. These barriers are summarized in Table 1. Barriers 1 through 5 are policy related while barriers 6 through 14 are technical. Nearly all have economic aspects. This table is very general and the barriers, especially policy barriers, vary by country. More work remains to address each of these barriers. International collaboration through the CSLF, other international organizations and bilateral efforts can help address these barriers and speed up overcoming them.

International Collaborations

CCUS research, development and demonstration (RD&D) activities, as well as efforts to develop the institutions for CCUS, are being conducted by many CSLF Members and in some non-Member countries. Several jurisdictions also have economic incentives for CCS. In addition to the CSLF, several other international organizations also work to advance CCS:

- The International Energy Agency (IEA) has undertaken a broad array of efforts to further CCS. Some of these are the responsibility of its Working Party on Fossil Fuels; others are carried out by the IEA Secretariat. Two IEA Implementing Agreements are particularly focused on CCS:

  - The IEA Greenhouse Gas R&D Programme (IEA GHG) is an international research collaboration which studies and evaluates technologies that can reduce greenhouse gas emissions derived from the use of fossil fuels. The major focus of the IEA GHG is on CCS.

  - The IEA Clean Coal Centre is a research organization for clean coal technologies. Much of its recent work has focused on CCS in coal-based facilities.

- The Global Carbon Capture and Storage Institute (Global CCS Institute) was launched in 2009 to accelerate the deployment of CCS technologies through 20 fully integrated industrial-scale demonstration projects by 2020. The Global CCS Institute has committed to work collaboratively with the IEA, the CSLF and other CCS organizations.

- At the second Clean Energy Ministerial in April 2011, Energy Ministers from around the world agreed to take action based on the recommendations of the CCUS Action Group (a CEM initiative) to accelerate the global deployment of CCUS technologies.

- Multilateral development banks, such as the World Bank and Asian Development Bank, are starting to include CCS in their activities. The World Bank conducts capacity building activities on CCS and both the World Bank and the Asian Development Bank are exploring financing of CCS in developing countries.

Table 1. Barriers to Development and Deployment

Barrier	Progress to Date	Current Situation
1. Inadequate legal/ regulatory frameworks	• Various jurisdictions have enacted legislation and regulations for CCS.	• Not all jurisdictions have enacted frameworks • Gaps in legal/regulatory frameworks remain
2. Gap in commercial financing	• Financial incentives have been enacted for demonstration projects in some jurisdictions.	• Except in certain niche markets or for demonstrations with large government incentives, commercial financing is unavailable.
3. Need for human and institutional capacity	• Initial efforts are being made in both industrialized and developing countries.	• Longer-term, more extensive efforts are needed. • Capacity building in developing countries relies on international collaboration.
4. Lack of public awareness, understanding and support.	• Some efforts to create public awareness of CCS, but much less than other greenhouse gas abatement measures.	• Public awareness of the need for CCS, how it works, and its safety remains limited. • Misperceptions abound.
5. Inadequate international frameworks	• CCS is included in London Convention and Protocol.	• London Protocol not ratified so cross-border CO_2 shipments not yet legal. • CCS is not included in international carbon trading mechanisms, but progress is now more likely.
6. Few industrial-scale integrated projects	• Only a few in operation, none in power generation	• Many projects are in various stages of development.
7. High capture cost	• R&D and pilot projects have made some progress.	• Capture costs are still too high. • Cost escalation is a concern. • Only some capture options addressed. • Industrial-scale projects needed.
8. High energy penalty	• Various options are being explored.	• Energy penalty is still too high. • Industrial scale projects are needed.
9. Limited work on capture from industrial sources	• Efforts in this area are limited.	• Significant work is just beginning.
10. Limited work on CO_2 utilization	• Efforts in this area are limited.	• Significant work is just beginning.
11. Lack of CO_2 transport infrastructure	• Transport from sources to storage is mandatory.	• CO_2 pipelines are commercial for EOR, not geologic storage. • Plans for networks being developed. • Ocean transport is not yet developed.
12. Limited geologic storage experience	• Many smaller-scale injections have been conducted. • Enhanced oil recovery (EOR) is widely used in some regions.	• Multiple large-scale injections in diverse formations are beginning.
13. Need to estimate storage capacity and demonstrate storage integrity	• Various regional and national storage capacity estimates have been made. • CSLF has developed storage capacity estimate standards. • Some projects experience has been gained.	• Considerable progress has been made but regional and national numbers could be improved. • More and diverse project experience widely disseminated would enable widespread deployment.
14. Storage assurance and risk management tools need further development	• Measurement, monitoring and accounting (MMA) practices and protocols have been developed. • Risk analysis techniques have been developed.	• More experience with MMA and risk management is needed. • Linkage between technical risk and legal/financial liability is not clear.

In addition to the international organizations listed above, a number of regional cooperative ventures on CCS are also being implemented. The European Commission aims to achieve 12 up-to-commercial-scale demonstration projects by 2020 across a range of technologies and, within the EU, CCS project network, six demonstration projects already actively exchange information. The Regional Carbon Sequestration Partnerships in the United States and Canada (a CSLF-recognized project) are conducting numerous regional studies. Similarly, the Asia Pacific Economic Cooperation has sponsored several studies on CCS. Each of these activities has also involved collaboration between the public and private sectors.

While not specifically focused on CCS, the Intergovernmental Panel on Climate Change (IPCC) provides an objective source of information about climate change initiatives through assessment on a comprehensive, objective, open and transparent basis, of the latest scientific, technical and socio-economic literature produced worldwide. The IPCC has published a Special Report on Carbon Capture and Storage (2005), updated the inventory guidelines for CCS (2007), and recognized CCS as an important greenhouse gas abatement technology in its Fourth Assessment Report (2008).[2]

CSLF Organizational Structure

The basic organization of the CSLF is defined in the CSLF Charter as consisting of a Policy Group, a Technical Group and Secretariat. The responsibilities of each of these are delineated in more detail in the CSLF Terms of Reference and Procedures. (See text box.)

Most of the ongoing substantive work of the CSLF takes place in task forces reporting to either the Policy Group, the Technical Group or both, all supported by the CSLF Secretariat. Task forces are created, modified or disbanded, as needed, by the decisions of the Policy Group or Technical Group and are chaired by Members of the CSLF. Participation in the task forces is voluntary and generally consists of experts in the subject matter of the task force. Participation is open to representatives of CSLF Members and, with the permission of the Task Force Chair, to Stakeholders. Numerous expert Stakeholders participate in CSLF task forces. Currently, there are 13 task forces. Of these, four report to the Policy Group, seven report to the Technical Group and two reports to both the Policy Group and Technical Group. Several new task forces are envisioned by this updated Strategic Plan. One Technical Group Task Force, the Task Force to Assess Progress on Technical Issues affecting CCS, has several working groups in specialized areas reporting to it.

The current organizational structure of the CSLF is shown in Figure 2.

Strategic Position

The strategic position of the CSLF is determined by the status of its ongoing activities, its strengths and weaknesses and the opportunities and threats it faces.

Status of CSLF Activities

Both the CSLF Policy Group and Technical Group made significant progress in achieving the goals of the CSLF through various task forces established to address specific areas of concern.

[2] These reports are available at: http://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml

FROM THE CSLF TERMS OF REFERENCE AND PROCEDURES

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:

- 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.

1.3. Secretariat. 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.

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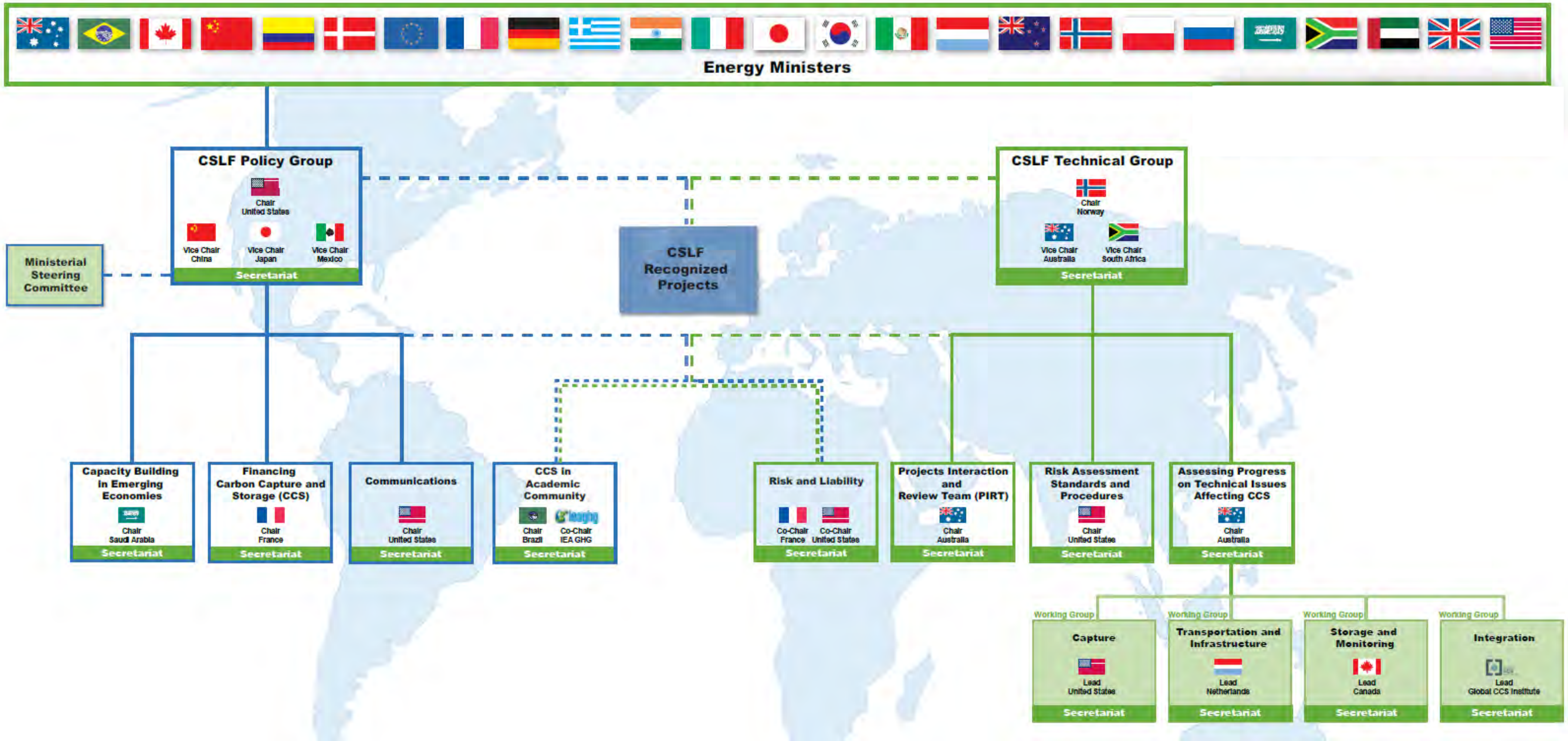
Figure 2. CSLF Organizational Chart



Since its inception, both the Policy Group and Technical Group have achieved notable successes that have advanced CCS, for example:

- Implementation of an international capacity building program on CCS;
- Definition of storage site selection criteria;
- Methodology for estimating storage capacity;
- Definition of legal and regulatory issues; and
- Recommendations (with the IEA) on CCS to the G8.

Tables 2 and 3 provide an overview of the achievements and current status of CSLF activities for the Policy Group and Technical Group, respectively. In one achievement involving both Groups, the CSLF has recognized 31 major international projects that advance the state-of-the-art of CCS, each of which makes information publicly available on a global basis. Nine of those projects have been completed.

While much progress has been made, moving CCUS forward will require global cooperation on an unprecedented scale. This cooperation is needed to meet the challenges of advancing the technology, to reduce costs, to engage developing countries, and to collaborate with the private sector to deploy this technology.

Strengths, Weaknesses, Opportunities and Threats (SWOT) Analysis

The CSLF's strengths, weaknesses, opportunities and threats remain those identified when this analysis was first performed in 2009 for the first update of the CSLF Strategic Plan. A number of changes since 2009 are indicated in **bold**.

- Strengths: The CSLF has demonstrated several key strengths. Foremost, is that the CSLF has demonstrated global convening power, both to facilitate information exchange on CCS and to bring together experts from around the world to address common problems such as developing standards for risk assessment and storage capacity estimates. CSLF reports are recognized as authoritative reference works worldwide.
- The CSLF is an organization of national governments.
- CSLF Members represent a large portion of the world's energy supply and demand and represent both industrialized and developing countries.
- The participation of developing countries, in particular, is a unique strength. Until the recent formation of the Global CCS Institute, the CSLF was the only international organization focused solely on CCS.
- Stakeholders participate in its task forces and activities.
- **The scope of the CSLF is expanding to include utilization.**
- **The first funded project of the CSLF (capacity building) sets a precedent for further funding of projects.**

These characteristics make the CSLF a unique forum for ongoing collaboration on CCS.

Table 2. CSLF Policy Group Accomplishments and Their Status

Accomplishment	Significance	Status
1. CSLF Strategic Plan 2004, 2009 Update and 2011 Update	• The Strategic Plan represents consensus of the Members on future activities.	• Strategic Plan has been agreed upon by the Members. • The term of the CSLF Charter is anticipated to be extended indefinitely beyond 2013 at the 2011 Ministerial.
2. Recommendations to the G8	• These recommendations form the basis for activities to advance CCS throughout the world.	• In response to the G8, the CSLF and IEA made recommendations on how to advance CCS in near-term applications.
3. Progress towards a financing approach	• Financing is a major constraint on CCS, in both industrialized and developing countries.	• Work is ongoing. Several workshops on financing have been held and a Task Force continues work in this area.
4. Communications on CCS	• Public understanding is critical to CCS deployment.	• Public outreach materials for use by Members have been developed. • Daily email news on CCS is provided to CSLF Member and Stakeholders.
5. CSLF capacity building initiative	• This is a major demonstration of commitment to developing country Members.	• Six capacity building workshops have been held so far in four countries. Each has received enthusiastic response from participants and expressions of interest for more. • The CSLF Capacity Building Fund was established with approximately $3 million in commitments. • Nine projects in five countries are currently underway using the Fund and more are under consideration. • CSLF Collaborates with World Bank and Global CCS Institute.
6. Guidelines for legal-regulatory frameworks	• Legal and regulatory frameworks are necessary to CCS deployment.	• Worked with IEA to hold two workshops. • Developed guidelines which accelerated consideration of legal and regulatory framework. • By agreement, IEA has lead in further work in this area.
7. CCS in the academic community	• The academic community needs to teach and conduct advanced research on CCUS.	• Surveyed academic programs on CCS in North and South America and Europe; many programs were identified.
8. Project recognition	• This provides a basis for information sharing on 31 of the most important projects throughout the world covering all aspects of CCS.	• Projects report progress regularly to the CSLF. • Completed projects have already created the basis for later projects to build on their findings.

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Table 3. CSLF Technical Group Accomplishments and Their Status

Accomplishment	Significance	Status
1. CSLF Technology Roadmap to identify and address gaps in R&D	• The CSLF Technology Roadmap reflects a consensus of leading international experts on the technical developments necessary to develop and deploy all aspects of CCS. • 2011 Roadmap emphasizes integration of complete value chain, needs to achieve commercial viability and global storage potential.	• The CSLF Technology Roadmap was first completed in 2004 and updated in 2009, 2010 and 2011. • The CSLF Technology Roadmap is widely accepted.
2. Technology Gaps Analysis	• Gaps analysis is a global consensus of experts on areas where further research, development and demonstration are needed.	• Outcomes have led to identification of a suite of future areas of activities. • Extensive gaps analysis activities are a continuing priority.
3. International standards for storage capacity estimates	• CSLF storage capacity estimation has gained international acceptance. • Methodology establishes a consistent basis for estimating, comparing and valuing geologic storage capacity for CO_2.	• This capacity estimation methodology has been developed on a theoretical basis by the foremost experts in the world.
4. Assessment and identification of gaps in MMV	• This assessment describes gaps in MMV technologies and practices where further R&D is required.	• Task Force report is complete. • Additional work to close identified gaps will require further study incorporating lessons learned from multiple projects.
5. Technical risk analysis	• Technical risk assessment is a key enabler of commercial deployment and public acceptance.	• Risk assessment standards and procedures examined. • Technical risks of injection and storage are being studied. • A Phase I Task Force report on risk identification and assessment has been completed.
6. Interactive information exchange	• Facilitates the exchange of technical information and real-world experience among project sponsors. • Knowledge sharing and information exchange will accelerate progress in commercialization of CCS technologies.	• An interactive forum has been successfully piloted with positive feedback from participants. • Planning for additional activities is underway.

As a voluntary organization of governments, the CSLF provides the basis for open discussions among governments and it does not impose the requirements of a funding organization.

Weaknesses: Being a voluntary organization, the CSLF has a limited internal budget and staffing resources. Also, it is not able to directly fund some of its outreach activities.

Opportunities: CCUS is now in transition from a largely experimental technology to a technology that is to be demonstrated at a commercial scale and will begin to be deployed commercially. Governments throughout the world can benefit from the open discussions and collaboration opportunities offered by the CSLF. Stakeholders can benefit from participation in the CSLF activities.

The precedent set by the CSLF Capacity Building Fund may indicate a way to overcome the weakness of the CSLF being a voluntary organization.

The two other international organizations with a major focus on CCS—the IEA and the Global CCS Institute—have complementary strengths. These provide the CSLF with the opportunities for cooperation that will greatly leverage its resources.

Threats: The primary threats faced by the CSLF are not threats to the CSLF as an organization, but rather the barriers—noted earlier—faced by CCUS as a greenhouse gas mitigation measure. Perhaps most important of those is that CCS is little known by the public and political decision makers. It is new and complex and, therefore, subject to considerable misunderstanding; it requires much more political championship globally.

Strategy

The CSLF will continue to provide an active forum for international collaboration to lower both policy and technical barriers to the development and widespread global deployment of CCS (or CCUS, given a widened mandate in a revised charter). The focus is in the areas in which the CSLF can provide the greatest value for its Members, including:

- Collaboration by experts from around the world to develop and improve policies, standards and procedures to be used by Members and make those more broadly available;
- Information exchange to accelerate or improve the policy development or technical progress of Members;
- Idea generation to advance CCUS for follow-up by Members individually or collaboratively;
- Capacity building in Member countries;
- Joint action to achieve mutual goals while reducing costs and accelerating progress; and
- Consensus facilitation in international policy discussions related to CCUS.

While remaining an organization of national governments, the CSLF invites the active involvement of non-governmental stakeholder experts to advance its initiatives.

The CSLF also works closely with other international organizations to advance CCUS, further broadening the scope and reach of international collaboration.

Action Plans to Implement the Strategy

Action Plans have been developed for future activities of the Policy Group, Technical Group and Secretariat. Each of these plans is designed to address a major challenge to the development and commercialization of CCUS or to facilitate the operation of the CSLF. There are a total of 22 Action Plans, six for the Policy Group, eleven for the Technical Group and five for the Secretariat. Each of the Policy Group and Technical Group Action Plans will be implemented by a task force. In some cases, these task forces have yet to be established.

Table 4 below enumerates these Action Plans. They are described in the following three sections.

Table 4. CSLF Strategy Action Plans 2011-2016

Action Plan	Priority
Policy Group Action Plans	
P1 – Bridging the Financing Gap	High
P2 – Financing Projects with CCS in Developing Countries	High
P3 – Incentives Registry	High
P4 – Capacity Building	Very High
P5 – Communications	High
P6 – CCS in Academic Community	High
Technical Group Action Plans	
T1 –Technology Gaps Closure	Very High
T2 – Best-practice Knowledge Sharing	High
T3 – Energy Penalty Reduction	Very High
T4 – CCS with Industrial Emissions Sources	High
T5 – Carbon-neutral and Carbon-negative CCS with Biomass	High
T6 – CO_2 Transport and Compression	High
T7 – Storage and Monitoring for Commercial Projects	Very High
T8 – Technical Challenges of using CO_2 EOR for CCS	Very High
T9 – Risk and Liability	Very High
T10 – CO_2 Utilization Options	Very High
T11 – Competition of Geologic Storage with Production of Other Resources	High
Secretariat Action Plans	
S1 – CSLF Administration	Very High
S2 – Administration of CSLF Capacity Building Program	Very High
S3 – Stakeholder Engagement	High
S4 – International Collaboration	High
S5 – Providing Information on CCS in International Negotiations	High

3. POLICY GROUP STRATEGY AND ACTION PLANS

Under the CSLF Charter, 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 Policy Group has developed Action Plans in four areas implemented by Task Forces that address the policy and institutional barriers identified in Table 1:

- Financing (Barrier addressed: gaps in commercial financing);
- Capacity Building (Barrier addressed: need for human and institutional capacity);
- Communications (Barriers addressed: lack of public awareness, understanding and support; and need for human and institutional capacity); and
- CCS in the Academic Community (Barrier addressed: need for human and institutional capacity).

Each area has one or more Action Plans as described below. The Policy Group also decides on recognition of projects recommended by the Technical Group.

Legal and regulatory frameworks have previously been addressed by the Policy Group in collaboration with the IEA. The CSLF has agreed that the IEA will take the lead in international collaboration in this area with the CSLF working with the IEA, as needed.

Financing

CCS technologies have a critical role in mitigating carbon emissions to achieve stabilization of atmospheric CO_2 concentrations. In order for this potential to be achieved, demonstration projects must make significant progress and the technology must then move from demonstration to commercial deployment. In moving to deployment, projects with CCS must earn revenues adequate to cover costs and attract private investment by offering competitive returns. A major difference between demonstration and commercial projects is that there are no commercial "CCS projects." Instead, commercial industrial projects and power plants with CCS must both produce output and raise capital competitively.

The CSLF and other organizations—in particular, the Asian Development Bank, IEA, and Global CCS Institute—have recently analyzed the potential to finance CCS in global markets. Identifying potential barriers to and opportunities for investment and funding to facilitate projects is recognized as the key issue for the deployment of CCS. In Europe, an analysis of CCS Costs by the Zero Emission Platform concluded that, following the European Union (EU) CCS demonstration program, post-demonstration CCS in the EU will be cost-competitive in the early 2020s with other sources of low-carbon power such as on- or offshore wind, solar power and nuclear (not including natural gas, currently priced well below $8/Million Btu).

In Financing Task Force activities, funding models in different parts of the world were presented by Alberta, Japan CCS, and several private companies (GDF-Suez, Conoco and Duke Power). Each model showed the value of adapting tools to regional strengths and weaknesses and project features in deploying projects with CCS.

The modeling showed that no single incentive was sufficient. The Task Force concluded that a suite of incentives and funding models are needed for governments to mobilize private investment capital. These must be tailored to regional attributes and development priorities (e.g., access to coal and fuels, power pricing, features of CCS sites, public attitudes, competing supply). The Task Force further concluded that the CSLF should support member countries in developing a "toolkit" of approaches and funding models that offers multiple combinations of incentives, which are negotiated.

Action Plan P1: Bridging the Financing Gap

Responsibility: Financing Task Force

Given global turmoil in credit markets since 2008, this activity will be ongoing. Similarly, lack of progress in negotiating a global climate regime under UNFCCC requires that alternative approaches be developed. Such approaches would complement any resolutions that emerge from UNFCCC or from other high level forums such as G20. In the absence of cap and trade, other funding approaches for financial incentives must be explored.

Action: The CSLF will explore through the Financing Task Force, and in collaboration with other organizations, the most effective way to overcome the gap between the costs and incentives available for CCS, in the absence of adequate prices for GHG savings (carbon prices), in order to accelerate early deployment of CCS. It will engage with the financial community and develop a financing roadmap and multiple options or approaches based on case studies of project successes and failures. To the extent that it is available and appropriate, analyses will be conducted using a financial analysis model of CCS currently being developed by the World Bank.

Outcome: Identification and evaluation of a suite of policies that governments could use to promote to facilitate private investment in industrial projects with CCS.

Milestones:

Assembly of project case studies (with IEA, Global CCS Institute)	***Dec. 2011***
Ongoing engagement (or interviews) of financial community	***2012***
Outline of options and approaches (modified CSLF Financing Roadmap)	***Summer 2012***
Updates	***2013-2015***

Priority: High

Action Plan P2: Financing Projects with CCS in Developing Countries

Responsibility: Financing Task Force working with Asian Development Bank

Due to their size and technical complexity, projects with CCS fundamentally involve international financing and engineering; no single country possesses all needed technologies. Progress in developing countries will entail many of the same engineering firms and key vendors as those in OECD countries. That experience is essential to commercial progress worldwide, and needs to be exchanged among CSLF Members.

Action: Update perspectives and investment outlook from industry, capital sources, and Stakeholders by interviews and attending other forums on the framework of risks and rewards for commercial deployment of projects with CCS in developing countries and potential financing approaches for those projects.

Work with World Bank, Asian Development Bank, key countries on financing options for projects with CCS in emerging economies. Participate in multilateral financing fora.

Outcome: Report by the CSLF Financing Task Force

Milestones: Report from the Task Force. ***Summer 2012***

Priority: High

Action Plan P3: Incentives Registry

Responsibility: CSLF Secretariat

Action: The CSLF will update and publish its Incentive Registry and maintain its currency through the CSLF Members**.**

This database will provide information on the types of incentives available to commercial projects with CCS. The data will be displayed at national and sub-national levels (e.g., country, state or province) including the type of incentive (e.g., capital subsidy, tax credit, feed-in tariff, etc).

The database will be prepared in cooperation with IEA and the Global CCS Institute.

Outcome: A searchable database that provides current information to interested parties

Milestones: Updated Registry ***2012 and Ongoing***

Priority: High

Capacity Building

The CSLF has conducted very successful capacity building activities since 2005. Deployment of CCS will require the building of skills and expertise, as well as creating institutional capability in both the public and private sectors. This will be a challenge for all CSLF Members, but especially developing country Members.

To achieve worldwide commercial deployment as early and effectively as possible it is critical that countries share their experience and know-how so each can enhance its own capacity to effectively deploy CCS.

The CSLF Capacity Building Program Plan, approved by the CSLF Policy Group and endorsed by Ministers in 2009, defines the mission of the CSLF Capacity Building Program as assisting all CSLF Members to develop the information, tools, skills, expertise and institutions required to implement CCS demonstrations and then move rapidly into commercial operation. The major focus of the Program is on meeting the needs of developing country Members, although all Members may participate in its activities.

The Program Plan further defines four Program initiatives:

- Disseminate practical information,
- Build capacity in emerging economies,
- Assist government and regulatory agencies, and
- Build academic and research institutions for CCS.

The capacity building activity is unique in that it is the only CSLF activity specifically funded by its Members. To this end, a CSLF Capacity Building Fund has been created with contributions of approximately US$3 million. In order to ensure proper management of the Fund, the Capacity Building Governing Council has been established to be responsible for the governance of the Fund.

The primary responsibility for capacity building concepts lies with the Policy Group Capacity Building Task Force. A country-driven approach to project identification and implementation has been developed to ensure responsiveness to the real needs of Members. Nine capacity building projects have been initiated to date using financial resources from the Fund and others may be initiated in the future. CSLF capacity building activities are coordinated with those of the World Bank and the Global CCS Institute.

Action Plan P4: Capacity Building

Responsibilities: Capacity Building Task Force
Capacity Building Governing Council (for the Fund)
Secretariat (day-to-day activities)

Action: The CSLF will continue to develop, implement and maintain a capacity building program tailored to the needs of each Member, subject to available resources. In addition, the Secretariat, under the direction of the Capacity Building Task Force and Governing Council Chairs, will be charged with the responsibility to carry out the day-to-day activities required to coordinate and execute the Capacity Building Program, including:

- Implement capacity building projects,
- Seek funding for capacity building activities,
- Ensure that information developed is effectively disseminated.

Outcome: Building of capacity in CSLF Members is responsive to their expressed needs.

Dissemination and sharing of information is effective.

Milestones:

Possible selection of additional projects	***2011***
Evaluation of lessons learned from first projects Report and Workshop	***Summer 2012***
Funding obtained and second round of projects	***Fall 2012***
Further rounds of funding and projects	***Annual***

Priority: Very High

Communications

Public awareness and acceptability for CCS falls into two areas: The global aspects of CCS as an important mitigation technology; and the local aspects of developing transportation and storage projects.

The CSLF will continue to focus on the global aspects of CCS as an important mitigation technology, rather than the development of storage projects locally. Project acceptability will be highly dependent on local conditions, which could be significantly different among locations. Individual CSLF Members, project developers and others are best suited to doing local outreach.

CSLF communications activities will continue to include the development of tools and informational materials that can be used by the CSLF and Member representatives, organizations such as the IEA and the GGCSI, Stakeholders (industry and NGOs), policy makers, regulators and project developers in order to promote the positive aspects of CCS.

Action Plan P5: Communications

Responsibility: Policy Group Communications Task Force

Action: Communications Task Force to continue refining an overall CSLF Communications Plan that includes the development of new materials and update of existing materials for CCS public awareness on the global aspects of CCS as an important mitigation technology. Annex 1 presents more detail on planned Communications activities.

Outcome: The visibility of both the CSLF and CCS as a viable technology is raised and key stakeholders and audiences are engaged with timely information.

Milestones:

Web site development/updating	***Ongoing***
Members identify CSLF spokespersons	***Ongoing***
Prepare calendar of CCS events	***Ongoing***
Communications vehicles/talking points	***Ongoing***
Communications materials/standard speech	***Ongoing***
Communications materials/PowerPoint presentation	***Ongoing***
Identify conference/speaking venues	***Ongoing***

Priority: High

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CCS in the Academic Community

Academic experts and institutions are necessary to conduct much of the research to develop CCS technologies and to educate future CCS experts and practitioners. Recognizing this, a Task Force was created in 2009 to develop contacts within the academic community, identify academic perspectives and programs on CCS for universities in CSLF Member countries, and determine the path forward for the CSLF in this area.

The Task Force is now reaching completion of Phase I activities, marked by the finalization of the first combined report on existing academic CCS programs and the CSLF development of a dedicated Bulletin Board as a forum for academic discussion. Once the first Phase has been finalized, the second Phase will begin with an analysis of the survey report and collation into a database to be made available to academics; and further gap analysis will further identify where CSLF could target future activities. One such future activity for the Task Force would be to investigate an exchange program for university professors in CCS curricula to enhance collaborations, strengthening the CCS network and information exchange within the academic community.

Following gap analysis of existing CCS programs, should it prove a priority, it will be possible to explore key areas which CSLF may wish to develop and enhance through strategic course material for CSLF Members. The Task Force may also consider the progress of CCS in academia, the growth of graduate students to assist decisions and targeting of investment, and dedicated meetings to provide a forum with academic institutions. The Task Force will align its activities with the Capacity Building Task Force.

Action Plan P6: CCS in the Academic Community

Responsibility: Task Force on CCS in the Academic Community
(This is a joint responsibility of the Policy Group and Technical Group.)

Action: The CSLF will identify and review the international development of academic CCS programs, encourage academic student/researcher collaboration, performing gap analysis to target future activities whilst enhancing the developments of strategic curricula for graduate and post-graduate programs.

Outcome: Programs are identified and catalogued. Academic network developed. Proposals for curricula developed.

Milestones:

First report on existing CCS programs	**September 2011**
Update of report on CCS programs	**Ongoing**
Analysis of CCS programs and collation into database	**March 2012**
Database available to academics	**December 2012**
Gap Analysis to identify curricula proposals	**2013**
Proposals for CSLF curricula	**2013**
Implementation of curricula proposals	**2014**
Dedicated report of activities	**2015**
Review Task Force activities	***Ongoing***

Priority: High

4. TECHNICAL GROUP STRATEGY AND ACTION PLANS

According to the CSLF Charter the CSLF Technical Group "reviews the progress of collaborative projects, identifies promising directions for the research, and makes recommendations to the Policy Group on needed actions." Specific responsibilities are delineated in the CSLF Terms of Reference and Procedure (Text Box, page 7).

The Technical Group's strategy has Action Plans in five broad areas which address the technical barriers identified in Table 1:

- Advancing Technical Collaboration (Barriers addressed: all technical barriers);
- Capture (Barriers addressed: high capture cost, high energy penalty, and limited work on capture from industrial sources and CO_2 utilization);
- Transport (Barrier addressed: lack of CO_2 infrastructure);
- Storage and Utilization (Barriers addressed: limited geologic storage experience, need to estimate storage capacity and demonstrate storage integrity, and storage assurance and risk management tools need further development); and
- Understanding the Impacts (Barrier addressed: storage assurance and risk management tools need further development).

In addition to work on these Action Plans, the Technical Group recommends projects to the Policy Group for recognition.

Advancing Technical Collaboration

The Technical Group will continue and expand its efforts to advance technical collaboration among its Members and Stakeholders. The keystones guiding these efforts are the CSLF Technology Roadmap and Technology Gaps Analyses. Both are vital methods of identifying areas of CCUS development that can be addressed through international collaboration or can be taken up by CSLF Members or Stakeholders.

Industrial-scale integrated projects will be going into operation in various parts of the world in the next several years, particularly in power generation. This makes the need for best-practice knowledge sharing even more important.

Action Plan T1: Technology Gaps Closure

Responsibility: Task Force on Assessing Technical Issues that Affect CCS

Action: The Technical Group will identify and monitor key CCS technology gaps and related issues and recommend any RD&D 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.

Milestones:

Review of CCS technology gaps and related issues	***Yearly***
Update of CSLF Technology Roadmap (Module 3)	***Yearly/Biannually***

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Thematic reports on the status of CCS technology gaps/issues ***TBD 2012-2016***

Priority: Very High

Action Plan T2: Best-practice Knowledge Sharing

Responsibility: Projects Interaction and Review Team

Action: The Technical Group will facilitate the sharing of knowledge, information, and lessons learned from CSLF-recognized projects and other CCS RD&D.

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

Milestones:

Thematic interactive projects "lessons learned" workshops	***TBD 2012-2016***
Update of CSLF Technology Roadmap (Modules 1, 2, and 4)	***Yearly***
Thematic reports on lessons learned	***TBD 2012-2016***
Development of interactive "lessons learned" references (jointly with Communications Task Force)	***TBD 2015-2016***

Priority: High

Capture

A large amount of energy is required in most capture technologies to separate carbon dioxide from other gas streams and compress it for geologic storage. This energy penalty adds significantly to the cost of capture and reduces the effectiveness of the capture. Reducing the energy penalty would improve both the technical and economic viability of capture.

As much as half of the potential emission reductions from CCUS are estimated to be from industrial process sources other than power generation or natural gas separation. Industrial applications for CCUS vary widely and, in some industries, CCUS is the only significant carbon abatement option. Yet, industrial sources have received far less attention than power generation and relatively few proposed demonstration projects involve industrial sources.

Combining CCUS for energy production with sustainably-grown biomass has the potential to be either carbon neutral or carbon negative in facilities where the biomass is either the sole feedstock or, in adequate proportions, is a co-feedstock with fossil fuels. The opportunities and constraints need to be better understood.

Action Plan T3: Energy Penalty Reduction

Responsibility: Technical Group/New Task Force or Working Group

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.

Milestones: Workshop to document knowledge and experiences of "early mover" projects — ***TBD 2013***
Report on successful trends and breakthroughs — ***TBD 2014***

Priority: Very High

Action Plan T4: CCS with Industrial Emissions Sources

Responsibility: Technical Group/New Task Force or Working Group

Action: The Technical Group will document the progress and application of CCS for industrial emissions sources and will identify and recommend 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

Milestones: Technology workshops on CCS for industrial sources — ***TBD 2013-2016***
Outreach activities for CO_2-intensive industries — ***TBD 2012-2016***
Reports on progress and issues unique to CCS with industrial sources — ***TBD 2013-2016***

Priority: High

Action Plan T5: Carbon-neutral and Carbon-negative CCS with Biomass

Responsibility: Technical Group/New Task Force or Working Group

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.

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

Milestones: Biomass CCS technical workshop — ***TBD 2013***
Interim Report — ***TBD 2014***
Final Report — ***TBD 2015***

Priority: High

Transport

A number of CO_2 pipelines are already in operation and many others are likely to be planned and built. It is important for governments, pipeline developers and operators and affected stakeholders to set appropriated standards for the construction, operation and maintenance of such standards.

Action Plan T6: CO_2 Transport and Compression

Responsibility: Technical Group/New or Existing Task Force or Working Group

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.

Milestones:	CO_2 transport workshop	***TBD 2014***
	Interim Report	***TBD 2015***
	Final Report	***TBD 2016***
Priority:	High	

Storage and Utilization

Geologic storage and monitoring will need to meet standards in order to assure their safety and effectiveness. Such standards will affect the design and operation of projects, as well as their financial viability. Regulations that set such standards have been implemented or proposed in a number of jurisdictions and "best practices" have been recommended based on prior research.

Injection of CO_2 for Enhanced Oil Recovery (EOR) has been practiced for decades and may be an early geologic storage application. EOR practices may be different from geologic storage, for example, in the recycling of CO_2.

Considerable technical research has been conducted by geologists on the risks of geologic storage. Yet, from the perspective of a developer of a geologic storage project, the concerns are not limited to just physical impacts; the potential for financial liability is also a concern and the linkage between the two is often unclear.

The mandate of the CSLF Charter is being expanded from CCS to CCUS. This raises questions that need to be explored about what the opportunities are for utilization.

Action Plan T7: Storage and Monitoring for Commercial Projects

Responsibility: Technical Group/New or Existing Task Force or Working Group

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

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

Milestones:	Interim Report	***TBD 2015***
	Final Report	***TBD 2016***

Priority: Very High

Action Plan T8: Technical Challenges for Converting CO_2 EOR Projects to CCS

Responsibility: Technical Group/New Task Force or Working Group

Action: The Technical Group will determine technical and economic factors that can affect Enhanced Oil Recovery (EOR) that are also used for geologic storage of CO_2.

Outcomes: Identification and recommendation of permitting, monitoring, and reporting requirements for CO_2 EOR projects that apply for CO_2 credits.

Milestones:	Interim Report	***TBD 2014***
	Final Report	***TBD 2015***
Priority:	High	

Action Plan T9: Risk and Liability

Lead: Risk Assessment Task Force (or participation in new joint Policy-Technical Task Force)

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

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

Milestones:	Risk and liability workshops	***TBD 2013-2014***
	Thematic report with proposed guidelines	***TBD 2015***

Priority: Very High

Action Plan T10: CO_2 Utilization Options

Responsibility: Technical Group/New Task Force or Working Group

Action: The Technical Group will investigate CO_2 utilization options.

Outcomes: Identification of most economically attractive CO_2 utilization options.

Milestones:	Interim Report	***TBD 2013***
	Final Report	***TBD 2014***

Priority: Very High

Understanding the Impacts

Each component of CCS—capture, transport and geologic storage—has the potential to compete for valuable resources such as land, water and pore space with other uses, for example, hydrocarbon production or other water or land uses. What is the nature of this potential competition? Where does it occur? How can it be minimized?

Action Plan T11: Competition of Geologic Storage with Production of Other Resources

Responsibility: Technical Group/New Task Force or Working Group

Action: The Technical Group will examine criteria for assessing competing development priorities between CCS (particularly CO_2 storage) and other economic resources.

Outcomes: Identification and recommendation of criteria for determining relative economic viability of CO_2 storage sites.

Milestones:

Interim Report	***TBD 2014***
Final Report	***TBD 2015***

Priority: Very High

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5. SECRETARIAT STRATEGY AND ACTION PLANS

The CSLF Charter states that, "The principal coordinator of the CSLF's communications and activities will be the CSLF Secretariat. The Secretariat will: (1) organize the meetings of the CSLF and its sub-groups, (2) arrange special activities such as teleconferences and workshops, (3) receive and forward new membership requests to the Policy Group, (4) coordinate communications with regard to CSLF activities and their status, (5) act as a clearing house of information for the CSLF, (6) maintain procedures for key functions that are approved by the Policy Group, and (7) perform such other tasks as the Policy Group directs. The focus of the Secretariat will be administrative. The Secretariat will not act on matters of substance except as specifically instructed by the Policy Group."

Pursuant to this mandate, these responsibilities fall into three areas:

- CSLF Administration,
- Stakeholder Engagement, and
- Collaboration with Other International Organizations.

CSLF Administration

This involves carrying out the administrative duties as set out by the CSLF Charter, as well as the administration of the CSLF Capacity Building Program.

Action Plan S1: CSLF Administration

Responsibility: CSLF Secretariat

Action: Conduct the day-to-day business of the CSLF.

Outcome: Administration of CSLF activities proceeds smoothly.

Milestones:

Support to and conduct of all CSLF meetings	***Ongoing***
Support to Policy Group, Technical Groups and Task Force Chairs	***Ongoing***
Coordination of activities	***Ongoing***
Member communications	***Ongoing***
Preparation of CSLF documents	***As needed***
Membership applications	***As needed***
Strategic Plan Implementation Report	***Quarterly***
Administration of Capacity Building Fund	***Ongoing***
Strategic planning coordination	***2011***
Other duties as assigned by the Policy Group Chair	***As needed***

Priority: Very High

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Action Plan S2: Administration of CSLF Capacity Building Program

Responsibility: CSLF Secretariat

Action: Conduct day-to-day business of the CSLF Capacity Building Program.

Outcome: Progress is made building the capacity of CSLF Members

Milestones:

Conduct needs assessments	***As needed***
Support project selection process	***As needed***
Support meetings of the Governing Council	***As needed***
Manage contractors on Capacity Building Projects	***As needed***
Manage the CSLF Capacity Building Fund	***Ongoing***
Financial Reports to the Policy Group	***Twice per year***

Priority: Very High

Stakeholder Engagement

CSLF Members recognize that significant Stakeholder involvement in the CSLF process is critical to attaining its goals and objectives. Stakeholders have participated in the CSLF since its inception by serving on Task Forces, and by providing resources for CSLF activities and input into the CSLF decision-making process. To achieve the CSLF strategic goals, it is expected that Stakeholders will play an increasing role in supporting the activities of the CSLF by serving on Policy and Technical Task Forces and providing expert views on major issues. Delivering industrial-scale CCS projects world-wide requires a central role for industry within the government-industry partnerships necessary to deliver these projects. In support of this, the CSLF will seek to facilitate greater interaction between CSLF Members and industry stakeholders. Other types of stakeholders are also critical to public acceptance and technology advancement.

The G8/IEA/CSLF workshops are a benchmark for Stakeholder engagement; therefore, the CSLF will implement that style of process more broadly. The CSLF will more effectively engage and draw upon the expertise of Stakeholders. To this end, the CSLF will undertake the following:

1. Ensure effective and efficient communication with Stakeholders to promote greater participation in CSLF activities;
2. Make facilities available for Stakeholders to hold a forum at each annual CSLF meeting, including Ministerial meetings;
3. Stakeholders, including those from non-CSLF Member countries, will continue to be encouraged to attend, participate and contribute to all Policy Group and Technical Group, Task Force and Ministerial Meetings.
4. A Stakeholder contact will be identified for each CSLF Member.
5. CSLF Members will encourage meetings with Stakeholders in their constituencies to inform and discuss with them CSLF and CCS issues.
6. Collaboration will continue with the IEA and Global CCS Institute on a calendar of events to be posted on the CSLF website.

Action Plan S3: Stakeholder Engagement

Responsibility: CSLF Secretariat/Policy Group

Action: The CSLF will more effectively engage and draw upon the expertise of Stakeholders.

Outcome: Greater Stakeholder participation and more robust CSLF products including wider acceptability and applicability.

Milestones:

Make facilities available for Stakeholders forum at each annual CSLF meeting, including Ministerial.	***Ongoing***
Stakeholders invited to all Policy Group and Technical Group and Task Force Meetings.	***Ongoing***
Stakeholder contact identified for each CSLF Member	**1 January 2010**
Collaborate with the IEA and Global CCS Institute on a calendar of events to be posted on CSLF website	**Ongoing**

Priority: High

Collaboration with other International Organizations

As noted earlier, a number of multilateral organizations now work to advance CCS and CCUS. Collaboration among these international organizations has the potential to improve the effectiveness of each and avoid duplication. The CSLF has a unique role internationally, which is as an organization of governments solely devoted to promoting CCUS globally, which gives it a unique perspective and enables it to work on a complementary basis with the other organizations.

The CSLF has collaborated with the IEA since the inception of the CSLF and with the Global CCS Institute since the inception of that organization. Other collaborations have taken place with the CCUS Action Group, the World Bank and the Asian Development Bank. Such collaborations will continue and be expanded.

Action Plan: S4 International Collaboration

Responsibility: CSLF Secretariat

Action: The CSLF will continue a formal, long-term working relationship with the IEA and Global CCS Institute, World Bank and other international organizations involved in CCS. The Global CCS Institute and the IEA will be invited to all CSLF events.

Outcome: A collaborative agreement identifies the lead and supporting roles of each organization; that each organization ensures that the others are invited to important meetings; and that there is a consistent exchange of information, ideas and developments on CCS.

Milestones:

Meet with the IEA and Global CCS Institute to ensure coordination and collaboration	***Ongoing***

Priority: High

Action Plan S5: Providing Information on CCS in International Negotiations

Responsibility: CSLF Secretariat

Action: Support the Members in advocating the inclusion of CCS in the post-Kyoto framework for climate change by facilitating the exchange of information on CCUS before the UNFCCC and in other fora relevant to the status of CCUS methods as a recognized approach for mitigation of greenhouse gas emissions.

Outcome: Members are effective in advocating inclusion of CCS in the post-2012 agreement

Milestones: Respond as requested to requests of the CSLF Policy Group. ***Ongoing***

Priority: High

Annex 1
Communications Task Force Strategy and Activities

Summary

As is evident in media coverage, high-level meetings, and public opinion, carbon capture and storage (CCS) is increasingly mentioned as a potential mitigation option for effectively reducing CO_2 emissions while contributing to the security of national energy supplies. Although this is a positive trend, the worldwide level of understanding about CCS, its technologies and potential is low to non-existent, emphasizing the importance of engaging opportunities for disseminating affirmative and useful information.

Studies indicate that exposure to information from experts increases stakeholder understanding and support for CCS technology. Even more importantly, the results also suggest that those who understand CCS tend to support its advancement. Ultimately, stakeholder communities can be potentially powerful advocates who can assist in communicating the benefits of CCS to strategic venues and media.

Through its significant role and mission in the international effort to minimize global CO_2 emissions and reduce the threat of potential climate change, the CSLF clearly should be in the forefront of efforts to educate stakeholders and constituent audiences about CCS technology. The organization's responsibility in this regard is articulated in the 2011 update of the CSLF Strategic Plan which, among its technical, political, and regulatory goals, includes the need to "address the barriers to public awareness and acceptance" and "engage stakeholders in the development and execution" of the plan's objectives.

In addressing these challenges, the Strategic Plan directs the CSLF to focus its communications and outreach efforts on the "global aspects of CCS as an important mitigation technology," since project acceptability will be highly dependent on local conditions that could differ greatly from location-to-location. A key to the CSLF successfully achieving this objective is an integrated and collaborative communications and outreach effort that effectively engages key stakeholders and audiences in a variety of ways with timely, interesting, and educational information.

In conveying the central message about CCS technology as a vital mitigation option, an effective and comprehensive outreach strategy and effort will also: Raise CSLF visibility and establish the organization as a credible source on CCS technologies and policies; Help extend public confidence in the viability of fossil fuel resources for meeting both increased future energy needs and concerns about CO_2's contribution to potential climate change; Promote efforts by the CSLF and its members to realize CCS's promise and potential.

An important point to note is the fact that the CSLF lacks a communications and outreach budget that would allow for a much more extensive and effective program. Therefore, the communications plan recommends activities aimed at marshalling the collective in-kind capabilities and existing communications vehicles of CSLF members and the Secretariat in a proactive manner in an attempt to bring about realization of the stated objectives.

Objectives of the Communications and Outreach Plan

The primary goals of the activities suggested are to:

- Raise CSLF visibility and communicate important CSLF-related information;
- Engage key stakeholders and audiences with timely information in an integrated effort;
- Achieve outreach objectives as identified in the CSLF Strategic Plan.

Key Components

To accomplish these goals, the communications plan suggests the organization and members use a variety of communications tools:

- Web Site – Continue to refine existing CSLF web site, build on strengths, continually improving functionality and content.
- Identifying and Deploying "Messengers" – Continue to identify "spokesperson" from each CSLF member nation.
- Creating Communications Vehicles – Develop new communications tools and materials and refine existing materials for the CSLF membership to help deliver consistent information and reinforce the CSLF identity.
- Maximizing Venue Use – Identifying on a country, regional, and international basis the most effective venues, meetings, and conferences for promoting CCS and the CSLF.
- Encouraging Media Coverage – Undertaking a proactive effort to engage trade and major media, locally, regionally, and internationally.
- Identify Strategic Partner Relationships – Create a list by members of potential "allies," both nationally and regionally, who can be engaged to leverage CSLF communications efforts.
- Making Adjustments – Conducting regular reviews of CSLF outreach efforts; make adjustments when necessary.
- Coordinate with other CSLF Task Forces as appropriate on outreach activities.

Key Activities

- Web Site Review/Updating
- Members Identify CSLF Spokespersons
- Communications Vehicles/Talking Points Preparation/Updating
- Communications Materials/Standard Speech Preparation/Updating
- Communications Materials/Power Point Preparation/Updating
- Identify Conference/Speaking Venues
- Media Initiatives/Develop Media Contact List
- Media Initiatives/Monitor CCS News Coverage
- Media Initiatives/Disseminating CSLF NewsAlerts
- Media Initiatives/Directing Media to Web Sites
- Media Initiatives/Creating Op-Eds
- Media Initiatives/Media Briefings
- Identify Strategic Partners
- Conduct Regular Reviews of Communications and Outreach Effort

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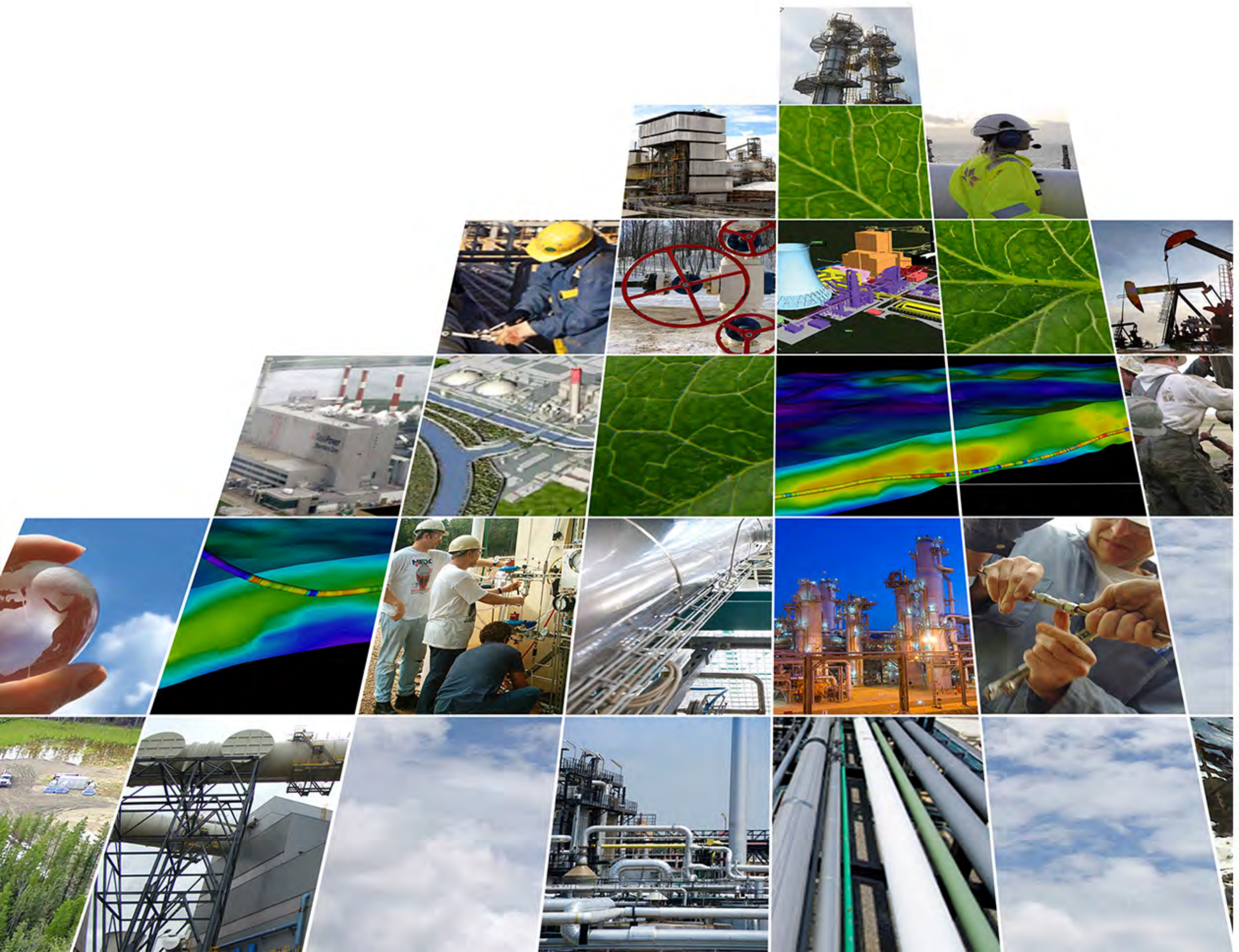
carbon sequestration leadership forum

2013

Carbon Sequestration

TECHNOLOGY ROADMAP



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Executive Summary

The CSLF has issued Technology Roadmaps (TRM) in 2004, 2009, 2010 and 2011. (The TRM 2011 updated only project and country activities, not technology.) This new TRM is in response to a meeting of the CSLF Technical Group (TG) in Bergen in June 2012. It sets out to answer three questions:

- What is the current status of carbon capture and storage (CCS) technology and deployment, particularly in CSLF member countries?
- Where should CCS be by 2020 and beyond?
- What is needed to get from point a) to point b), while also addressing the different circumstances of developed and developing countries?

The focus is on the third question. The TRM covers CCS in the power generation and industrial sectors. Carbon dioxide (CO_2) utilization, particularly in the near-term, is seen as a means of supporting the early deployment of CCS in certain circumstances and accelerating technology deployment.

The TRM is based on a 'status and gap analysis' document for CCS. The essence of the state-of-the-art summary was used to identify priority-action recommendations.

Key conclusions of the TRM are:

- First generation CO_2 capture technology for power generation applications has been demonstrated on a scale of a few tens of MW (in the order of 100,000 tonnes CO_2/year) and two large demonstration plants in the power generation sector (in Canada and the USA) are currently in the 'project execution' phase. Otherwise, CO_2 capture has been successfully applied in the gas processing and fertilizer industries.
- First generation CO_2 capture technology has a high energy penalty and is expensive to implement.
- There is a need to:
    - gain experience from large demonstration projects in power generation;
    - integrate CO_2 capture in power generation so that operational flexibility is retained;
    - identify and implement CO_2 capture for industrial applications, particularly in steel and cement plants; and
    - develop second and third generation CO_2 capture technologies that are designed to reduce costs and the energy penalty whilst maintaining operational flexibility as part of the effort to make CCS commercially viable.
- CO_2 transport is an established technology and pipelines are frequently utilized to transport CO_2 for Enhanced Oil Recovery (i.e., CO_2-EOR). However, further development and understanding is needed to:
    - optimize the design and operation of pipelines and other transport modes (e.g., improved understanding of thermodynamic, corrosion and other effects of impurities in the CO_2 stream; improve and validate dispersion models to address the case of pipeline failure and leakage; and advance the knowledge regarding CO_2 transport by ship); and
    - design and establish CO_2 collection/distribution hubs or clusters, and network transportation infrastructure.
- CO_2 storage is safe provided that proper planning, operating, closure and post-closure procedures are developed and followed. However, as demonstrated by three large-scale and many smaller-scale projects, the sites display a wide variety of geology and other *in situ*

conditions, and data collection for site characterization, qualification[1] and permitting currently requires a long lead-time (3-10 years). Identified research, development and demonstration (RD&D) actions need to:

- intensify demonstration of sizeable storage in a wide range of national and geological settings, onshore as well as offshore;
- further test to validate monitoring technologies in large-scale storage projects and qualify and commercialize these technologies for commercial use;
- develop and validate mitigation and remediation methods for potential leaks and up-scale these to commercial scale;
- further develop the understanding of fundamental processes to advance the simulation tools regarding the effects and fate of the stored CO_2; and
- agree upon and develop consistent methods for evaluating CO_2 storage capacity at various scales and produce geographic maps of national and global distribution of this capacity.

- There are no technical challenges per se in converting CO_2-EOR operations to CCS, although issues like availability of high quality CO_2 at an economic cost, infrastructure for transporting CO_2 to oil fields; and legal, regulatory and long-term liability must be addressed for this to happen.
- There is a broad array of non-EOR CO_2 utilization options that, when taken cumulatively, can provide a mechanism to utilize CO_2 in an economic manner. However, these options are at various levels of technological and market maturity and require:
  - technology development and small-scale tests for less mature technologies;
  - technical, economic, and environmental analyses to better quantify impacts and benefits; and
  - independent tests to verify the performance of any products produced through these other utilization options.
- Public concern and opposition to pipelines for CO_2 transport and geological storage of CO_2 in some countries is a major concern. Further RD&D on storage that includes the elements above and improves aspects of risk management of CO_2 transport and storage sites will contribute to safe long-term storage and public acceptance. The results should be communicated in plain language.

Priority Actions Recommended for Implementation by Policy Makers

Several priority actions for implementation by policy makers are listed in Chapter 5 of this roadmap. It is strongly recommended that governments and key stakeholders implement the actions outlined there. Below is a summary of the key actions that represent activities necessary during the years up to 2020, as well as the following decade. They are challenging but realistic and are spread across all elements of the CCS chain. They require serious dedication and commitment by governments.

Towards 2020 nations should work together to:

- Maintain and increase commitment to CCS as a viable greenhouse gas (GHG) mitigation option
- Establish international networks, test centres and comprehensive RD&D programmes to verify, qualify and facilitate demonstration of CCS technologies

[1] Qualification means that it meets certain internationally agreed criteria and risk management assessment thresholds that give confidence that a new CO_2 storage site is fit for purpose. It does not guarantee permitting approval.

- Gain experience with 1st generation CO_2 capture technologies and their integration into power plants
- Encourage and support the first industrial demonstration plants for CO_2 capture
- Develop sizeable pilot-scale projects for storage
- Design large-scale, regional CO_2 transport networks and infrastructure
- Agree on common standards, best practices and specifications for all parts of the CCS chain
- Map regional opportunities for CO_2 utilization, addressing the different priorities, technical developments and needs of developed and developing countries.

Towards 2030 nations should work together to:

- Move 2nd generation CO_2 capture technologies for power generation and industrial applications through demonstration and commercialisation, with possible targets of 30% reduction of energy penalty, normalized capital cost, and normalized operational and maintenance (O&M) costs compared to 1st generation technologies
- Implement large-scale national and international CO_2 transport networks and infrastructure
- Demonstrate safe, large-scale CO_2 storage and monitoring
- Qualify regional, and potentially cross-border, clusters of CO_2 storage reservoirs with sufficient capacity
- Ensure sufficient resource capacity for a large-scale CCS industry
- Scale-up and demonstrate non-EOR CO_2 utilization options.

Towards 2050 nations should work together to:

- Develop and progress to commercialisation 3rd generation CO_2 capture technologies with energy penalties and avoidance costs well below that of 1st generation technologies. Possible targets for 3rd generation CO_2 capture technology for power generation and industrial applications are a 50% reduction from 1st generation levels of each of the following: the energy penalty, capital cost, and O&M costs (fixed and non-fuel variable costs) compared to 2013 first generation technologies costs.

Recommendations for Follow-Up Plans

The CSLF will, through its Projects Interaction and Review Team (PIRT), monitor the progress of CCS in relation to the Recommended Priority Actions by soliciting input with respect to the progress of CCS from all members of the CSLF and report annually to the CSLF Technical Group and biennially, or as required, to the CSLF Ministerial Meetings.

1. Objectives, Scope and Approach of TRM

No single approach is sufficient to stabilize the concentration of greenhouse gases (GHGs) in the atmosphere, especially when the growing global demand for energy and the associated potential increase in GHG emissions are considered. Carbon capture and storage (CCS) is one of the important components of any approach or strategy to address the issue of GHG emissions along with improved energy efficiency, energy conservation, the use of renewable energy and nuclear power, and switching from high-carbon fuels to low-carbon fuels.

The CSLF issued Technology Roadmaps (TRM) in 2004, 2009, 2010 and 2011, fulfilling one of its key objectives being to recommend to governments the technology priorities for successful implementation of CCS in the power and industrial sectors. At the meeting of the CSLF Technical Group (TG) in Bergen in June 2012, it was decided to revise the latest version of the TRM.

The TRM sets out to give answers to three questions:

- What is the current status of CCS technology and deployment, particularly in CSLF member countries?
- Where should CCS be by 2020 and beyond?
- What is needed to get from point a) to point b), while also addressing the different circumstances of developed and developing countries?

The focus is on the third question. This TRM will cover CCS in the power generation and industrial sectors. CO_2 utilization, particularly in the near-term, is seen as a means of supporting the early deployment of CCS in certain circumstances and accelerating technology deployment. A CSLF report (CSLF, 2012) divides CO_2 utilization options into three categories:

- Hydrocarbon resource recovery: Applications where CO_2 is used to enhance the production of hydrocarbon resources (such as CO_2-Enhanced Oil Recovery, or CO_2-EOR). This may partly offset the initial cost of CCS and contribute to bridging a gap for the implementation of long-term CO_2 storage in other geological storage media such as deep saline formations.
- Reuse (non-consumptive) applications: Applications where CO_2 is not consumed directly, but re-used or used only once while generating some additional benefit (compared to sequestering the CO_2 stream following its separation). Examples are urea, algal fuel or greenhouse utilization.
- Consumptive applications: These applications involve the formation of minerals, or long-lived compounds from CO_2, which results in carbon sequestration by '*locking-up*' carbon.

For a CO_2-usage technology to qualify as CCS for CO_2 storage in e.g. in trading and credit schemes, it should be required that a n*et amount of* CO_2 is eventually securely and permanently prevented from re-entering the atmosphere. However, emissions can also be reduced without CO_2 being permanently stored, by the substitution of CO_2 produced for a particular purpose with CO_2 captured from a power or industrial plant, as in, e.g., greenhouses in the Netherlands, where natural gas is burned to increase the CO_2.

Economic, financial and policy issues are outside the scope of this CSLF TRM. However, technology improvements will have positive effects both on economic issues and public perception, and in that sense economic and policy issues are implied.

This document was prepared using the following approach:

1. Producing a 'status and gap analysis' document for CCS, including a dedicated CCS technology status report by SINTEF, Norway (2013).
2. Summarizing the CCS status based on the SINTEF report and other available information, including that provided by the Global CCS Institute (GCCSI, 2012) (Chapter 3).

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3. Identifying implementation and RD&D needs (Chapter 4).
4. Producing high-level recommendations (Chapter 5).

Towards the completion of this TRM, a report assembled by CO2CRC for the CSLF Task Force on Technical Gaps Closure became available (Anderson et al., 2013). That report, as well as the report by SINTEF (2013), provides more technological details with respect to the technology status and research needs highlighted in this TRM.

The present TRM has endeavoured to consider recent recommendations of other agencies working towards the deployment of commercial CCS, as the issue cuts across organisational and national boundaries and a concerted informed approach is needed.

There has been communication with the International Energy Agency (IEA) during the development of this TRM as the IEA developed a similar document (IEA, 2013). The IEA CCS Roadmap is focused on policy issues and measures, although it includes detailed technology actions in an appendix. In addition, the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) has issued recommendations for research in CCS beyond 2020 (ZEP, 2013). The ZEP document only addresses technological aspects of CO_2 capture and it does not address policy issues; its recommendations on CO_2 transport and storage are to be found in the ZEP document (ZEP, 2010)

A Steering Committee comprising members of the CSLF TG and chaired by the TG Chair supervised the work of the TRM editor.

2. Vision and Target - the Importance of CCS

The CSLF Charter, modified at the CSLF Ministerial-level meeting in Beijing in September 2011 to include 'CO_2 utilization', states the following purpose of the organization:

"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 CCS. This could include promoting the appropriate technical, political, economic, and regulatory environments for the research, development, demonstration, and commercial deployment of such technology."

The CSLF has not explicitly stated a vision or specific technology targets. However, according to the IEA Energy Technology Perspectives (ETP) 2012 (IEA, 2012a) the amount of CO_2 captured and stored by 2030 and 2050 will have to be 2.4 and 7.8 $GtCO_2$/year, respectively, to stay within the '2^oC scenario' ('2DS'). The cumulative CO_2 reduction from CCS will need to be 123 $GtCO_2$ between 2015 and 2050 and the emissions reductions through the application of CCS by 2050 will have to be split almost equally between power generation and industrial applications. Whereas power generation will have alternatives to CCS for emission reductions, many industries will not. The IEA World Energy Outlook (WEO) 2012 (IEA, 2012b) shows similar contributions from CCS in the 450 ppm scenario up to 2035 and the EU Energy Roadmap 2050 (EU, 2012) points out that CCS will play a significant role to reach 80% reduction of carbon emissions by 2050.

The IEA ETP 2012 (IEA, 2012a) states that, in order to reach 0.27 $GtCO_2$/year captured and stored by 2020, about 120 facilities will be needed. According to views expressed in ETP, *"development and deployment of CCS is seriously off pace"* and *"the scale-up of projects using these technologies over the next decade is critical. CCS could account for up to 20% of cumulative CO_2 reductions in the 2DS* *by 2050. This requires rapid deployment of CCS and this is a significant challenge since there are no large-scale CCS demonstrations in power generation and few in industry"*.

The CSLF and its TRM 2013 aspire to play important roles in accelerating the RD&D and commercial deployment of improved, cost-effective technologies for the separation and capture of CO_2, its transport and its long-term safe storage or utilization.

3. Assessment of Present Situation

3.1. Implementation

In January 2013 the Global CCS Institute published its updated report on the Global Status of CCS (GCCSI, 2013). This report identified 72 Large-Scale Integrated CCS Projects (LSIPs)[2], of which eight were categorized as in the 'operation' stage and nine in the 'execution' stage. These 17 projects together would contribute a CO_2 capture capacity of approximately 0.037 $GtCO_2$/year by 2020. Thus the capture *capacity* by 2020 will at best be half of the needed *actual long-term storage* according to the 2DS, even when pure CO_2-EOR projects are included[3]. In this January 2013 update of the 2012 Global Status Report (GCCSI, 2012) the number of projects on the 'execute' list increased by one, whereas the total number of LSIPs went down from 75.

The projects in the 'operation' and 'execution' stages are located in Algeria, Australia, Canada, Norway and the USA. Of the 17 projects in these two categories, six are/will be injecting the CO_2 into deep saline formations, the rest using the CO_2 for EOR operations. So far, the Weyburn-Midale project in Canada is the only CO_2-EOR project that carries out sufficient monitoring to demonstrate permanent storage and has been identified and recognized as a storage project. Two of the 17 projects in the 'operation' and 'execution' stages are in the power generation sector[4]. The other projects capture the CO_2 from sources where the need for additional CO_2 processing before being collected, compressed and transported is limited, such as natural gas processing, synthetic fuel production or fertilizer production. In other industries, projects are in the 'definition' stage (e.g. iron and steel industry in the United Arab Emirates) or the 'evaluation' stage (e.g., cement industry in Norway).

In 2012, there were nine newly identified LSIPs relative to 2011. More than half of these are in China and all will use CO_2 for EOR. Eight LSIPs in the 'definition' or earlier stages were cancelled between 2011 and 2012, due to regulatory issues, public opposition and/or the high investment costs that were not matched by public funding.

3.2. Capture

There are three main routes to capture CO_2: pre-combustion decarbonisation, oxy-combustion and post-combustion CO_2 capture, as presented in Table 1. The table also provides the readiness (High, Medium, Low) of the 1st generation CO_2 capture technologies with reference to power generation

[2] The definition of a LSIP by the Global CCS Institute is that it involves a complete chain of capture, transport and storage of:

- at least 800,000 tonnes per year for coal-based power plants
- at least 400,000 tonnes per year for other plants, including gas-based power plants.

[3] In general, IEA does not count CO_2-EOR projects

[4] The Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project in Canada that applies post-combustion capture and the Kemper County IGCC in the USA that applies pre-combustion. Both are coal-fired power generation plants.

using solid fuels (predominantly coal) and natural gas, as well as the identified development potential on a rather coarse basis (SINTEF, 2013).

Table 2 summarizes the CO_2 treatment in 1st generation CO_2 capture technologies and the challenges for the 2nd and 3rd generation[5] (SINTEF, 2013). Common challenges – and barriers to implementation – to all capture technologies are the high cost (i.e. capital and operational expenses) and the significant energy penalty associated with the additional equipment. Here we assume 2nd generation technologies will be due for application between 2020 and 2030 and 3rd generation after 2030.

Table 1: Readiness and development potential of main CO_2-capture techniques.

	Readiness for demonstration		Development potential	
Technology	Coal	Natural gas	Coal	Natural gas
IGCC w/CCS*	Medium-High	N/A	High	N/A
Oxy-combustion	Medium-High	Low	High	Medium-High
Post-combustion	High	High	Medium-High	Medium-High

** Integrated Gasification Combined Cycle (IGCC) plant with CCS, i.e. pre-combustion decarbonisation of the power plant.*

There are many demonstration and pilot-scale projects for CO_2 capture technologies, particularly for post-combustion capture and oxy-combustion technologies. The scale of these is generally in the order of 20-30MW_{th}, or a capture capacity of up to a few hundred thousand tonnes of CO_2/year. Dedicated test facilities for the capture of CO_2 have been established in, e.g., Canada, China, Norway, the UK and the USA.

In general, post-combustion CO_2 separation technologies can be used in many industrial applications. ULCOS (Ultra–Low CO_2 Steelmaking) is a consortium of 48 European companies and organizations that launched a cooperative RD&D initiative to enable drastic reductions in CO_2 emissions from steel production. The aim of the ULCOS programme is to reduce CO_2 emissions by at least 50 percent. A demonstration plant in France was planned as part of ULCOS II, but was shelved in late 2012, at least temporarily, as a decision was made to close the steel plant. There has been another project for the steel industry - COURSE50 - in Japan. In this project, two small-scale plants have been operated, one for chemical adsorption and the other for physical adsorption. The European cement industry has carried out a feasibility study on the use of post-combustion capture technology to remove CO_2 from a stack where the various flue gases from the kiln are combined.

[5] Definitions according to the UK Advanced Power Generation Technology Forum (APGTF; 2011):

- 1st generation technologies are technologies that are ready to be demonstrated in 'first-of-a-kind' large-scale projects without the need for further development.
- 2nd generation technologies are systems generally based on 1st generation concepts and equipment with modifications to reduce the energy penalty and CCS costs (e.g. better capture solvents, higher efficiency boilers, better integration) – this may also involve some step-changes to the 'technology blocks'.
- 3rd generation technologies are novel technologies and process options that are distinct from 1st generation technology options and are currently far from commercialisation yet may offer substantial gains when developed.

Table 2: CO_2 treatment in first generation technologies and the challenges facing second and third generations

	CO_2 treatment 1st generation	Possible 2nd and 3rd generation technology options	Implementation challenges
IGCC with pre-combustion decarbonisat-ion	• Solvents and solid sorbents • Cryogenic air separation unit (ASU)	• Membrane separation of oxygen and syngas • Turbines for hydrogen-rich gas with low NO_x	• Degree of integration of large IGCC plants versus flexibility • Operational availability with coal in base load • Lack of commercial guarantees
Oxy-combustion	• Cryogenic ASU • Cryogenic purification of the CO_2 stream prior to compression • Recycling of flue gas	• New and more efficient air separation, e.g. membranes • Optimized boiler systems • Oxy-combustion turbines • Chemical looping combustion (CLC) - reactor systems and oxygen carriers	• Unit size and capacity combined with energy demand for ASU • Peak temperatures versus flue-gas re-circulation • NO_x formation • Optimisation of overall compressor work (ASU and CO_2 purification unit (CPU) require compression work) • Lack of commercial guarantees
Post-combustion capture	• Separation of CO_2 from flue gas • Chemical absorption or physical absorption (depending on CO_2 concentration)	• New solvents (e.g. amino acids) • 2nd & 3rd generation amines requiring less energy for regeneration • 2nd & 3rd generation process designs and equipment for new and conventional solvents • Solid sorbent technologies • Membrane technologies • Hydrates • Cryogenic technologies	• Scale and integration of complete systems for flue gas cleaning • Slippage of solvent to the surrounding air (possible health, safety & environmental (HS&E) issues) • Carry-over of solvent into the CO_2 stream • Flue gas contaminants • Energy penalty • Water balance (make-up water)

It should be mentioned that the world's largest CO_2 capture plant is a Rectisol process run by Sasol, South Africa, as part of its synfuel/chemical process and captures approximately 25 million tonnes of CO_2 per year.

In short, capturing CO_2 works and there has been significant progress with CO_2 capture from industrial sources with high CO_2 concentration. However, certain challenges remain:

- The cost and energy penalty are high for all 1st generation capture technologies.
- The scale-up and integration of CO_2 capture systems for power generation and industries that do not produce high-purity CO_2 are limited, and may not sufficiently advance for at least the next 5 – 10 years.
- CO_2 capture technologies suited to a range of industrial processes exist, but have not been adopted, demonstrated and validated for specific use. Examples of such industries include cement, iron and steel, petrochemical, aluminium, and pulp and paper.
- Health, safety and environmental assessment must be an integral part of technology and project development. For example, extensive studies have concluded that health and environmental issues connected to amine-based capture technology can be controlled (Maree et al, 2013; Gjernes et al, 2013).

3.3. Transport

Transport of CO_2 in pipelines is a known and established technology, with significant experience gained from more than 6,000 km of CO_2 pipelines onshore in the USA used for transporting CO_2 for EOR operations, mainly across sparsely populated areas. However, there is very limited experience with CO_2 pipelines through heavily populated areas, and the 153km pipeline at Snøhvit is the only offshore CO_2 pipeline. There is also experience of CO_2 transport by ships, albeit in small quantities. These CO_2 streams are almost pure and there is limited experience with CO_2 streams containing impurities.

Standards and best practices on CO_2 transport have emerged (e.g. DNV, 2010). The objectives of further RD&D will be to optimize the design and operation of pipelines and ships and increase the operational reliability in order to reduce costs.

To achieve large-scale implementation, it will also be necessary to think in terms of networks of CO_2 pipelines, ships, railway and road transportation, the latter two particularly in the early stages of a project. Such concepts have been studied at both national and regional levels. Studies have been made around hubs and clusters for CO_2 in the UK, Australia, and in the Dutch ROAD project[6], as well as in the United Arab Emirates and Alberta, Canada (GCCSI, 2012).

In Europe, where CO_2 pipelines will often have to go through heavily populated areas with many landowners, the permitting process and 'right-of-way' negotiations have led to long lead-times for construction. Another factor that may cause long lead-time and expensive pipelines is the increased global demand for steel and pipes.

3.4. Storage

Deep saline formation (DSF) storage projects have been in operation for more than 15 years and CO_2 has been used for EOR since the early 1970s. The three large-scale DSF projects in operation[7], as well as some smaller ones (e.g., in Canada, Germany, Japan and the USA) and a gas reservoir storage project (the Netherlands) have been subjected to extensive monitoring programmes that include a range of technologies, such as time-lapse seismic and down-hole pressure and temperature monitoring, time-lapse gravimetry, controlled-source electromagnetic monitoring, passive seismic monitoring, electrical resistivity imaging, geochemical surveys, inferometric synthetic aperture radar (InSAR) detection, groundwater monitoring, soil-gas detection, microbiological surveys, complex wireline logging and other techniques for plume tracking.

The experience from these and other operations has shown that (GCCSI, 2012):

- CO_2 storage is safe with proper planning and operations. However, presently, there is no experience with closure and post-closure procedures for storage projects (terminated and abandoned CO_2-EOR projects are usually not followed up).
- Current storage projects have developed and demonstrated comprehensive and thorough approaches to site characterization, risk management and monitoring.
- All storage sites are different and need individual and proper characterization. Characterization and permitting requires long lead-times (3-10 years).

Monitoring programmes and the data that they have made available have stimulated the advancement of models that simulate the CO_2 behaviour in the underground environment, including

[6] As of June 2013, the Final Investment Decision (FID) for the ROAD project has not been made but ROAD remains a planned project, close to FID
[7] In Salah, Algeria; Sleipner, Norway; and Snøhvit, Norway

geochemical and geomechanical processes in addition to flow processes. DSF projects in the 'execution' stage have developed extensive monitoring programmes and have been subjected to risk assessments (e.g., the Gorgon Project in Australia and the Quest Project in Canada) and the experience will be expanded when these become operational.

In addition to the impact on CO_2 transport and injection facilities, impurities in the CO_2 stream can have effects on the storage of CO_2 in deep saline formations. Contaminants such as N_2, O_2, CH_4 and Ar will lead to lower storage efficiency (e.g. Mikunda and de Coninck, 2011; IEAGHG, 2011; and Wildgust et al., 2011), but since they have a correspondingly large impact on CO_2 transport costs (compression and pumping), it will be cost-efficient to lower the concentrations to a level where the impact on CO_2 storage efficiency will be minor. Other impurities (e.g. H_2S and SO_2) can occur in concentrations up to a few percent for CO_2 sources relevant for storage. These are generally more reactive chemically (for pipelines, compressors and wells) and geochemically (for storage) than CO_2 itself. So far, there are no indications that the geochemical reactions will have strong impact on injectivity, porosity, permeability or caprock integrity (Mikunda and de Coninck, 2011; IEAGHG, 2011); however, the geochemical part of the site-qualification work needs to take the presence of such impurities into account. Still, geological injection of 'acid gas' (i.e. CO_2 + H_2S) is considered safe (Bachu and Gunter, 2005), and injection of CO_2 with minor concentrations of H_2S should be even more so.

Impurities may also affect the well materials. Most studies have been laboratory experiments on the effects of pure CO_2 streams (Zhang and Bachu, 2011), but well materials may be affected if water returns to the well after injection has stopped (IEAGHG, 2011).

Countries including Australia, Canada and the USA, as well as international bodies like the European Commission (EC) and the OSPAR and London Convention organisations, have implemented legislation and/or regulations concerning CO_2 storage either at the national/federal level or at the provincial/state level[8]. Standards and recommended practices have been published (CSA, 2012; DNV, 2012), in addition to a range of specialized best practice manuals (e.g. on monitoring and verification, DoE 2009 and 2012a; site screening DoE 2010; risk assessment, DoE, 2011 and DNV, 2013; well integrity DNV 2011 and DoE 2012b). The International Organization for Standardization (ISO) has initiated work on a standard covering the whole CCS chain.

Despite this progress, the Global CCS Institute (GCCSI, 2012) stated that most remaining issues regarding regulations for CCS are storage-related, particularly the issue of long-term liability. All these documents will therefore need future revisions based on experience. As an example, the EC CO_2 storage directive is regarded by industrial stakeholders as a regulation that puts too high a liability burden on storage operators. Furthermore, some modifications are still necessary in international regulations such as the London Protocol.

The last few years have seen increased activity in national and regional assessments of storage capacity with the issuing of CO_2 storage 'atlases' in many countries (e.g. Australia, Brazil, Germany, Italy, Japan, North-American countries, the Scandinavian countries, South Africa and the UK). Methods are available for CO_2 storage capacity estimation and comparisons have been made (Bachu, 2007 and 2008; Bachu et al., 2007a and 2007b; DoE, 2008), but there is no generally used common methodology, although in the CO2StoP project, funded by the EC, EU Member States geological surveys and institutes will use a common methodology to calculate their CO_2 storage capacities.

[8] See e.g. http://www.globalccsinstitute.com/networks/cclp

There are additional geological candidates to deep saline formations for CO_2 storage, such as abandoned oil and gas reservoirs and un-minable coal seams, but their capacity is much less than that of deep saline formations. More exotic and unproven alternatives include storing CO_2 in basalts, serpentine-/olivine-rich rocks (but one must find ways to reduce by several orders of magnitude the reaction time between the rock and CO_2 and the energy penalty associated with crushing), as well as in organic-rich shale (but here the effect of hydraulic fracturing of the geological formations has to be better understood).

Experience has shown that the major perceived risks of CCS are associated with CO_2 storage and CO_2 transport. Onshore storage projects have been met with adverse public reaction in Europe although a survey found that just under half (49%) of respondents felt well informed about the causes and consequences of climate change (EC, 2011). However, only 10% of respondents had heard of CCS and knew what it was. A workshop summary (University of Nottingham, NCCCS and University of Sheffield, 2012) provides a detailed overview of the public engagement and perception issues and solutions about CCS projects in Europe as well as their presence in the press.

The risk management of geological storage of CO_2 and early and continued engagement of the local community throughout the lifetime of the CO_2 storage project is therefore essential. Further RD&D on storage should include the elements of risk management of CO_2 storage sites that will help provide the technical foundation to communicate that CO_2 storage is safe. This will include tested, validated and efficient monitoring and leak detection technologies, flow simulations and mitigating options. Equally, plain language communication of technical issues at community level is essential.

3.5. Infrastructure and the Integrated CCS Chain

Coping with the large volumes of CO_2 to be collected from future power plants and industrial clusters, pursuant to, e.g., the 2DS, will require new infrastructure to connect CO_2 sources with CO_2 sinks. In the planning of this infrastructure, the amount of collectible CO_2 – from multiple single CO_2 sources and from CO_2 hubs or clusters – and the availability of storage capacity for the CO_2 must be taken into account to balance the volumes of CO_2 entering the system. This will involve integration of CO_2 capture systems with the power or processing plants, considerations regarding the selection of processes, the integration of different systems, understanding the scale-up risks, solutions for intermediate storage as well as seaborne or land transport ('hub and spokes'), understanding the impact of CO_2 impurities on the whole system, as well as having proper storage sites, which may have a long lead time for selection, characterization and permitting and may be project limiting.

Whilst one can start to gain experience from the integration of CO_2 capture systems into power plants[9], there are presently no CCS clusters and transport networks currently in operation. The closest are EOR systems that inject CO_2 into oil reservoirs as in the Permian basin in the USA, where clusters of oilfields are fed by a network of pipelines. There are initiatives for CO_2 networks, including proposals, in Australia, Canada, Europe (the Netherlands and the UK) and the United Arab Emirates (GCCSI, 2012).

3.6. Utilization

CO_2 for EOR is the most widely used form of CO_2 utilization, with more than 120 operations, mainly in North America. Other specific applications for CO_2-enhanced hydrocarbon recovery include enhanced coal bed methane production (ECBM), enhanced gas recovery (EGR), enhanced gas hydrate recovery (EGHR), hydrocarbon recovery from oil shale and the fracturing of reservoirs to

[9] http://www.cslforum.org/meetings/workshops/technical_london2011.html

increase oil/gas recovery. However, these other applications are processes still being developed or tested in pilot-scale tests (CSLF; 2012, 2013).

Other potential utilization options of CO_2 that will lead to secure long-term storage are the use of CO_2 as the heat-transfer agent in geothermal energy systems, carbonate mineralization, concrete curing, bauxite residue and some algae cultivation. Mixing CO_2 with bauxite residue ('red mud') is being demonstrated in Australia (GCCSI, 2011). In addition, there are several forms of re-use of CO_2 already in use or being explored, including in urea production, utilization in greenhouses, polymers, methanol and formic acid production, and the cultivation of algae as a pathway to bio-energy and other products. These will not lead to permanent storage but may contribute to the reduced production of CO_2 or other CO_2 emitting substances. Also, there may be other related benefits: as an example, the utilization of waste CO_2 in greenhouses in the Netherlands already leads to a better business case for renewable heating and a rapid growth of geothermal energy use in the sector. Finally, the public opinion on CCS as a whole may become more positive when utilization options are part of the portfolio.

For many of the utilization options of CO_2 the total amount that can be permanently stored is, for all practical and economic purposes, limited for the moment. However, in some countries utilization provides early opportunities to catalyse the implementation of CCS. In this way, the CO_2 utilization pathways can form niche markets and solutions as one of the routes to commercial CCS before reaching their own large-scale industrial deployment. This applies not only to oil producing countries but also to regions with evolved energy systems that will allow the implementation of feasible CO_2 business cases.

Recent reviews of utilization of CO_2 are CSLF (2012, 2013), GCCSI (2011), ADEME (2010), Styring (2011), Dijkstra (2012), Tomski (2012) and Markewitz et al. (2012). In April 2013 The Journal of CO2 Utilization was launched, providing a multi-disciplinary platform for the exchange of novel research in the field of CO2 re-use pathways.

4. Identified Technology Needs

4.1. Capture

The main drawbacks of applying first generation CCS technologies to power generation are the increased capital and operational costs that result in higher cost of electricity to the end-user. One cause is the increased fuel demand (typically 30%) due to the efficiency penalty (typically around 10-12%-points in power generation).

Hence, in pursuing 2^{nd} generation technologies, efforts should be made to reduce the energy penalty. This especially applies to:

- CO_2 separation work;
- CO_2 compression work; and,
- to a smaller extent, auxiliary equipment like blower fans and pumps.

The first two components represent the most significant gaps that need improvement in the future.

First generation CO_2 capture technologies have limitations in terms of the energy required for separation work, typically in the range of 3.0–3.5GJ/tCO_2. The theoretical minimum varies with the CO_2 partial pressure, as shown in Figure 1, and is generally below 0.20GJ/tCO_2 for post- and pre-combustion systems. Although this does not include the total energy penalty of a technology, since heat and power are sacrificed in other parts of the process, it indicates that there is a potential for 2^{nd} and 3^{rd} generation capture technologies to reduce the energy penalty by, say, a factor of two.

Note, however, that Figure 1 does not determine which system is best; only a complete analysis of the full systems can tell which case is the better one.

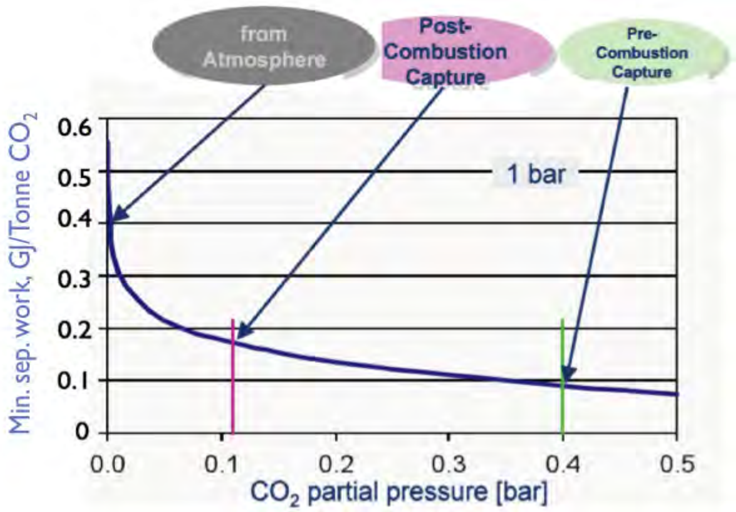

Figure 1: Theoretical minimum separation work of CO_2 from a flue gas depending on the partial pressure of CO_2 [modified from Bolland et al., 2006]

A state-of-the-art, four-stage CO_2 compressor train with inter-cooling requires 0.335GJ/tCO_2 and has a theoretical minimum of about half this value. Hence, it seems that only marginal improvements can be made in compressor development. However, in considering new power generation cycles, process integration is an important aspect. The integration should strive at reducing the overall compression work. In this context, pressurised power cycles should be looked at, especially oxy-combustion cycles and gasification technologies.

History suggests that a successful energy technology requires typically 30 years from the stage it is deemed available to reaching a sufficient market share (typically 1% of the global energy mix). With CCS, in order to have the desired impact on climate change (i.e. the IEA's '2DS'), this transition period must be reduced to just one decade. This requires targeted research with the ambitious goal that 2nd generation CCS technologies will be ready for commercial operations as early as possible between 2020 and 2030, and 3rd generation technologies to be enabled very soon after 2030. Cost reductions will also come from 'learning-by-doing', hence there will be a need for increased installed capacity.

Bio-energy with CO_2 capture and storage ('BECCS') offers permanent net removal of CO_2 from the atmosphere (IEA; 2011, 2013). How 'negative' the emissions may be will depend on several factors, including the sustainability of the biomass used.

The RD&D needs in the CO_2 capture area include:

- Gaining knowledge and experience from 1st generation CO_2 capture technologies.
- Identifying and developing 2nd and 3rd generation CO_2 capture technologies.
- Scaling-up systems for power generation.
- Adapting and scaling-up for industrial applications.
- Integrating a CO_2 capture system with the power or processing plant. Considerations will have to be made regarding process selection, heat integration, other environmental control systems (SO_x, NO_X), part-load operation and daily cycling flexibility, impacts of CO_2 composition and impurities, for 'new-build' plants as well as for retrofits.

- Health, safety and environmental assessment as an integral part of technology and project development, including BECCS; in particular identifying and mitigating/eliminating negative environmental aspects of candidate CO_2 capture technologies.
- Identifying specific cases to demonstrate and validate CO_2 capture technologies suited for a range of industry processes (e.g., cement, iron and steel, petrochemical, and pulp and paper).

4.1.1. Recommendation 1: CO_2 Capture Technologies in Power Generation

Towards 2020: Implement a sufficient number of large-scale capture plants and sizeable pilots to:

- Increase understanding of the scale-up risks. Lessons learned will be used to generate new understanding and concepts complying with 2nd generation CCS.
- Gain experience in the integration of CO_2 capture systems with the power or processing plant, including heat integration and other environmental control systems (SO_x, NO_x).
- Gain experience in part-load operations and daily cycling flexibility, as well as in the impacts of CO_2 composition and impurities.
- Gain experience in the integration of power plants with CCS into electricity grids utilizing renewable energy sources.

Towards 2030:

- Develop 2nd generation CO_2 capture technologies with energy penalties and avoidance costs well below that of 1st generation technologies. Possible targets for 2nd generation capture technology for power generation and industrial applications are a 30% reduction of the each of the following the energy penalty, normalized capital cost, and normalized operational and maintenance (O&M) costs (fixed and non-fuel variable costs) compared to 1st generation technologies[10,11].

Towards 2050:

- Possible targets for 3rd generation CO_2 capture technology for power generation and industrial applications are a 50% reduction of each of the following: the energy penalty, normalized capital cost, and normalized O&M costs (fixed and non-fuel variable costs) compared to 1st generation technologies[12].

4.1.2. Recommendation 2: CO_2 Capture in the Industrial Sector

Towards 2020:

- Further develop CO_2 capture technologies for industrial applications and implement pilot-plants and demonstrations for these.

Towards 2030:

- Implement the full-scale CCS chain in cement, iron and steel and other industrial plants.

The road map for CO_2 capture technology is illustrated in Figure 2.

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[10] Energy penalty = (Power output (state-of-the-art plant w/o CCS) - Power output(state-of-the-art plant w/CCS)) / Energy input (state-of-the-art plant w/o CCS)
Normalized cost = (Cost (state-of-the-art plant w/CCS) – cost (state-of-the-art plant w/o CCS)) / Cost (state-of-the-art plant w/o CCS) E.g. if the energy penalty is 10% in 2013, the penalty should be 7% in 2030.

[11] The target is supported by the UK Carbon Capture and Storage Cost Reduction Task Force of the Department of Energy and Climate Change (DECC, 2013), which states that a reduction of 20% is deemed possible by 2020 and significant further reductions in generation and capture costs are possible by the late 2020s and beyond.

[12] The US Department of Energy/National Energy Technology Laboratory (DOE/NETL, 2011) has a research target of 55% for reduction of the overall economic penalty imparted by current carbon capture technology. DOE/NETL does not attach a date to the target, but state it is aggressive but achievable.

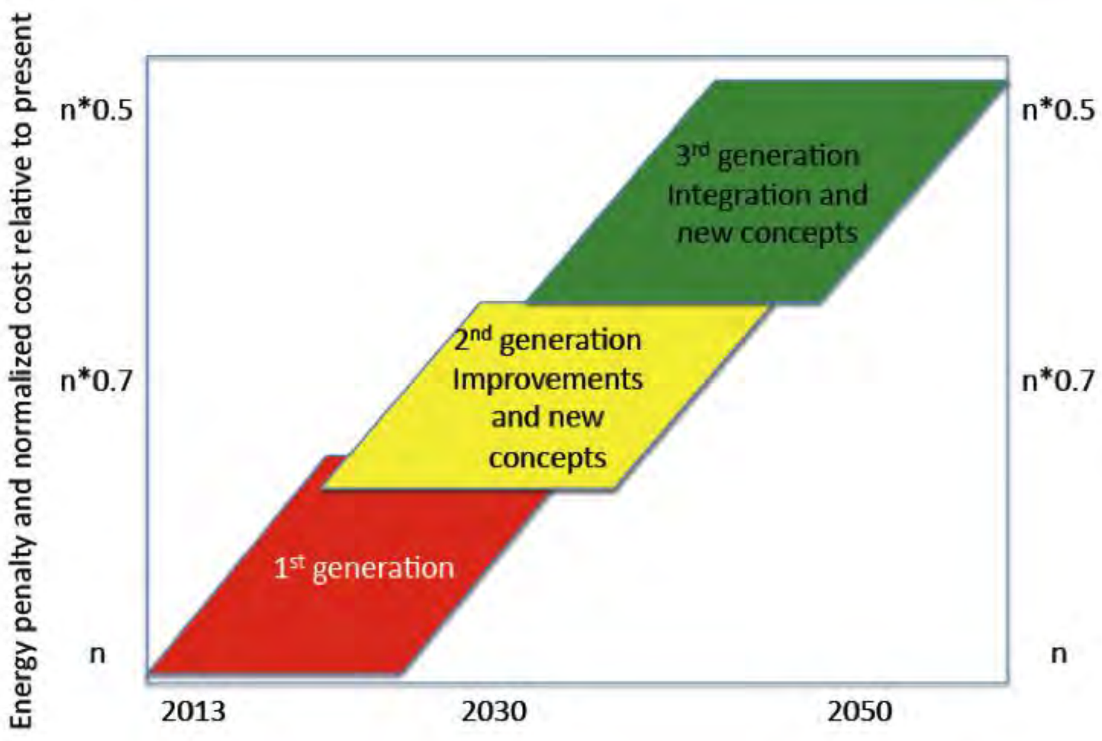

Figure 2: Priorities for CCS technology development. The energy penalty and normalized costs are shown in relation to the present level (n), i.e. equivalent to reduction by 30% in 2030 and 50% towards 2050.

4.2. Transport

RD&D will contribute to optimizing systems for CO_2 transport, thereby increasing operational reliability and reducing costs. The needs include improved understanding and modelling capabilities of properties and the behaviour of CO_2 streams, e.g., the impact of impurities on phase equilibria and equations-of-state of complex CO_2 mixtures, as well as of flow-related phenomena. Other RD&D needs are improved leakage detection and establishment and validation of impact models for the assessment of incidents pursuant to leakage of piped CO_2, the identification and qualification of materials or material combinations that will reduce capital and/or operational costs (including improved understanding of the chemical effect of impurities in the CO_2 stream on pipeline materials, including seals, valves etc.) and the adoption/adaptation of technology elements known from ship transport of other gases to CO_2 transport by ship.

4.2.1. Recommendation 3: CO_2 Transport

Towards 2020:

- Acquire data for, and understand the effects of, impurities on the thermodynamics of CO_2 streams and on pipeline materials, and establish and validate flow models that include such effects.
- Establish and validate dispersion models for the impact assessment of incidents pursuant to leakage of CO_2 from the CO_2 transport system (pipelines, ships, rail and trucks).
- Develop common specifications for pipelines and the CO_2 stream and its components.
- Qualify pipeline materials for use in CO_2 pipes with impurities.

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4.3. Storage

Of the three DSF storage projects in operation, two are located offshore and the third one is located in a desert environment. Also the DSF projects currently in the 'execution' stage will be in sparsely populated areas. When attempts have been made to implement CO_2 storage in more heavily populated areas, e.g. in Germany and the Netherlands, they have met considerable public and political opposition that led to project cancellation. A strong reason that the Barendrecht project in the Netherlands did not get approval from the authorities was that CCS is a new technology and is not proven. The public questioned why it should be subjected to the risks of CCS (Spence, 2012; see also Feenstra et al. 2010). The public concerns of risks associated with CCS seem to be mainly around CO_2 storage and this is also where most remaining issues concerning regulations are found, particularly the long-term liability, despite the fact that some countries and sub-national bodies have issued the first versions of CO_2 storage regulations already.

Risk assessment, communication and management are essential activities to ensure qualification of a site for safe, long-term storage of CO_2 by, e.g., a third party and the subsequent approval and permitting by regulatory authorities. However, such qualification does not automatically lead to permission. The risk assessment must include induced seismic activity and ground motion, as well as leakage of CO_2 from the storage unit to the air or groundwater.

Although the effects of impurities in the CO_2 stream on the storage capacity and the integrity of the storage site and wells due to geochemical effects on reservoir and caprock begin to be theoretically understood, there is still need for experimental verification, particularly focussed on site-specific areas. These effects represent risks to storage and need to be better studied and understood.

Geology varies and no two storage sites will be exactly the same, thus CO_2 storage risks are highly site-specific. However, there are many general issues where RD&D is needed to reduce the perceived risks of CO_2 storage and to reduce costs, including risk management.

Elements of risk management where continued and intensified RD&D is needed include:

- Development of methods and protocols for the characterization of the proposed CO_2 storage site that will convince the regulatory agency and the public that storage is secure and safe.
- Development of a unified approach to estimating CO_2 storage capacity.
- Development, validation and commercialization of monitoring methods and tools that are tested and validated for the respective site conditions.
- Improvement of the understanding and modelling of fundamental reservoir and overburden processes, including hydrodynamic, thermal, mechanical and chemical processes.
- Development of good well and reservoir technologies and management procedures.
- Development of tested and verified mitigation measures.
- Identification of where CO_2 storage conflicts with/impacts on other uses and/or resource extraction and inclusion in resource management plans.
- Improvement of understanding and verification of the effects of impurities in the CO_2 stream on all aspects of CO_2 storage.
- Acquisition experience with closure and post-closure procedures for CO_2 storage projects (currently totally lacking).

All these topics require sufficient access to CO_2 storage sites of varying sizes for testing and verification *in situ* and acquisition of data to verify all sorts of models (flow, geomechanical, geochemical etc).

Other issues that need RD&D are:

- Development of a uniform, internationally accepted methodology to estimate CO_2 storage capacity at various scales.
- Proving safe and economic CO_2 storage in alternative geological media such as basalts, serpentine-/olivine-rich rocks and organic-rich shale.

In addition, although not a general RD&D activity but rather a site-specific one, RD&D is needed in:

- Characterizing CO_2 storage sites – this needs to begin as early as possible in any CCS project. There is no shortcut to site characterization.

4.3.1. Recommendation 4: Large-Scale CO_2 Storage

Towards 2020:

- Demonstrate CO_2 storage in a wide range of sizes and geological settings, including deep saline formations, depleted oil and gas fields and producing oil and gas fields (EOR and EGR) around the world.
- Improve the understanding of the effects of impurities in the CO_2 stream, including their phase behaviour, on the capacity and integrity of the CO_2 storage site, with emphasis on well facilities.

Towards 2030:

- Qualify CO_2 storage sites for safe and long-term storage in the scale of tens of millions of tonnes of CO_2 annually per storage site from clusters of CO_2 transport systems.

Towards 2050:

- Have stored over 120 $GtCO_2$ in geological storage sites around the world.

4.3.2. Recommendation 5: Monitoring and Mitigation/Remediation

Towards 2020:

- Further testing, validation and commercialization of monitoring technologies in large-scale CO_2 storage projects, onshore and offshore, to prove that monitoring works and leaks can be prevented or detected, and to make monitoring cost-efficient.
- Develop mitigation and remediation methods for leakage, including well leakage, and test in small-scale, controlled settings.
- Validate mitigation technologies on a large scale, including well leakage.
- Demonstrate safe and long-term CO_2 storage.

Towards 2030:

- Develop a complete set of monitoring and mitigation technologies to commercial availability.

4.3.3 Recommendation 6: Understanding the Storage Reservoirs

Towards 2020:

- Further advance the simulation tools.
- Develop and agree on consistent methods for determining CO_2 storage capacity reserves at various scales (as opposed to storage resources) and global distribution of this capacity (important for policy makers).

4.4. Infrastructure and the Integrated CCS Chain

Building the infrastructure needed to handle large volumes of CO_2 requires that one moves on from the studies and projects mentioned in Section 3.5. Some of the needed technology activities are mentioned above, such as the integration of a CO_2 capture system with the power or processing plant and understanding the scale-up risks.

Other RD&D needs include:

- Designing a CO_2 transport system that involves pipelines, solutions for intermediate CO_2 storage and seaborne or land transport (hub and spokes).
- Developing systems that collect CO_2 from multiple sources and distribute it to multiple sinks.
- Characterizing and selecting qualified CO_2 storage sites, which have a long lead-time and may be project limiting. Several sites must be characterized, as a given site will not be able to receive a constant flow of CO_2 over time and flexibility with respect to site must be secured.
- Safety and environmental risk assessments for the whole chain, including life-cycle analysis (LCA).

In addition to these technology challenges, there are non-technical risks that include the cooperation of different industries across the CCS value-chain, the lack of project-on-project confidence, the completion of projects on cost and on schedule, operational availability and reliability, financing and political aspects. These risks are outside the scope of the CSLF TRM 2013.

4.4.1. Recommendation 7: Infrastructure

Towards 2020:

- Design large-scale CO_2 transport networks that integrate capture, transport and storage, including matching of sources and sinks, particularly in non-OECD countries.
- Map the competing demands for steel and pipes and secure the manufacturing capacity for the required pipe volumes and other transport items.
- Develop systems for metering and monitoring CO_2 from different sources with varying purity and composition that feed into a common collection and distribution system.
- Start the identification, characterization and qualification of CO_2 storage sites for the large-scale systems.

Towards 2030:

- Implement large-scale CO_2 transport networks that integrate CO_2 capture, transport and storage, including matching of sources and sinks, particularly in non-OECD countries.

4.5. Utilization

There are technical and policy reasons to further examine the technical challenges of the utilization of CO_2. The recent reviews of utilization by CSLF (2012, 2013), GCCSI (2011) and Styring (2011) all point to several possible topics requiring RD&D, including:

- Improving the understanding of how to increase and prove the permanent storage of CO_2 in CO_2-EOR operations. A recent CSLF Task Force Report (Bachu et al., 2013) points out the similarities and differences between CO_2-EOR and CO_2 injected for storage. One conclusion from this report is that there are no technical challenges per se in converting CO_2-EOR operations to CCS, although issues like availability of high quality CO_2 at an economic cost, infrastructure for transporting CO_2 to oil fields; and legal, regulatory and long-term liability must be addressed.
- Improving the understanding of how to increase and prove the permanent storage of CO_2 in EGR, ECBM, EGHR, enhanced shale gas recovery and other geological applications of CO_2.
- Developing and applying carbonation approaches (i.e. for the production of secondary construction materials).
- Developing large-scale, algae-based production of fuels.
- Improving and extending the utilization of CO_2 in greenhouses, urea production and other reuse options.

CO_2-EOR has the largest potential of the various CO_2 utilization options described previously, and has not been sufficiently explored to date as a long-term CO_2 storage option. So far only the CO_2-EOR

Weyburn-Midale project in Canada has performed extensive monitoring and verification of CO_2 stored in EOR operations.

4.5.1. Recommendation 8: CO_2 Utilization

Towards 2020:

- Resolve technical challenges for the transition from CO_2-EOR operations to CO_2 storage operations.
- Establish methods and standards that will increase and prove the permanent storage of CO_2 in EGR, ECBM, EGHR and other geological applications if CO_2 injection becomes more prevalent in these applications.
- Research, evaluate and demonstrate carbonation approaches, in particular for mining residue carbonation and concrete curing, but also other carbonate mineralization that may lead to useful products (e.g. secondary construction materials), including environmental barriers such as the consequences of large mining operations and the disposal of carbonates.
- Map opportunities, conduct technology readiness assessments and resolve main barriers for the implementation of the CO_2 utilization family of technologies including life-cycle assessments and CO_2 and energy balances.
- Increase the understanding of CO_2 energy balances for each potential CO_2 re-use pathways and the energy requirement of each technology using technological modelling.
- Address policy and regulatory issues related to CO_2 utilization, particularly in enhanced hydrocarbon recovery.

5. Priority Actions Recommended for Implementation by Policy Makers

Towards 2020 nations should work together to:

- Maintain and increase commitment to CCS as a viable GHG mitigation option, building upon the global progress to date.
- Establish international networks of laboratories (like the European Carbon Dioxide Capture and Storage Laboratory Infrastructure, ECCSEL) and test centres, as well as comprehensive RD&D programmes to:
  - verify and qualify 1st generation CO_2 capture technologies;
  - continue development of 2nd and 3rd generation CO_2 capture technologies; and
  - share knowledge and experience.
- Implement large-scale demonstration projects in power generation in a sufficient number to gain experience with 1st generation CO_2 capture technologies and their integration into the power plant;
- Encourage and support the first demonstration plants for CO_2 capture in other industries than the power sector and gas processing and reforming, particularly in the cement and iron and steel industries.
- Develop common specifications for impurities in the CO_2 stream for the transport and storage of CO_2
- Establish R&D programmes and international collaborations that facilitate the demonstration and qualification of CO_2 storage sites.
- Develop internationally agreed common standards or best practices for establishing CO_2 storage capacity in geological formations.
- Develop sizeable pilot-scale projects for CO_2 storage that can provide greater understanding of the storage medium, establish networks of such projects to share the knowledge and experience for various geological and environmental settings, jurisdictions and regions of the world, including monitoring programmes.

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- Develop common standards or best practices for the screening, qualification and selection of CO_2 storage sites in order to reduce lead-time and have the sites ready for permitting between 2020 and 2025, including CO_2-enhanced oil recovery (CO_2-EOR) sites.
- Design large-scale, regional CO_2 transport networks and infrastructure that integrate CO_2 capture from power generation as well as other industries, CO_2 transport and storage, with due consideration to:
    - competition with other resources and access;
    - matching of sources and sinks, particularly in non-OECD countries;
    - competing demands for steel and pipes and securing the necessary manufacturing capacity; and
    - lead-times for qualification and permitting of CO_2 storage sites and planning and approval of pipeline routes.
- Conduct regional (nationally as well as internationally) impact assessments of large-scale CCS implementation as part of an energy mix with renewables and fossil fuels.
- Map regional opportunities for CO_2 utilization and start implementing projects.
- Continue R&D and small-scale testing of promising non-EOR CO_2 utilization options.
- Address the different priorities, technical developments and needs of developed and developing countries.

Towards 2030 nations should work together to:

- Move 2nd generation CO_2 capture technologies for power generation and industrial applications through demonstration and commercialisation. Compared to 1st generation technologies possible targets for 2nd generation capture technology for power generation and industrial applications are a 30% reduction of each of the following: the energy penalty, normalized capital cost, and normalized operational and maintenance (O&M) costs (fixed and non-fuel variable costs) compared to 1st generation technologies.
- Implement large-scale regional CO_2 transport networks and infrastructure, nationally as well as internationally.
- Demonstrate safe, large-scale CO_2 storage and monitoring
- Qualify regional, and potentially cross-border, clusters of CO_2 storage sites with sufficient capacity.
- Ensure sufficient resource capacity for a large-scale CCS industry.
- Scale-up and demonstrate non-EOR CO_2 utilization options.

Towards 2050 nations should work together to:

- Develop and progress to commercialisation 3rd generation CO_2 capture technologies with energy penalties and avoidance costs well below that of 1st generation technologies. Possible targets for 3rd generation capture technology for power generation and industrial applications are a 50% reduction from 1st generation levels of each of the following: the energy penalty, capital cost, and O&M costs (fixed and non-fuel variable costs) compared to first generation technologies.

6. Summary and Follow-Up Plans

Since the last full update of the CSLF TRM in 2010, there have been advances and positive developments in CCS, although at a lower rate than is necessary to achieve earlier objectives. R&D of CO_2 capture technologies progresses, new Large-Scale Integrated Projects (LSIPs) are under construction or have been decided, legislation has been put in place in many OECD-countries and several nations have mapped potential CO_2 storage sites and their capacities. An important next step will be to develop projects that expand the range of CO_2 capture technologies for power and industrial plants to demonstration at a large scale. This will provide much-needed experience at a scale approaching or matching commercial scale and the integration of capture technologies with the rest of the plant, paving the way for subsequent cost reductions. There is also a need to get experience from a wider range of CO_2 transport means, as well as of CO_2 of different qualities. Furthermore, there are only a limited number of large-scale CO_2 storage projects, and experience is needed from a large number of geological settings and monitoring schemes under commercial conditions.

A rapid increase of the demonstration of all the 'links' in the CCS 'chain', in power generation and industrial plants, as well as continued and comprehensive RD&D will be essential to reach, e.g., the '2DS' emission target. The CSLF will need to monitor progress in light of the Priority Actions suggested above, report the findings at the Ministerial meetings and suggest adjustments and updates of the TRM. The CSLF can then be a platform for an international coordinated effort to commercialize CCS technology.

Several bodies monitor the progress of CCS nationally and internationally, the most prominent probably being the Global CCS Institute through its annual Global Status of CCS reports. However, the CSLF will need to have these status reports condensed in order to advise Ministerial meetings in a concise and consistent way. To this end, it is recommended that the CSLF will, through its Projects Interaction and Review Team (PIRT), monitor the progress in CCS in relation to the Recommended Priority Actions.

Through the CSLF Secretariat, the PIRT will:

- solicit input with respect to progress of CCS from all members of the CSLF;
- gather information from a wide range of sources on the global progress of CCS;
- prepare a simple reporting template that relates the progress of the Priority Actions;
- report annually to the CSLF TG; and
- report biennially, or as required, to the CSLF Ministerial Meetings.

The PIRT should be given the responsibility to prepare plans for and be responsible for future updates of the CSLF TRM.

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Abbreviations and Acronyms

2DS	IEA ETP 2012 2^{o}C scenario
ACTL	Alberta Carbon Trunk Line
APGTF	Advanced Power Generation Technology Forum (UK)
ASU	air separation unit
BECCS	bio-energy with carbon capture and storage
CCS	carbon capture and storage
CO_2-EOR	enhanced oil recovery using CO_2
CSLF	Carbon Sequestration Leadership Forum
CSA	Canadian Standards Association
CSU	CO_2 purification unit
DECC	Department of Energy and Climate Change (United Kingdom)
DOE	Department of Energy (USA)
DSF	deep saline formation
EC	European Commission
ECBM	enhanced coal bed methane recovery
ECCSEL	European Carbon Dioxide Capture and Storage Laboratory Infrastructure
EGHR	enhanced gas hydrate recovery
EGR	enhanced gas recovery
EOR	enhanced oil recovery
ETP	Energy Technology Perspectives (of the IEA)
EU	European Union
GCCSI	Global CCS Institute
HS&E	health, safety and environmental
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas Research and Development Programme
IGCC	integrated gasification combined cycle
InSAR	inferometric synthetic aperture radar
ISO	International Organization for Standardization
LCA	life-cycle assessment
LSIP	large-scale integrated project
NCCCS	Nottingham Centre for Carbon Capture and Storage
NETL	National Energy Technology Laboratory (USA)
O&M	operation and maintenance
OECD	Organization for Economic Co-operation and Development
OSPAR	Oslo and Paris Conventions
RD&D	research, development and demonstration
ROAD	Rotterdam Opslag en Afvang Demonstratieproject (Rotterdam Capture and Storage Demonstration Project)
TG	Technical Group (of the CSLF)
TRM	Technology Roadmap
WEO	World Energy Outlook (of the IEA)
UK	United Kingdom
ULCOS	Ultra-low CO_2 Steelmaking consortium
USA	United States of America
ZEP	European Technology Platform for Zero Emission Fossil Fuel Power Plants

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TECHNICAL GROUP

Final Report by the CSLF Task Force on CCS Technology Opportunities and Gaps

Background

At the September 2011 CSLF Ministerial Meeting in Beijing, a Task Force was formed to investigate CCS Technology Opportunities and Gaps. The Task Force mandate was to identify and monitor key CCS technology gaps and related issues, to determine the effectiveness of ongoing CCS RD&D for addressing these gaps, and to recommend any RD&D that would address CCS gaps and other issues. This document is the Final Report from the Task Force.

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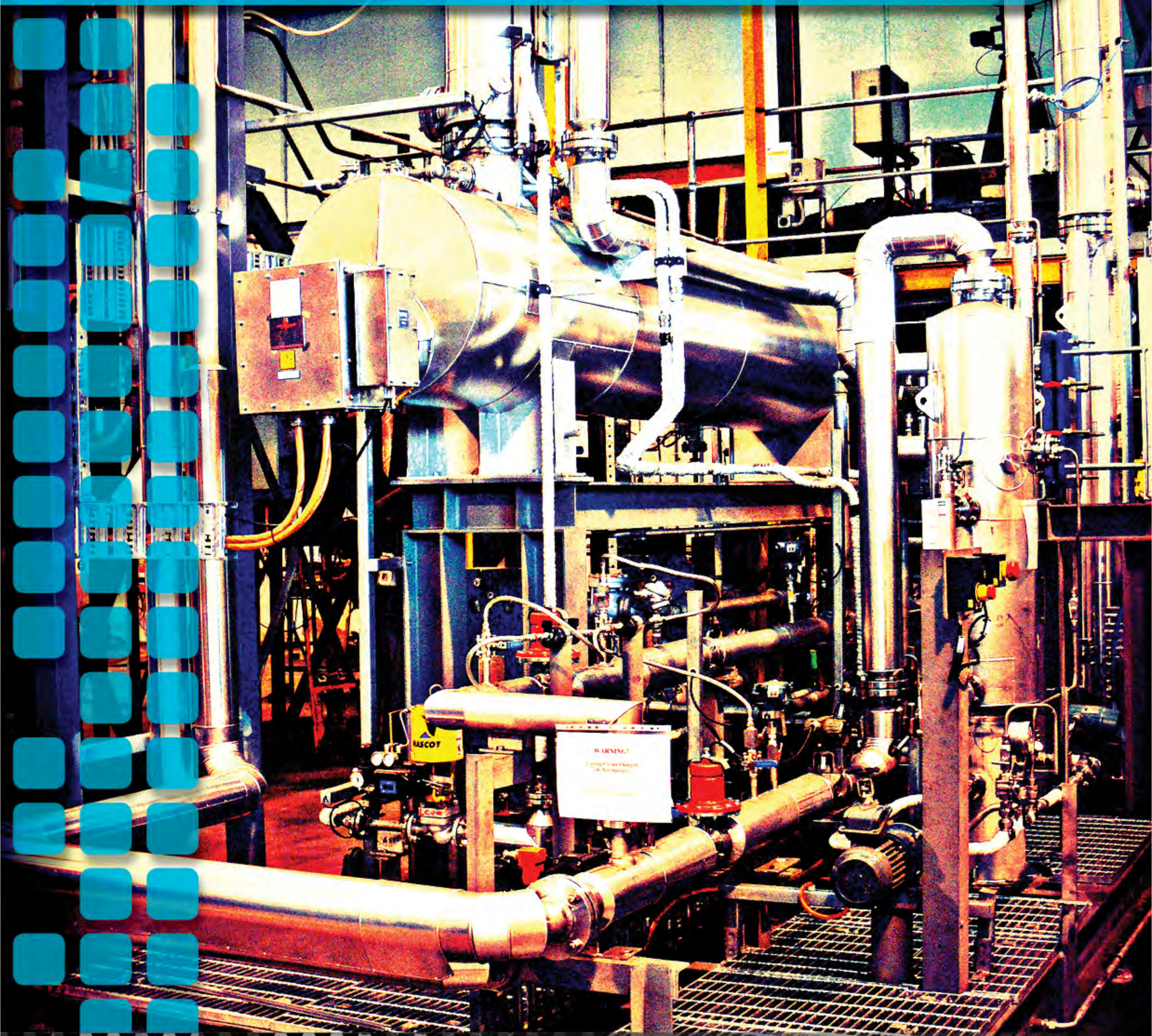
CCS Technology Development

Gaps, Opportunities and Research Fronts

Prepared for the CSLF by The CRC for Greenhouse Gas Technologies (CO2CRC)



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1. Executive Summary

It is now clear that climate change management involving CCS deployment will be less expensive than alternative strategies (see IEA 2013 and ETI 2013). To realise and enhance the full potential of CCS at a global level, continued technology development is essential.

In recent years, a strong field of CCS science and engineering has emerged. At a high level there are no major technology gaps. CCS has been and can be deployed. The focus of technology development is now on driving down costs and securing more efficient operational, monitoring and regulatory outcomes.

This report sets out some of the key technical issues and research fronts in CCS technology and identifies opportunities and gaps relevant to policy makers and technology development strategists. The report is complemented by a global listing of pilot plant projects in both capture and storage. The high level observations and recommendations to the CSLF concerning CCS technology are:

Capture and Integrated Combustion

1. A number of capture technologies are available today (mostly solvent-based) and deployed on large scale demonstrations or industrial processes; capture costs can be expected to fall substantially by 2025-2030, particularly if promising technologies are moved though the development pathway.
2. There is a need to continue to support 2nd and 3rd generation technology development, from pilot to large scale demonstration[1], to secure the lowest cost technologies for the future, noting the lead times can run to decades. Adsorbents and membranes are likely to play a big role.
3. For all capture technologies, improvements must focus on all dimensions: (1) materials, (2) equipment, (3) impurity handling/tolerance, (4) process design and heat integration, and (5) environmental impact.
4. Retrofit of current coal-fired power stations can result in much lower cost of electricity than closing viable stations and building new low emission coal-fired stations.
5. More work is required on the flexible operation of power plants with CCS, synchronised with electricity market prices and links to renewable energy production.
6. For oxyfuel technologies; on coal combustion the technology is mature, but for natural gas combustion an important new technology field is opening up. The latter will play a big part linked to the new role of shale gas. New turbine design is an important R&D front. Lower cost oxygen will benefit all oxyfuel technologies.
7. Chemical looping is an important emerging technology for some industrial processes such as cement manufacture and also for fluidised bed combustion of coal; moving the technology to larger scale is a priority.

[1] In USA, EU, China, Korea, Japan, competitions allow prospective capture technologies to compete for funding for large scale demonstration projects.

CO_2 Transport

The technology for transport of CO_2 is well established, with over 6,500 km of CO_2 pipelines in the US transporting 48 – 58Mtpa. There are however still technology improvement opportunities, with the key points being:

1. Transport pipeline technology is mature and available; however, some technology improvements are needed to get costs down and increase safety, including managing and designing for variations in CO_2 composition in multiple source hubs (includes understanding equations of state and operational implications), fracture propagation control, corrosion control and CO_2 dispersion modelling for safety case and risk assessment purposes.
2. Large scale transport of CO_2 by ship offers promise and needs to be demonstrated at scale.
3. Experience is needed in planning, designing and implementation of large-scale CO_2 transport networks, including hubs and multiple points of capture.

Storage

A significant established body of technology from the oil and gas industry has combined with the research and demonstration on CCS over the last 10-15 years to underpin a strong consensus that safe CO_2 storage is possible today. New knowledge will be gained from the numerous larger scale deployments underway. This will fine tune the technology for large scale deployment. Key research and improvement areas are:

1. Modelling the CO_2 behaviour, this is a vital element of storage research and technology integration. The main development issues require:
   a. Fundamental research, laboratory work and data gathering on physical and chemical parameters to better underpin detailed modelling of fluid flow behaviour, chemical reactions and geomechanical outcomes;
   b. More integrated dynamic models of fluid flow, geochemistry and geomechanics running on very large computers;
   c. The ability to build robust basin scale fluid flow models for operators, regulators and governments involved in resource allocation and resource conflict resolution;
   d. Modelling and strategies associated with the hydraulic integrity of intra-formational seals and faults, and the number and thickness of cap rock required; and
   e. Developing stronger models and underpinning data sets on possible migration pathways (fault, seal, strata/structure), to improve risk management.
2. Improvements to optimise operational effectiveness and storage efficiency include:
   a. Development of strategies to optimise drill patterns and angles for CO_2 injection and pressure management to increase injectivity and control the behaviour of the CO_2 plume;
   b. Understanding induced seismicity and development of pressure management strategies to avoid minor induced seismic events and the potential to compromise cap rocks;
   c. Approaches to enhance residual trapping, in-situ mineral trapping and mineralisation and also injection strategies for storage in low-permeability rocks;
   d. Development of methodologies to manage high permeability thief zones and differential pressure effects that can reduce efficient reservoir use; and

e. Understanding of fines migration, mineral dissolution and precipitation and the effects of subsurface microbes that could compromise operational efficiency and storage resource effectiveness.

3. Development (based on oil and gas industry practice) of internationally consistent standards for:
    a. Storage site characterisation methodologies;
    b. Storage efficiency factors; and
    c. Capacity estimation and reporting standards.

4. Technology and risk management strategies to mitigate or manage unintended CO_2 migration, including:
    a. Well integrity, including developing CO_2 resistant well cement and simulation modelling of migration through wells;
    b. Mitigation strategies, such as pressure management, and profile modification[2];
    c. The attribution of leaked CO_2 and associated measuring and accounting issues; and
    d. Strategies to give even greater confidence in long term storage.

Monitoring, Measurement and Verification (MMV)

MMV continues to be a vital part of CCS technology development, as it underpins operational decisions as well as the relationship with regulators and the community. Some key observations and recommendations are:

1. Establish technologies and methodologies for offshore (sub marine) MMV, as a significant portion of global storage capacity is offshore;
2. Improve onshore and offshore MMV technology and models:
    a. The whole package of geology between the storage reservoir and the surface, to assess the timing and possible modes of potential CO_2 movement and to inform remediation and mitigation strategies;
    b. CO_2 plumes in the subsurface, particularly with respect to the relationship between CO_2 saturation and plume resolution; and
    c. MMV in aquifers which cover large areas, where specific plume movement may be more difficult to precisely predict, particularly in laterally unconfined aquifers.
3. Continue work on controlled release calibration and natural analogues; these experiments are important for CO_2 detection and accounting;
4. Develop an agreed methodology and language for dealing with what will be the principal result of most monitoring – a null result;
5. Continue the rapidly evolving trend to continuous, high resolution, low cost, low impact subsurface monitoring;[3]

[2] This involves modifying the strata in certain zones with agents such as gels and surfactants to change the flow rates of CO_2

6. Continue to develop new seismic interpretation and inversion techniques for enhanced CO_2 detection including:

    a. Quantitative interpretation of 4D seismic, including 4D inversion (deterministic, stochastic, etc) and 4D full-waveform inversion;
    b. Using changes in seismic attenuation and seismic anisotropy of the rocks;
    c. Integrating reservoir & seismic modelling with 4D seismic into the closed loop prediction/correction workflow and improving signal sensitivity with new data analysis algorithms;
    d. Using rock physics data and models to enhance fundamental understanding of CO_2 injection-related changes in the rock properties;
    e. Deployment of permanent sources, massive buried receiver arrays; and
    f. Combining active as well as passive seismic methods and novel processing algorithms.

7. Develop and/or improve:

    a. Subsurface (down well) solid state detectors for CO_2 and ensure that they can be deployed for long periods of time in the subsurface; and

    b. A portable low cost C-14 detection system (CO_2 from fossil fuels has no C-14 content).

Building Technical Knowledge Capability and People

The broad deployment of CCS will require a significant pool of technically skilled people as well as continuing growth and dispersion of the CCS technology knowledge base. Governments are encouraged to:

1. Continue R&D and technology development to both develop the knowledge base and to train engineers and scientists in CCS technologies.
2. Stimulate international collaboration by:

    a. Supporting researchers to travel and join smaller collaborative research projects involving exchange of researchers and complementary work programs;
    b. Allocating resources and funds for researchers to contribute to, or buying a stake in consortia of international researchers around larger demonstration projects where particular teams can bring a unique or complementary set of skills; and
    c. Involving industry, government and researchers in international CCS projects.

Industry dynamics associated with exploration and technology development

One of the most pressing problems for global CCS deployment at scale is getting the requisite amount of exploration started when there is a weak price on carbon. The lead times from initiating exploration through approvals and construction will often be as long as 10-15 years. This has implications for the degree to which CCS can contribute to 2050 targets and the rate of technology development[4]. Governments are encouraged to:

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[3] The extent to which this is required on any specific project will depend on the cost, the proponent's needs, the stage and status of their project and the relationship to regulators and local communities.

[4] If exploration is slow, large scale deployment will be slow, which will in turn slow learning-by-doing for current technologies and market pull for the next generation of technologies. Conversely, if governments

1. Start the identification and pre-competitive data generation of prospective storage basins, making assessments of the likely realistic storage capacity.
2. Either start exploration or incentivise the private sector to start exploration.

In summary, governments around the world now have a technology at their fingertips that can be deployed to manage carbon emissions, but the rate of take-up and the associated improvements in technology needs to be incentivised. There are profound role-of-government lessons from the development of the nuclear industry and SO_2 scrubbing in the US and also from the global LNG industry. Governments played a decisive role in both the development and the diffusion of these technologies. Governments must continue to be involved in the same way in CCS development; where the diffusion and take-up of the technologies is strongly driven by the credibility of incentives for industry to invest in commercial scale projects and technology development.

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incentivise the market to act, with carbon prices, taxes or mandates, the result will be synergistic for both exploration and discovery of storage capacity and also for technology development. The result will be lower costs, which will in turn drive the market dynamics more strongly.

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2. Introduction

This document identifies the key research fronts in CCS technology being pursued today and highlights some of the high-level global gaps and opportunities required to move technology forward to facilitate the deployment of safe, low cost CCS to attempt to stay within the IEA's '2^{o}C scenario' (2DS). It provides additional information on CCS technologies to support the 2013 CSLF Technology Road Map (TRM) and supplement the comprehensive carbon capture and storage status report by SINTEF (2013). Understanding where the key research fronts and prospects are can be helpful in seeing the challenge ahead. This document is also supported by a compilation of the major capture and storage pilot plants around the world (see Appendices A - B).

Technology Horizons			
Technology Development Status	**Definition**	**Paradigm**	**Time Horizon to commercial deployment**
First generation technologies or Horizon 1	Technologies in operation today that are the subject of further improvement through research and learning by doing	"Improvement of current technology"	In large scale operation today
Second generation technologies or Horizon 2	New technologies, tested at bench scale, that offer significant operating cost/ performance or environmental benefits	"Highly prospective new technologies proven at bench scale"	10-15 years
Third generation technologies or Horizon 3	Early stage, potentially game changing technology concepts that have only limited theoretical or laboratory work	"Paradigm shifting technologies offering major improvements"	15-25 years

Table 1: Technology Horizons

The global effort on CCS is moving to large scale demonstration where current technologies are being pushed to successfully demonstrate large scale CCS. This is supported by a small (relative to the magnitude of the problem) but growing base of scientists and engineers and an increasing level of research, development and pilot scale demonstration. This scientific and research effort will be vital to fine tuning and improving the current technologies (first generation technologies) for immediate deployment

The lead times on technology development in the energy and resources sphere are long, often running for 20-30 years. The research front associated with CCS technology development will be with us for many decades as the technology is developed, deployed and improved. It is thus important for the CSLF to note the second and third generation technologies that offer the potential to ensure technology is developed to reach 2050 targets with the lowest cost to global communities. (Note that table 1 overleaf provides definitions of each generation or horizon of technologies.)

Achieving significant cost reductions will not only require a vigorous and sustained level of research and development but also a substantial level of deployment where further learning and improvements can develop. A critical part of the equation will be the need for a market pull for CO_2 technologies.

In assessing current CCS technologies, it is helpful to understand the position of the technologies on the generic technology learning curve or “Grubb” curve (Figure 1). The concept of the curve is that most technologies follow the curve in their development as they progress to commercial application. Firstly, as the technology matures, the accuracy of performance of cost estimates tends to improve, but there is also a learning effect as more and more units are deployed that drives down the cost. In Figure 1 the key areas of CCS technology are plotted on a generic curve. It should be noted that those in black are the current technologies that will continue to improve.

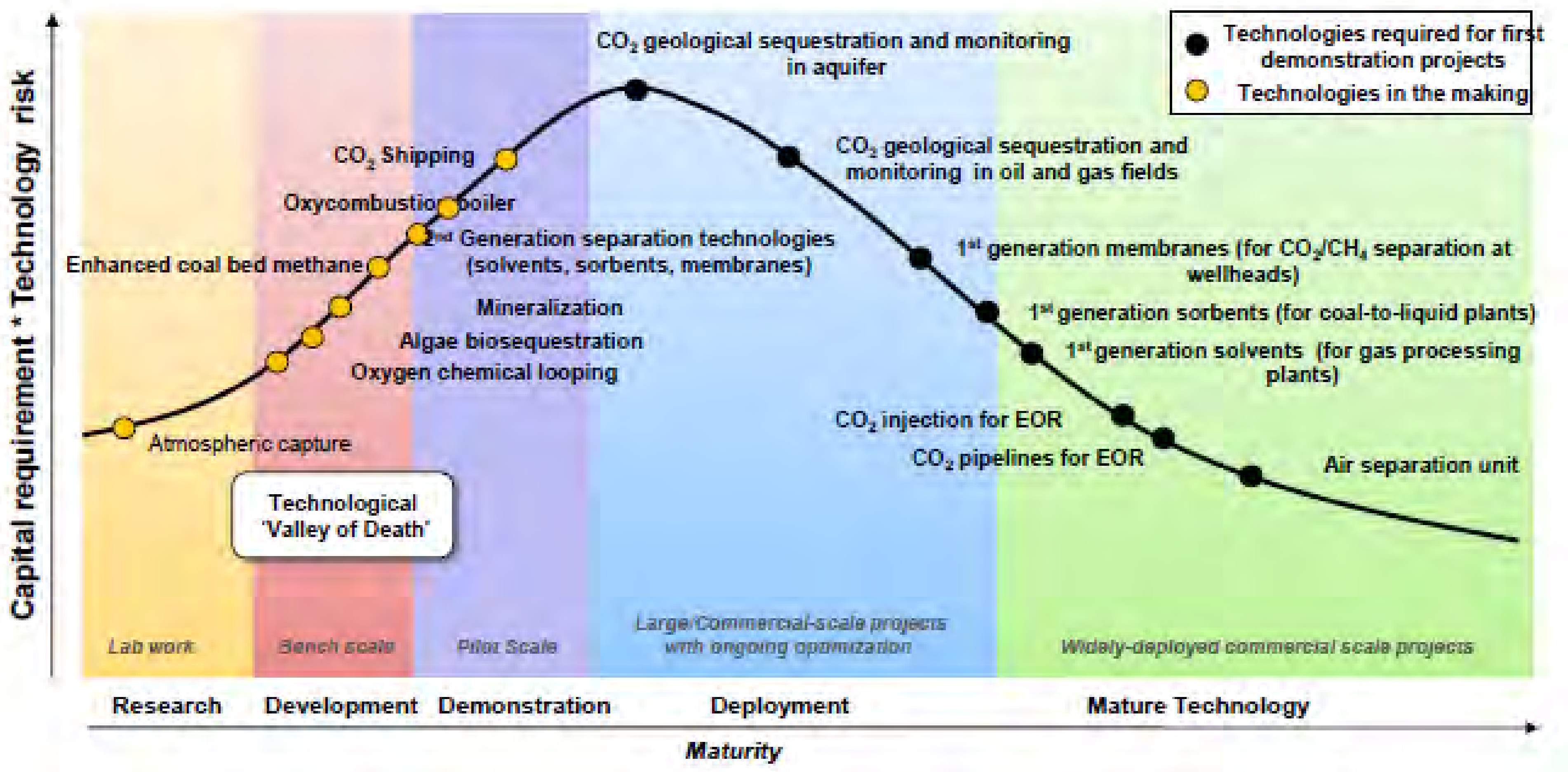

Figure 1 - Understanding the status and pathways of CCS technology on the Grubb Curve

From *"Leading the Energy Transition: Bringing Carbon Capture & Storage to Market"* SBC Energy Institute 2012

3. CO_2 Capture Technologies

Significant CO_2 emissions from stationary sources, which can be mitigated using CCS, come from power generation and industrial processes. The condition (pressure, temperature, flow, concentration) in which the CO_2 is available for separation varies with the stationary emission source. For example, in natural gas processing the CO_2 is at significantly higher pressure and sometimes concentration than in the flue gases of thermal power stations, which influences the choice of technology. A summary of the emission sources and relevant CO_2 capture technologies is given in Figure 2.

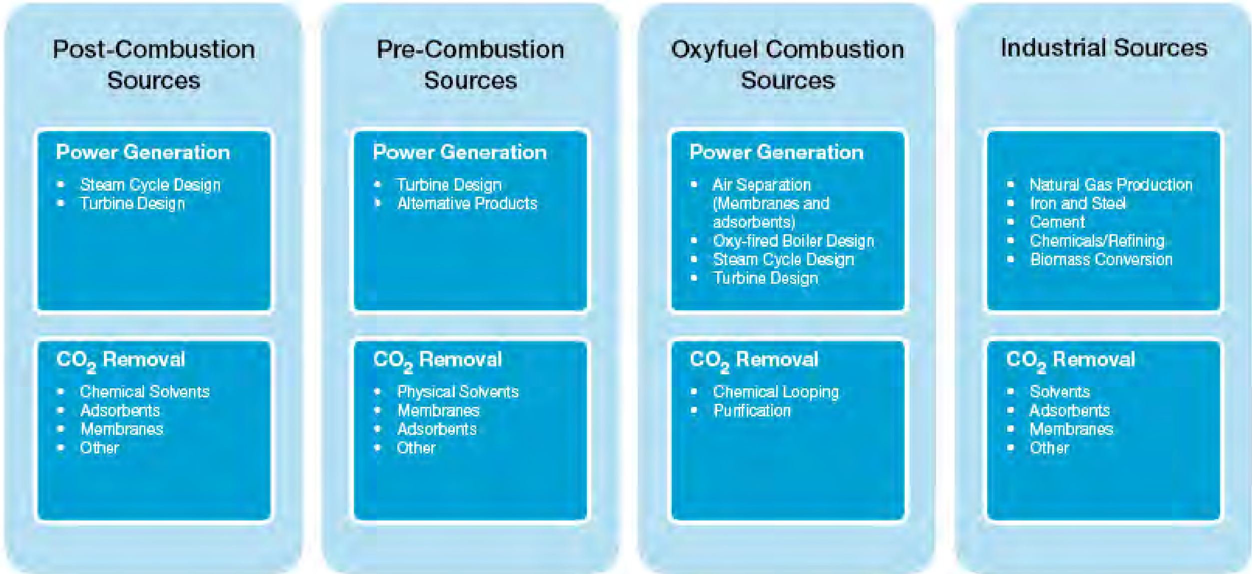

Figure 2 - CO_2 Emission Sources with CO_2 Capture Options

The three leading capture technologies for CO_2 capture are currently (i) solvent absorption, (ii) membrane separation and (iii) gas adsorption. There is significant research, pilot plant and engineering activity in these areas. Other technologies, such as hydrates/cryogenics, hybrid technologies and chemical looping are also emerging as having potential for CO_2 capture but do not have the same commercial foundation in gas processing as solvent absorption, membrane separation and gas adsorption.

To accelerate the large scale deployment of CCS by 2050 to meet the requirements of the 2DS scenario (IEA 2012), significant advances in CO_2 capture technologies must occur. The technologies which are available today and are likely to be implemented in the larger scale demonstration projects by 2020 are termed first generation. Technologies that are likely to be commercially available by 2030 and 2050 are termed second and third generation technologies, respectively.

In terms of power generation, first generation capture technologies reduce the absolute efficiency of the power station by 10-15 percentage points, where the absolute efficiency of the power station is the ratio of the electricity produced to the energy available in the fuel source based on higher heating value (HHV). Second generation and third generation capture technologies are expected to significantly reduce the impact of this energy penalty on the power station. To progress from first generation to second generation and then to third generation innovation needs to occur holistically within the following themes to enable the significant reduction in costs required.

1. Materials: improved separation efficiency and reduced material cost
2. Equipment: reduced size, cost and footprint
3. Impurity handling/tolerance: improved durability, reduced size, cost and footprint
4. Process design and heat integration: efficient flowsheet design with reduced energy penalty through reduced steam/heat and direct electric power requirements and integration with the power station
5. Environmental impact: CO_2 removal without any other negative environmental impacts
6. Water consumption: CO_2 removal with minimal water use

These themes are discussed in the following sub-sections in relation to emerging next (second and third) generation capture technologies for the various emission sources.

3.1. Solvents

3.1.1 Materials

Solvent technologies are well established for removing CO_2 from gas streams and have been used commercially for several decades in the oil and gas, chemical and refining industries. First generation solvent technologies are ready for application to pre and post-combustion capture along with capture from industrial sources, but they have significant energy penalties and high costs.

The challenge for next generation solvents is to find materials which will result in much lower regeneration energies and have a low cost. Next generation solvents, which will be most relevant to post-combustion capture, include advanced amines and amino acids, carbonate systems (including precipitating carbonates), solvent blends, immiscible liquids and ionic liquids. A summary of the next generations of competing solvent materials is given in Figure 4. The specific challenges for these solvents are also presented here along with prospective areas for future research.

Figure 3 presents an example of cost reductions that can be achieved from changing the solvent material (from a first generation monoethanol amine (MEA) and state of art (SOA) amine to a second generation precipitating carbonate system The waterfall diagram presented here also shows other process improvements, which are discussed under the subsequent themes.

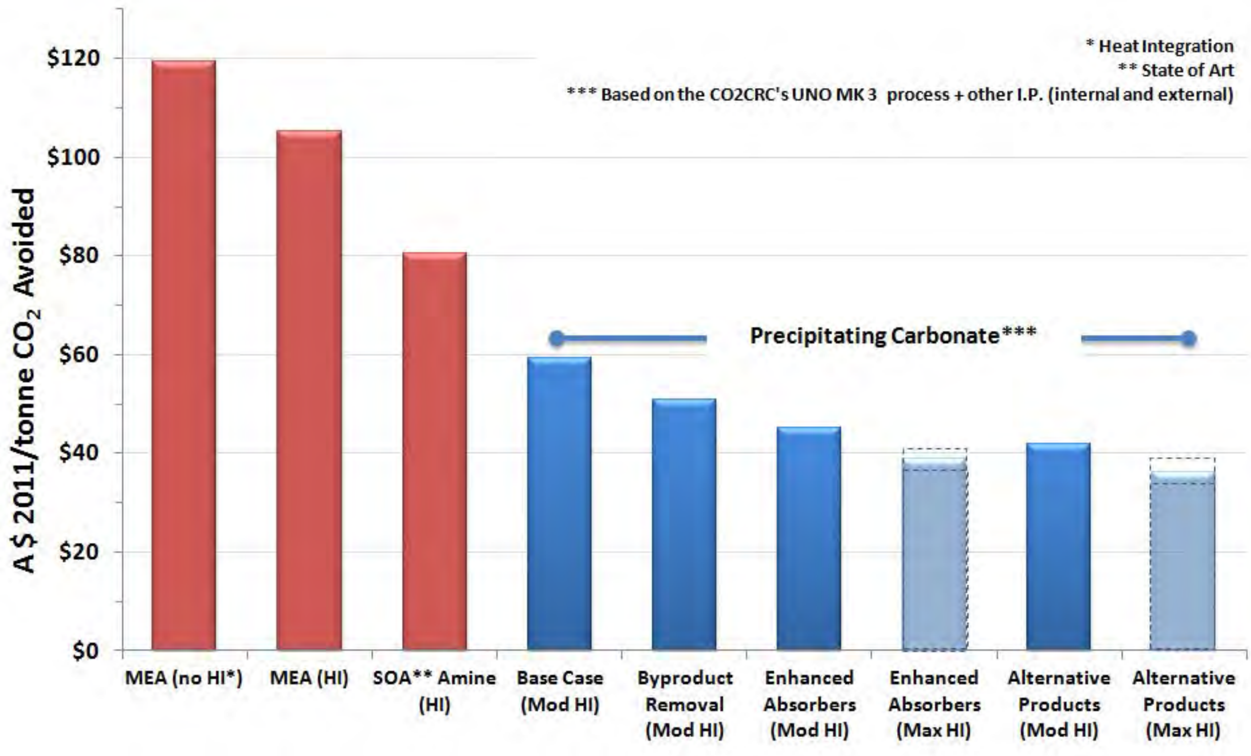

Figure 3 - Impact of Process Improvements using the UNO MK 3 Solvent Process as an Example.

Further details on the UNO MK 3 process used as the example here can be found elsewhere (Anderson et al 2012). The example presented here is based on retrofitting CCS to an Australian brown coal power station.

The first big improvement in the cost occurs through changing the process from a standard amine-based solvent process (shown in red) to an advanced solvent process (UNO MK 3 shown in blue) that allows multi-component capture, uses a less expensive solvent and has a smaller regeneration circuit. Further improvements are then made by producing fertiliser products (second blue column) from the SOx and NOx impurities in the flue gas.

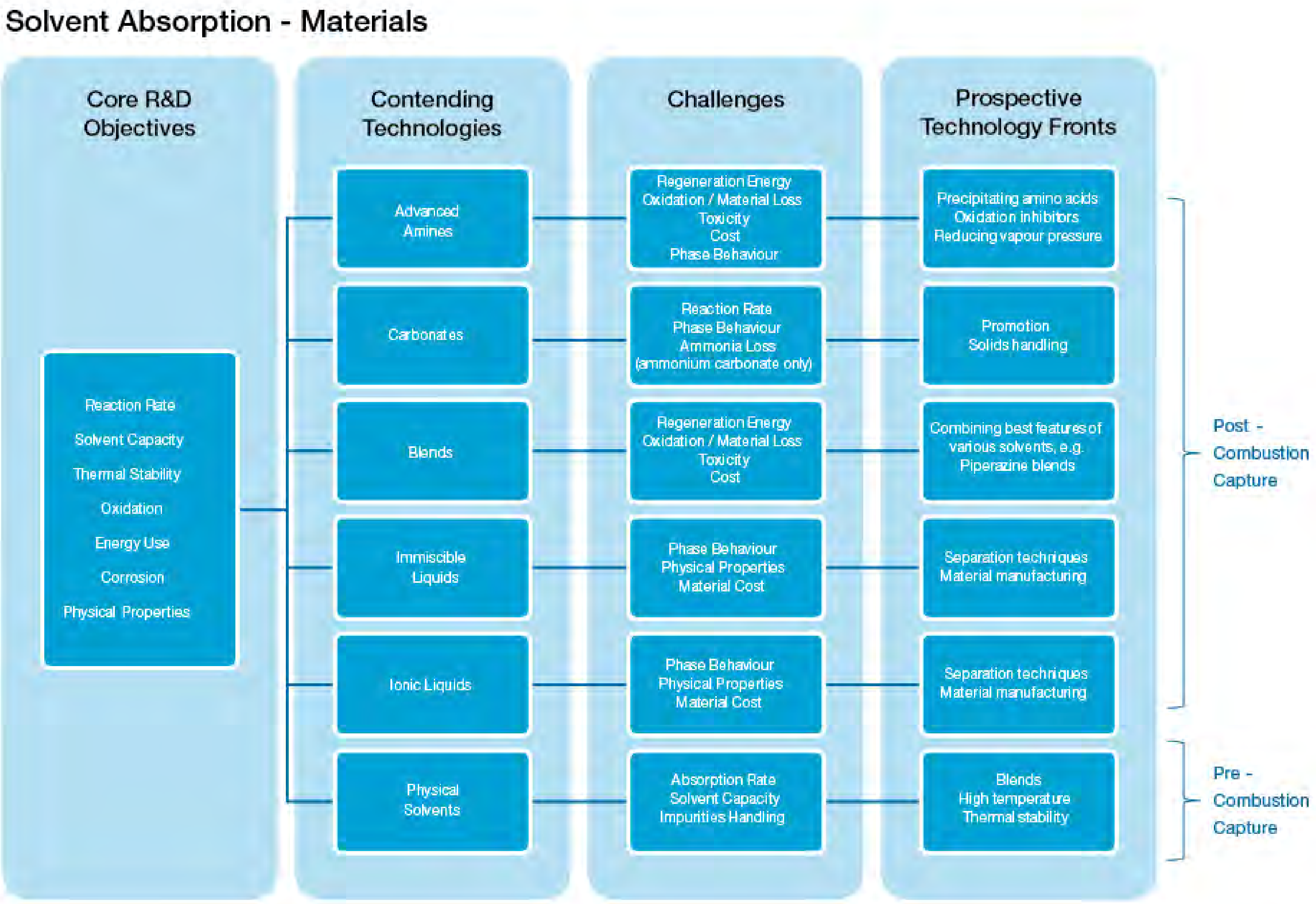

Figure 4 - Next Generation Solvent Materials, Prospective Technology Fronts

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3.1.2 Equipment

The largest equipment items in solvent absorption processes are the absorber and regeneration columns. Improvements in the height and size of these columns are needed to enable significant reductions in capital cost. An example of such an improvement is a concentric column design (Hooper et al 2008), which combines the two columns into one and includes construction using alternative materials to steel. An indication of the possible cost reduction for this particular equipment was shown previously in Figure 3. A summary of the next generation equipment for solvent absorption is presented in Figure 5.

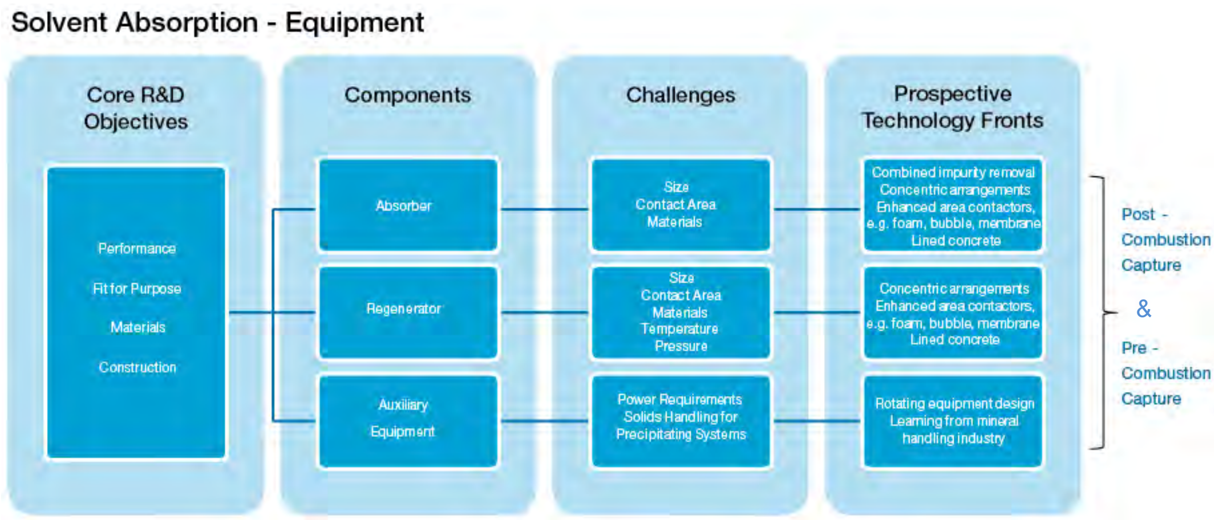

Figure 5 - Next Generation Solvent Absorption Equipment, Prospective Technology Fronts

3.1.3 Impurity Handling/Tolerance

Traditional amine-based solvents degrade in the presence of SO_x, NO_x and oxygen due to a reaction of the amine with these components which produces heat stable salts along with other degradation compounds such as nitrosamines. While power stations in the USA and Europe are fitted with flue gas desulphurisation (FGD) units, further treatment is often required to remove the SO_x and NO_x to the even lower levels tolerated by the amine-based solvents.

Solvent absorption processes that do not require any pre-treatment to remove impurities prior to absorption will be advantageous. In particular, solvents which are primarily inorganic materials will be tolerant to oxygen along with the SO_x and NO_x present in post-combustion capture applications.

CO2CRC's UNO MK 3 process for example does not require any pretreatment of the flue gas and produces a valuable fertiliser byproduct from the SO_x and NO_x impurities.

3.1.4 Process Design and Heat Integration

The impact on the cost of CO_2 avoided using heat integration for solvent absorption was demonstrated previously in Figure 3 by the difference in the first two red columns (impact of moderate heat integration) and the dark blue and light blue bars (impact of maximum heat integration).

The standard way of reporting the energy usage for solvent processes is the energy required by the regeneration process (e.g. ~ 4 MJ/tonne CO_2 removed). For the promotion of CCS, it may be more useful to present the energy usage following heat integration. As part of the ETIS project, CO2CRC determined that following heat integration, the energy requirement of the three main capture technologies (solvent absorption, membrane separation and gas adsorption) is very similar at 1 GJ/tonne of CO_2 captured (Qader et al 2011a).

3.1.5 Environmental Impact

A major challenge facing the next generation of solvents is the environmental impact when considering CCS in wide scale deployment. While the global warming potential of the power station will be reduced, amine-based solvents degrade, which when emitted to the atmosphere, significantly increase the environmental impact of the power station as shown through other environmental indicators such as human toxicity potential (Merkewitz et al 2009). This is mostly due to the formation of nitrosamines from the reaction of secondary and tertiary amines with NOx (Statoil 2010). In response to this issue there is currently a lot of research activity in improving the environmental impact of amine-based solvent processes.

The established method for assessing environmental impact is Life Cycle Assessment (LCA), which is a practice set out by ISO Standards 14040 to 14042. LCA deduces the environmental impact of a process based on all the inputs and outputs to and from the process and has been used as an assessment tool for the environmental impact of various MEA-based solvent processes (Schreiber et al 2012). Along with the negative impacts on the environment from amine-based solvents, the results of these LCA also show that if carbon dioxide from the additional power required to operate capture facility is not avoided, the capture efficiency drops from 90% capture to 60%-75% capture.

3.2 Membrane Separation

3.2.1 Materials

First generation materials such as cellulose acetate and polyimides are well established for commercial separation of CO_2 using membranes in the natural gas industry where the available system pressure is high.

The development of membrane technologies for post combustion capture is focused on improved materials that have moderate CO_2/N_2 selectivities (30-50) and high permeabilities (>1000 GPU). These process conditions have been shown to provide the smallest energy penalty (Ho et al 2008, and Merkel et al 2010). Emerging candidate membrane materials include the Membrane Technology & Research (MTR) Polaris©, polymers of intrinsic microporosity (PIMs) (Guiver & Moo 2013) and thermally rearranged polymers (Park et al 2010). Facilitated transport systems, such as those based on poly vinyl alcohol (Deng et al 2009 and Zou & Ho 2006) or room temperature ionic liquids (Bara et al 2010) also show promise. There is also significant research effort being directed to mixed matrix membranes, which combine the best features of adsorbent technology into a membrane format.

Other active areas of development for membrane technologies in the application of pre-combustion capture include the development of membrane reactors for the water gas shift process, and palladium based membranes for hydrogen separation. In addition, ion and oxygen transport membranes for air separation are being developed for oxyfuel and pre-combustion applications.

Figure 6 presents a summary of next generation of materials for membrane separation.

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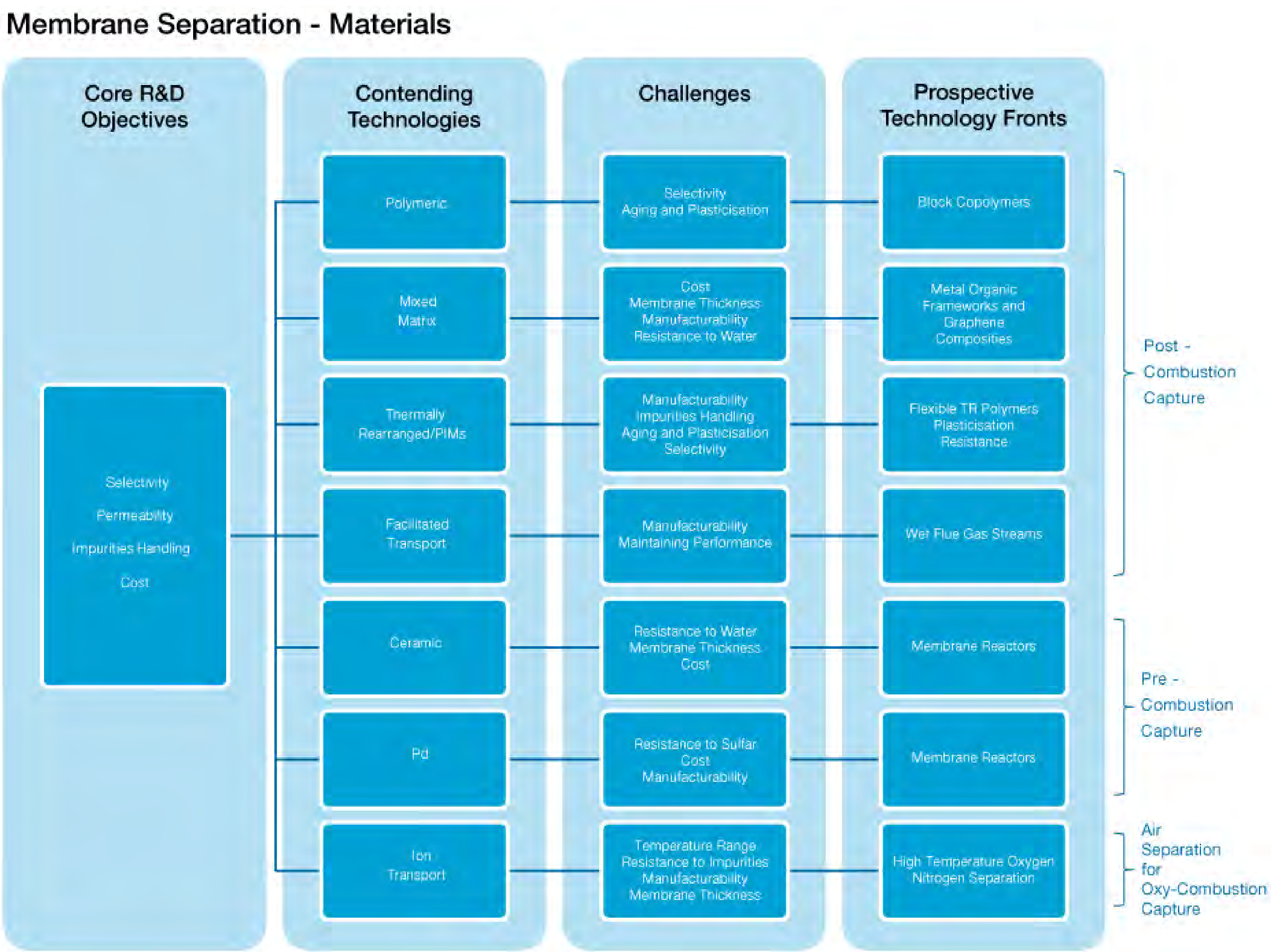

Figure 6 - Next Generation Membrane Materials, Prospective Technology Fronts

3.2.2 Equipment

For the application of post-combustion capture, the challenge facing the next generation of membrane equipment design is the need to develop low pressure drop, countercurrent flow modules. While spiral wound membranes may provide the best resistance to fly ash fouling, which can increase pressure drop, they are not able to accommodate countercurrent flow arrangements. For this reason, MTR have recently trialed the use of plate and frame arrangements. Other groups are focusing on hollow fibre modules, which can provide a good mix of pressure drop, fouling resistance and countercurrent flow.

A further mechanism for reducing equipment costs is to utilise membrane contactors. In this case, a standard gas sorption solvent is contained within a hollow fibre membrane module. Such an approach provides a dramatic reduction in equipment foot print and reduces issues with foaming and flooding. However, performance can drop over time due to membrane pore wetting, which reduces the mass transfer coefficient. Pore wetting can also be induced by unbalanced pressure drop control during startup and shutdown and so elaborate pressure drop control mechanisms may be required.

Most process flowsheets for post combustion capture incorporate a vacuum on the permeate side of the membrane. As membrane technology reaches a larger scale, research will be required to develop the necessary large scale vacuum pumps. The flue gas will be wet, so these are likely to be ring type pumps.

A summary of the next generation equipment for membrane separation is presented in Figure 7.

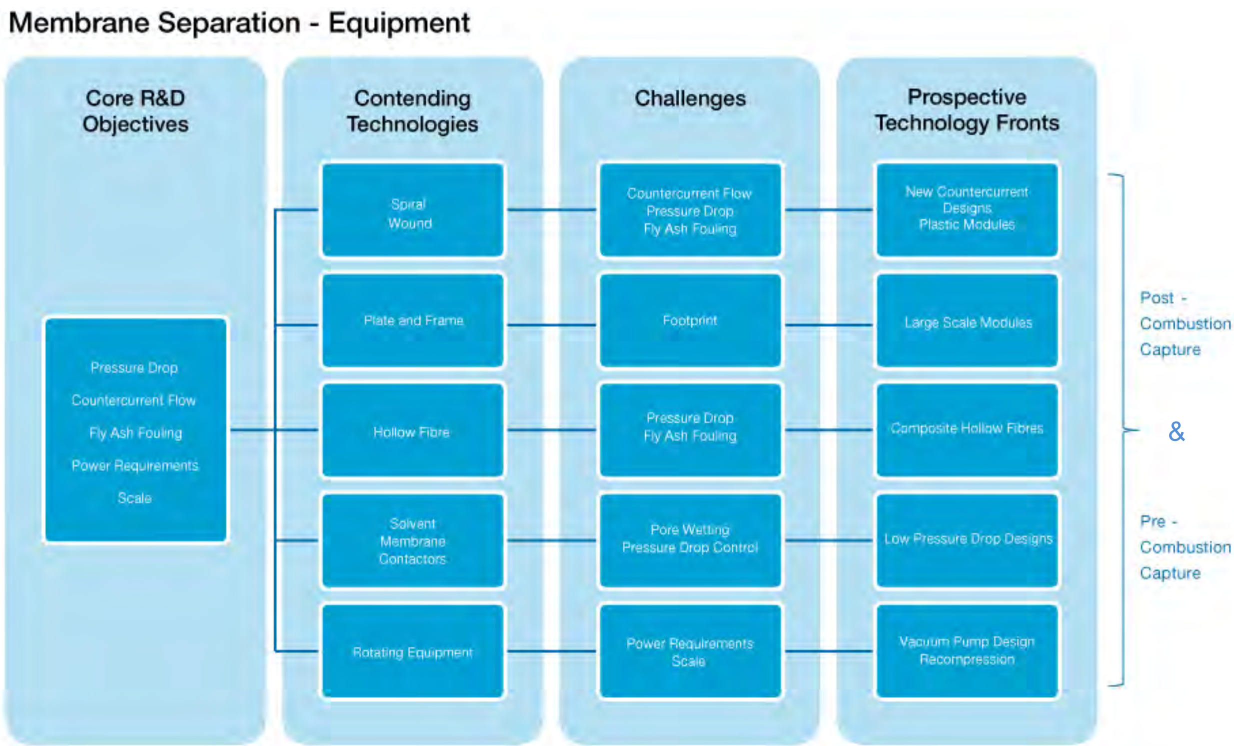

Figure 7 - Next Generation Membrane Separation Equipment, Prospective Technology Fronts

3.2.3 Impurity Handling/Tolerance

To avoid pretreatment, membrane materials will need to be tolerant to water along with oxygen and sulphur and nitrogen compounds. Most polymeric membrane materials show resistance to these compounds, which increases their attractiveness for post combustion applications. The only limitation is the requirement to maintain the level of condensable impurities (such as water) at around 10^{o}C below the dew point. This is readily achievable using a simple cycle of cooling, knockout and reheat.

In the post combustion application, membrane materials if placed upstream of pretreating equipment such as flue gas desulphurisation (FDG) or a direct contact cooler (DCC) will also need to adequately handle fly ash compounds. Initial work by CO2CRC indicates that dry fly ash does not reduce membrane permeability, but the presence of water and fly ash together can be an issue. Fly ash will add to pressure drop concerns within the membrane module.

Resistance to water and sulfur compounds is an issue with many inorganic membranes targeted at pre-combustion capture applications. Zeolite membranes often show poor resistance to water and Palladium membranes are readily compromised by sulfur. The use of mixed matrix membranes which combine both inorganic and organic elements within one structure will also suffer from these issues.

3.2.4 Process Design and Heat Integration

Of all of the technologies reviewed in the National Energy Technology Laboratory (NETL) study published in March 2012, the MTR membrane process, which represents a next generation process, provided the lowest cost of CO_2 avoided for post combustion capture from black coal (NETL 2012). The reduction in energy penalty is achieved through the use of the combustion air feed to the boiler as a sweep gas flow to a countercurrent membrane module. A downstream cryogenic separation is used to reach the necessary CO_2 purity. Work by CO2CRC has shown that further benefits may be gained by enriching the oxygen content of this combustion air feed.

3.2.5 Environmental Impact

Unlike solvent absorption, there are no chemicals continuously used in membrane separation, which bodes well for low environmental impact. The environmental impacts will primarily come from the manufacture of the membrane materials and the energy required by the membrane separation process taken from the power station. Consideration will also need to be given to the ultimate disposal of the membrane elements; currently these are sent to landfill.

3.3 Gas Adsorption

3.3.1 Materials

Like solvent absorption and membrane separation, gas adsorption is also a well established technology in the natural gas industry, although generally used for gas dehydration rather than CO_2 removal.

The developments of new adsorbent materials, which have high selectivities and high adsorption capacities, along with process improvements make gas adsorption a promising technology for next generation capture technologies. Promising adsorbent materials for next generation capture include alumina, zeolite, activated carbon, metal organic frameworks, organic-inorganic hybrids and dry regenerable sorbents.

A number of these materials fall under into the broad category of solid sorbents (Samanta et al 2012 and Sjostrom & Krutka 2010). Solid sorbents are currently in use at pilot scale demonstration at sizes up to 10 MW (Park et al 2011). Specifically, next generation solid sorbents, which may be most relevant to post-combustion capture, include carbonates and solid amines. For pre-combustion capture, oxides such as magnesium oxide and calcium oxide may be more relevant.

The challenges associated with these materials relate to selectivity, capacity, kinetics, oxidation, and thermal stability along with the ability to handle impurities and water, regeneration and mechnaical strength. Materials will need to be developed with modified compositions and surface chemistry to meet these challenges.

Figure 8 presents a summary of next generation of materials for gas adsorption.

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Gas Adsorption - Materials

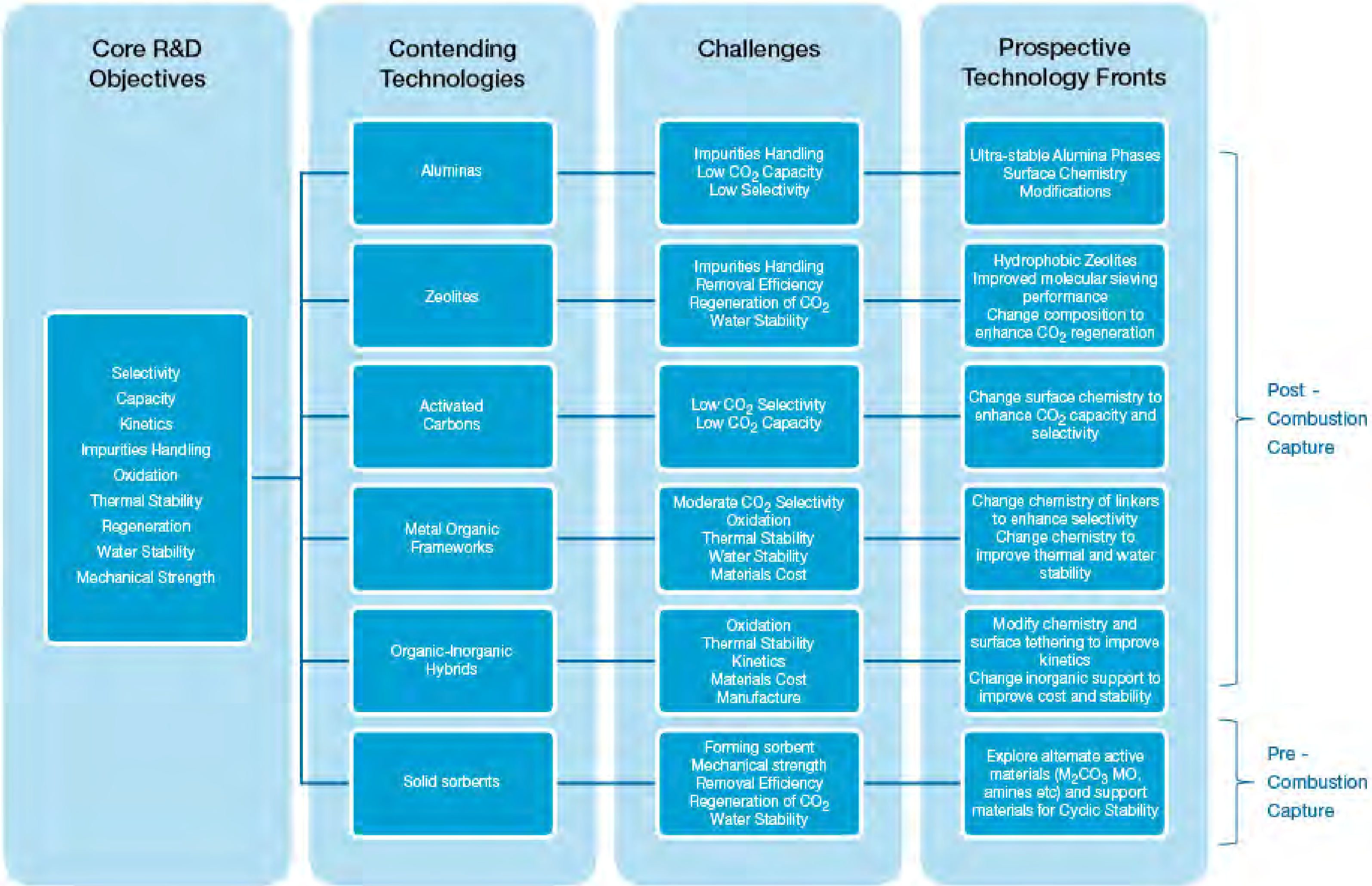

Figure 8 - Next Generation Gas Adsorbent Materials, Prospective Technology Fronts

3.3.2 Equipment

For gas adsorption technologies, equipment improvements will be imperative in the areas of gas/solid contact, regeneration and rotating equipment (e.g. vacuum pumps).

The possible configurations for contacting CO_2-containing gas streams with solid sorbents are fixed bed, fluidised bed, and moving bed. Compared with the other contactor arrangements, fluidized bed contactors have the advantages of (i) excellent gas-solid contact due to vigorous agitation of sorbent particles, (ii) minimum diffusional resistance, (iii) uniformity of temperature, and (iv) faster overall kinetics. Fluidised bed tests have been successfully conducted for the removal of CO_2 from flue gases (at a scale of 0.5 MW) for more than 700 hrs of continuous operation (Park et al 2011). Several regeneration options are available when using adsorbents to capture CO_2. Pressure Swing Adsorption (PSA) is common in cases where the feed is already at pressure (such as pre-combustion capture) or when the high energy costs associated with pressurising a low pressure feed are more than offset by improvements in system performance and capital costs.

Post-combustion capture from low pressure flue gas streams do not benefit from pressurising the feed stream. Instead, vacuum must be applied to the bed to remove the CO_2. This vacuum swing adsorption process (VSA) is appropriate for small scale capture plants and current research must address the very low vacuum levels needed (5kPa) to regenerate the bed and recover CO_2 at sufficiently high purity for sequestration. Other options for bed regeneration include thermal swing processes. Low quality heat can be used to regenerate the adsorbent bed either in the form of steam purge or hot CO_2 purge. The former is used in the TDA Advanced CO_2 Absorber.

The TDA Advanced CO_2 Absorber is a next generation adsorbent process reported in the 2012 NETL Report (NETL 2012). This process resulted in costs only slightly higher than those reported for the MTR membrane process (NETL 2012). The KIER “Dry Sorbent CO_2 Capture Process” has been trialed at 0.5 MWe and is the first pilot plant to show the feasibility of CO_2 capture technology using dry sorbent spheres (Park at el 2011, 2012, Yi et al 2013).

The drawbacks of the thermal regeneration process is the large time scale needed for heating and cooling the porous adsorbent – future research efforts must be directed at reducing this time scale so that larger size TSA units become practical.

Hybrid schemes employing thermal assisted vacuum swing adsorption processes are promising options for future adsorption based technology. All of these gas adsorption processes need appropriate materials with good CO_2 capacity, selectivity and thermal stability as well as tolerance to impurities and water.

A summary of the next generation equipment for gas adsorption is presented in Figure 9.

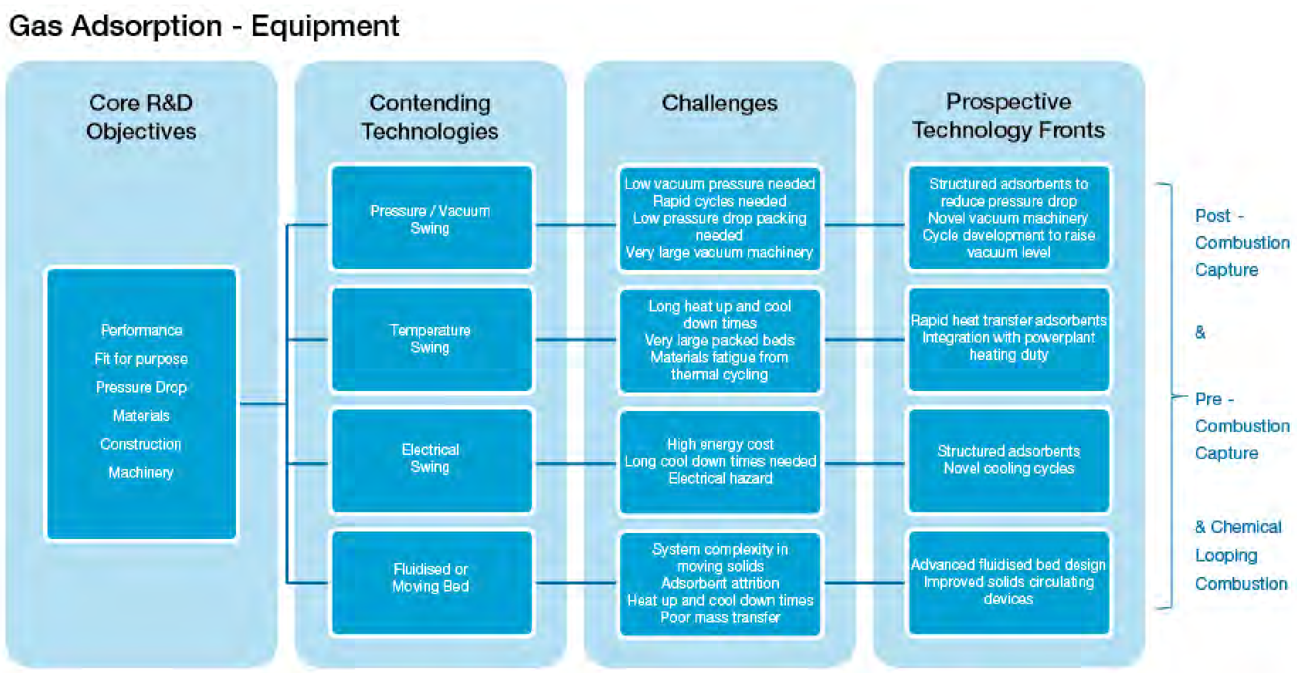

Figure 9 - Next Generation Gas Adsorption Equipment, Prospective Technology Fronts

3.3.3 Impurity Handling/Tolerance

Like membrane separation materials, gas adsorption materials will also need to be tolerant to various impurities including water.

Potential materials include ultra-stable alumina phases, hydrophobic zeolites, activated carbon, metal organic frameworks, organic-inorganic hybrids and solid sorbents.

Solid sorbents which are primarily inorganic materials will be tolerant to oxygen along with SO_x and NO_x present in post-combustion applications. However, water does influence the carbonation and regeneration reaction for alkali carbonate sorbents (Lee et al 2011).

3.3.4 Process Design and Heat Integration

The energy penalty for adsorption-based processes primarily comes from the heat required for temperature swing regeneration and/or the power required to drive vacuum regeneration. Reductions in the energy penalty can be made by using waste heat for regeneration and/or by reducing the pressure swing required. The next generation adsorbent process reported in the NETL study was the TDA Advanced CO_2 Absorber. This process resulted in costs only slightly higher than those reported for the MTR membrane process (NETL 2012).

3.3.5 Environmental Impact

Like membrane separation, there are no chemicals continuously used in gas adsorption, which also bodes well for low environmental impact. The environmental impacts will primarily come from the manufacture of the adsorbent materials and the energy required by the gas adsorption process taken from the power station. If the adsorbent materials are manufactured from organic materials, then the environmental impacts of degradation products such as nitrosamines may be an issue.

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3.4 Chemical Looping Processes

Chemical looping processes are based on chemical reactions that take place in two different reactors and a reactive solid that is circulated between the reactors, thus the name looping. Different chemical looping processes are being studied or applied in small scale for application to CO_2 capture. They all appear attractive alternatives to other CO_2 capture systems, mainly due the potential lower energy penalty. However, none of the technologies have been proved at scales much larger than laboratory scale or small pilot and they all need further research or upscaling.

3.4.1. Chemical Looping Combustion

Chemical Looping Combustion (CLC) is an approach that is usually placed in the oxy-fuel category. It utilises a solid carrier, usually a metal oxide, which is able to adsorb oxygen from air and release it in the presence of a gaseous fuel such as natural gas. The oxidation takes place in what is commonly referred to as the air reactor and subsequent reduction takes place in the fuel reactor. The exhaust from the air reactor is N_2 and trace gases in air, from the fuel reactor CO_2 and H_2O. The net amount of heat generated over the two reactors is the same as oxygen during normal combustion. Some advantages of CLC over other technologies are:

- Almost pure CO_2 is ready for storage after condensation of the fuel reactor flue gas
- N_2 is removed before combustion
- Greater safety - combustion takes place without the presence of free gaseous oxygen.
- The energy penalty will be lower than other technologies, as there is no need for a separate air separation unit nor for scrubbing systems.

Some remaining challenges for CLC include:

- Finding an optimal metal oxide
- Developing reliable looping systems
- Obtaining efficient heat integration
- Application to solid fuel.

Comprehensive reviews of the status of CLC can be found in Adanez et al (2012), Pröll & Hofbauer (2011) and Bozzuto (2012)

3.4.2. Chemical Looping Reforming

Chemical looping can also be applied in a pre-combustion mode, as auto-thermal Chemical Looping Reforming, often referred to as CLR (Adanez et al, 2012 and Pröll & Hofbauer, 2011). CLR differs from CLC in that it is operated at understoichiometric conditions, i.e. insufficient air is added to the air reactor to completely oxidise the fuel. In addition, steam is added to the fuel reactor along with the fuel. The output of CLR is H_2, CO_2, CO and H_2O. Benefits and challenges for CLR are as for CLC.

3.4.3. Calcium Carbonate Looping

Calcium Carbonate looping (Blamey et al, 2010 and GCCSI 2013) can be used as a post-combustion CO_2 capture solution. Flue gas is fed to a carbonator with calcium oxide (CaO) that reacts with the CO_2 in the flue gas to form calcium carbonate ($CaCO_3$). The $CaCO_3$ is transferred to a calciner to which is then added air, heat and fuel. Advantages of the calcium looping process are:

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- The output from the calciner is high purity CO_2.
- The exothermic heat of the CO_2 absorption reaction is recovered for use in steam generation, which reduces the energy penalty.
- The raw material ($CaO/CaCO_3$ found for example in dolomite and natural gypsum) is abundant and inexpensive.

Remaining work includes improving and understanding the reactivity of the sorbent, and research activities are needed to improve sintering of the sorbent and overcome challenges related to attrition and fragmentation of the sorbent and ash fouling in the calciner. Taiwan inaugurated the world's largest carbon capture plant employing calcium looping process technology in June 2013.[5] Operating at one metric tonne of CO_2 per hour, it is reported that 90 percent of CO_2 produced during the cement manufacturing process is captured and requires less than 20 percent additional energy. There is potential to increase the scale of activity.

3.4.4. Sorption Enhanced Reforming (SER)

This process also uses CaO as an absorbent (Blamey et al, 2010). Fuel (natural gas or syngas from a gasifier) and steam is fed into the carbonator (or reformer), CO_2 is absorbed by the CaO to become $CaCO_3$, which in turn is transferred to the calciner (or combustor). Here air or oxygen is added, possibly with some fuel, and calcinated to CaO, which is returned to the carbonator under the addition of heat. Output from the carbonator is H_2-rich syngas and from the calciner CO_2-rich exhaust. The hydrogen can be used as fuel or for electricity production, thus this version of calcium looping can be regarded as a pre-combustion solution. Benefits and challenges are basically as for calcium carbonate looping.

SER has been patented for use in combination with a solid oxide fuel cell (SOFC) to produce electricity. Waste heat from the SOFC is used in the SER process, so that an overall efficiency of > 80% is claimed (ZEG Power 2013).

3.5 CO_2 Compression

Another example of significant equipment improvement is Ramgen "Shockwave" Compression. Ramgen Compression is expected to use less power and be less expensive than traditional in-line compression, which will again improve the cost of CO_2 avoided (Dreher et al 2011).

A summary of the next generation equipment for CO_2 compression is presented in Figure 10.

[5] The plant was built in collaboration with Taiwan Cement Corp Situated in Sioulin Township, Hualien County—a cement production hub for Taiwan. Source : Taiwan Today 12 Jun 2013 http://taiwantoday.tw/ct.asp?xItem=206192&CtNode=436

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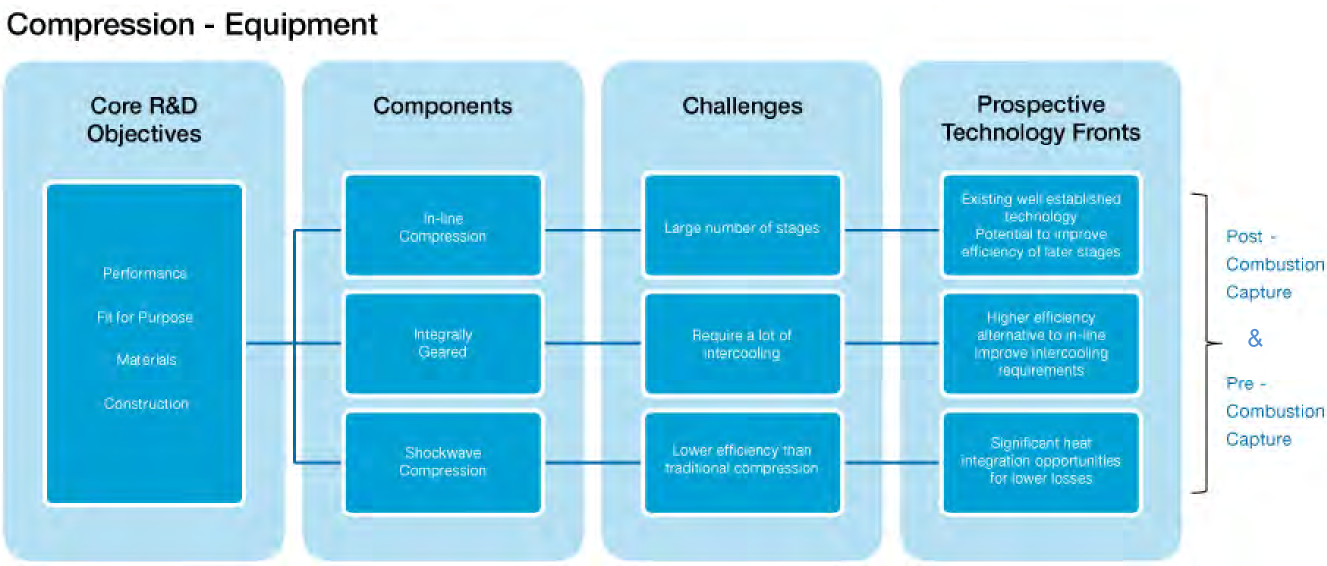

Figure 10 - Next Generation Compression Equipment, Prospective Technology Fronts

3.6 Future Directions

3.6.1 Technology Development Status at 2013

Figures 11, 12 and 13 show the current status of the technology development for solvent absorption, membrane separation and gas adsorption, respectively, using the generic Grubb Curve format (SBC Energy Institute 2012).

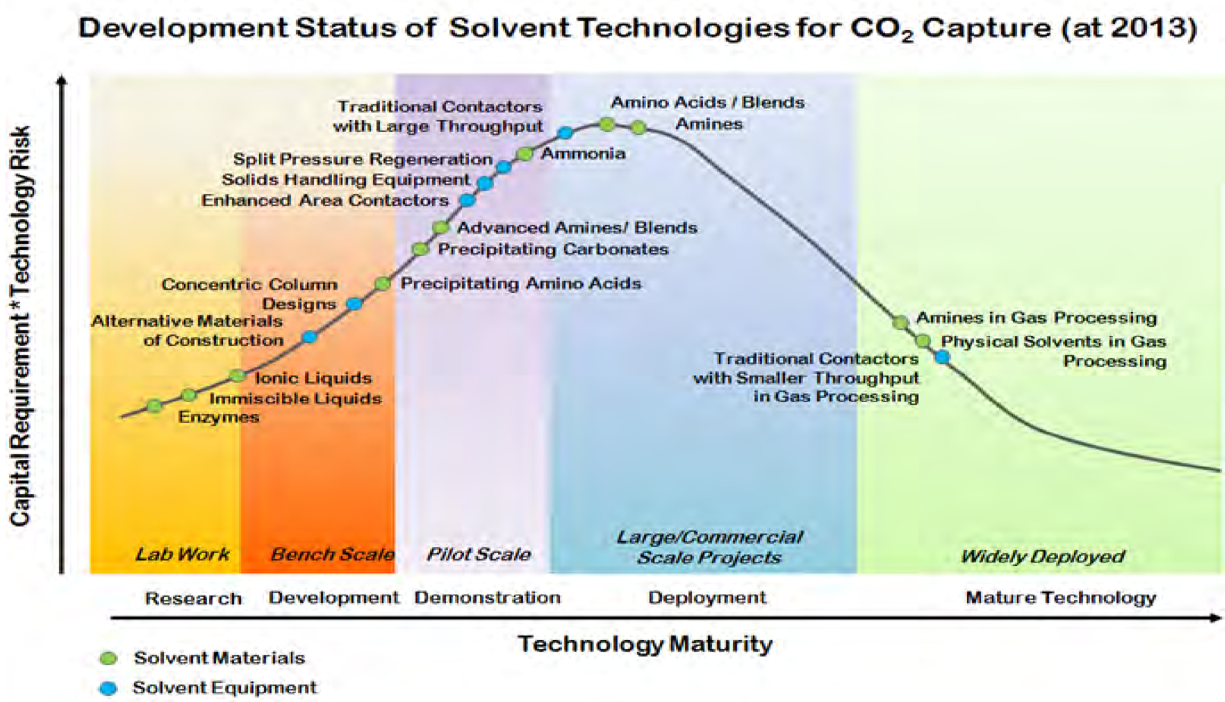

Figure 11 - Current Status of Solvent Absorption Technology

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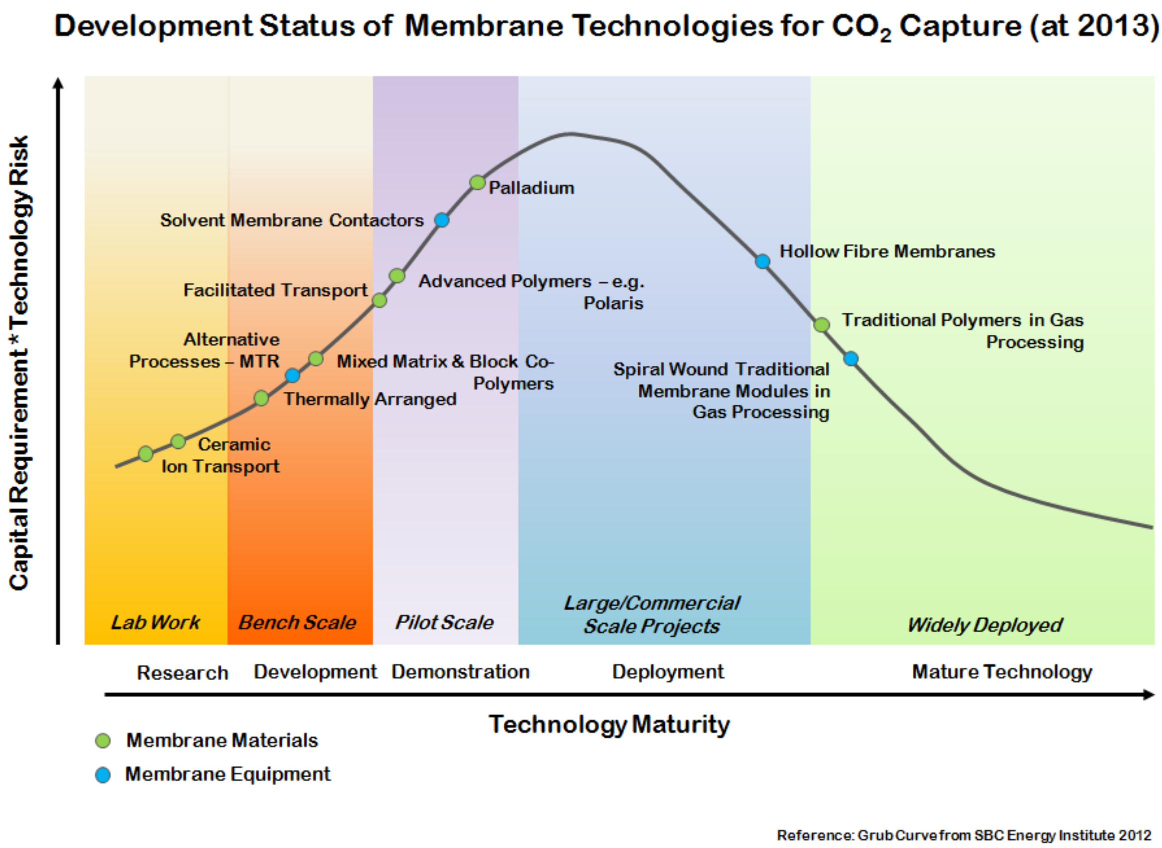

Figure 12 - Current Status of Membrane Separation Technology

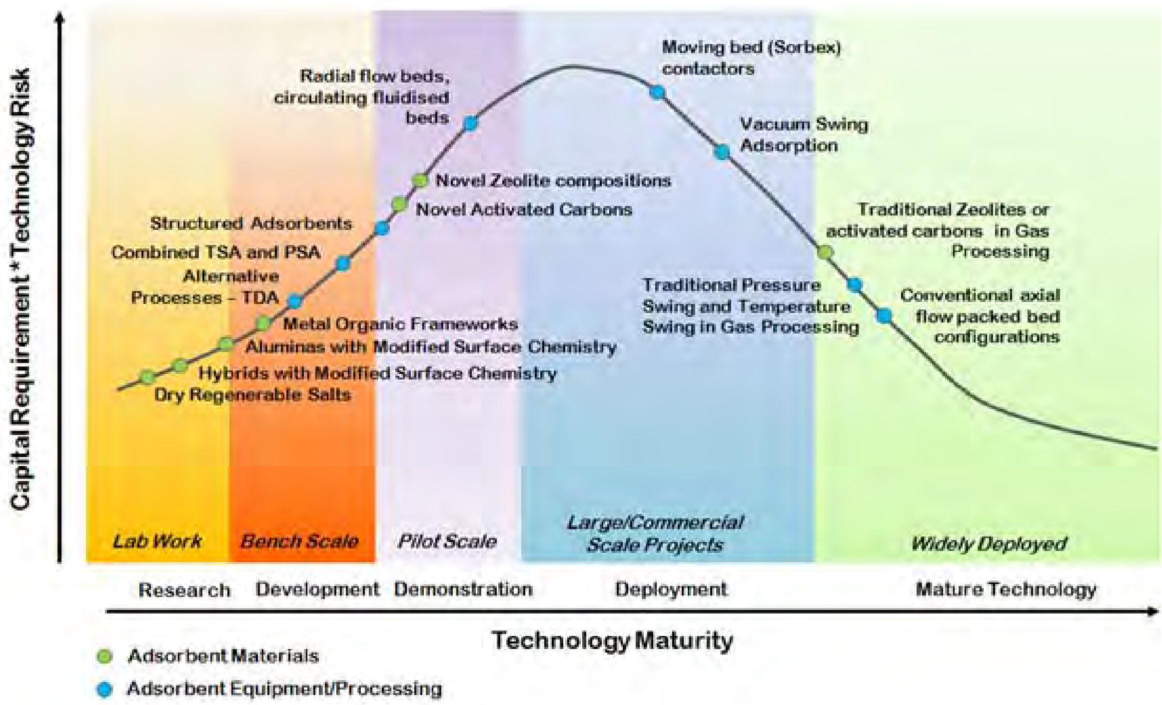

Figure 13 - Current Status of Gas Adsorption Technology

3.6.2 Technologies Beyond 2030

The larger scale CO_2 capture technologies in application beyond 2030 are likely to still be within the leading fields of solvent absorption, membrane separation and gas adsorption because of the research activities in these areas today. Other technologies such as cryogenics and chemical looping may be starting to appear although probably on a smaller scale and potentially associated with more advanced power generation systems such as pre-combustion and oxy-combustion capture.

The CO_2 separation materials used as part of solvent absorption, membrane separation and gas adsorption that will be employed beyond 2030 will be highly efficient, have low energy use and be tolerant to impurities. In addition, the CO_2 capture process will be highly integrated with the emission sources (such as power stations) to minimise overall energy losses. The combined characteristics of future CO_2 capture technologies should enable the significant cost reductions required.

Finally, CO_2 capture technologies beyond 2030 will have a low environmental impact such that installation of the CO_2 capture facility and reduction of the greenhouse gas emissions does not create other environmental problems (such as existing amine-based solvent absorption processes would do).

3.6.3 CCS Implementation Pathways

In addition to the technical innovation required to reduce costs, appropriate funding mechanisms are necessary to pull the technology forward from lab and pilot scale through to large scale development. This needs to be done through suitable policy frameworks which allow commercial progression in a timely manner.

The pathway of retrofitting existing power stations with carbon capture is considered to be important for the uptake of CCS. Retrofit pathways will be discussed further in Section 3.6.4. In addition, allowing flexibility in the design of carbon capture facilities such that the technology can be upgraded in future will also play a role in accelerating CCS as discussed further in Section 3.6.5. Finally, a list of the current pilot plants demonstrating CO_2 capture is given in Appendix A.

3.6.4 Retrofit and Flexible Operation with Energy Market Pricing

Retrofitting post-combustion CCS to existing power stations can provide important capital cost savings for the implementation of CCS. Studies completed by CO2CRC suggest that retrofitting CCS to existing brown and black coal pulverised power stations may result in levelised costs of electricity (LCOE) 40% lower than new build power stations with CCS. This is due to the reduced capital requirements from using existing power generation equipment and the potential to effectively use waste heat to reduce energy penalties. While retrofit may not be possible in all cases it should be given serious consideration. Retrofitting capture may incorporate a repowering component that is designed as an integrated capture solution.

Retrofitting/repowering with CCS is being demonstrated such as projects like Boundary Dam. However, over time, it is expected that new build power stations with CCS will ultimately provide the most efficient solutions.

Modeling of post-combustion capture operating in environments where electricity markets are established, giving variable pricing, indicates that having the ability to change the rate of CO_2 capture can substantially lower the average cost of capture. For example, at times of the day with high electricity prices in an environment with low to moderate carbon prices it may make sense to stop capture and take as much value from the higher electricity prices, paying the penalty to emit more CO_2. At times of very low electricity prices, capture plant would be operated at full capacity to avoid the carbon prices.

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3.6.5 Avoiding Technology "Lock-In"

Large scale CO_2 capture facilities which will be built in the coming decade are likely to use first generation capture technologies. These technologies may bring large energy penalties to the associated power stations or industrial sources depending on how they are configured, e.g. heat integration opportunities. The nature of basic absorption/stripping designs is such that new and improved solvents are likely to be able to be used in first generation plants. This is likely to avoid, or limit, so called technology 'lock-in'. More elaborate new generation solvents (such as those using phase change) and novel technologies such as membranes and adsorbents will undoubtedly require different equipment configurations. Should this be an issue proponents may wish to consider the implications of these alternative generations technology in defining emissions reduction pathways.

3.6.6 Pilot Plant Facilities

Pilot scale trials are critical to taking the technology to the next stage. A list of the pilot plants demonstrating CO_2 capture are given in Table 1 in Appendix A. Several of the demonstration sites are now working together on collaborations.

Key Observations and Recommendations to the CSLF on Capture Technologies

1. A number of capture technologies are available today (mostly solvent based), deployed on large scale demonstrations or industrial processes; capture costs can be expected to fall to US substantially by 2025-2030, particularly if promising technologies are moved though the development pathway.
2. There is a need to continue to support 2nd and 3rd generation technology development, from pilot to large scale demonstration[6], to secure the low cost technologies for the future, noting the lead times can run to decades. Adsorbents and membranes are likely to play a big role.
3. For all capture technologies improvements must focus on all dimensions: (1) materials, (2) equipment, (3) impurity handling/tolerance, (4) process design and heat integration and (5) environmental impact.
4. Retrofit of current coal-fired power stations can result in much lower cost electricity than closing viable stations and building new low emission coal-fired stations.
5. More work is required on the flexible operation of power plants with CCS synchronised with electricity market prices and links to renewable energy production.
6. Capture on natural gas combustion, an important new technology field, is opening up. This will play a major part linked to the new role of shale gas. Flue gas recirculation, low flue gas pressures and high oxygen contents will all be important research areas, as will oxyfuel combustion (see next chapter). New turbine design is also an important R&D front.

[6] In USA, EU, China, Korea, Japan, competitions allow prospective capture technologies to compete for funding for large scale demonstration projects.

7. Chemical looping is an important emerging technology for some industrial process such as cement manufacture and also for fluidised bed combustion of coal; moving the technology to larger scales is a priority.

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4. Oxyfuel Combustion Technology for Coal- and Gas-Fired Power Plant

4.1 Introduction

Oxyfuel combustion for power generation with CO_2 capture is the use of oxygen and recycling of part of the flue gas instead of air as oxidant to the fuel. This results in a flue gas with very high CO_2 and H_2O concentration therefore requiring physical separation to deliver the specified purity of CO_2 for transport and storage.

With a number of research activities on Oxyfuel Combustion Technology (OxyCT), particularly for coal-fired plant application, this technology has reached a significant level of maturity. However, for the application of this technology to gas-fired power plant, it is still considered to be at an early stage of development.

This section of the report will cover the status of the technology and the identification of the gaps and opportunities for both coal and natural gas.

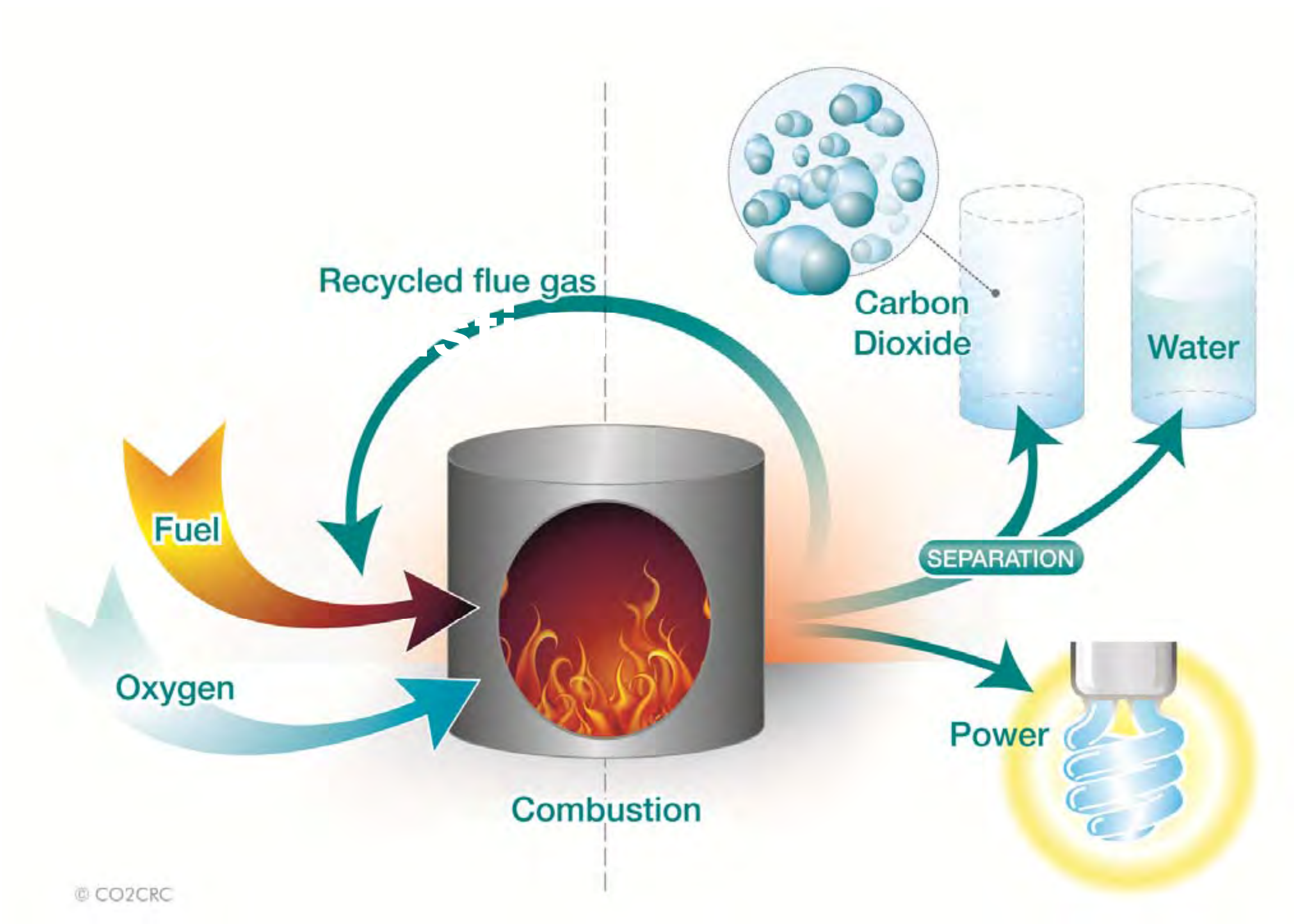

Figure 14 - Diagram showing the main components of Oxyfuel combustion technology

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4.2 Oxyfuel Combustion for Coal Fired Power Plant

In the past ten years, significant RD&D investment has been made in the development of oxyfuel combustion technology for coal-based power production. The technology has reached a significant level of maturity and the next step is for it to be demonstrated in a large scale plant in order of 100 to 300MWe to benefit from learning by doing. This should provide the opportunity for the technology to develop enhanced efficiency and achieve lower cost and risk.

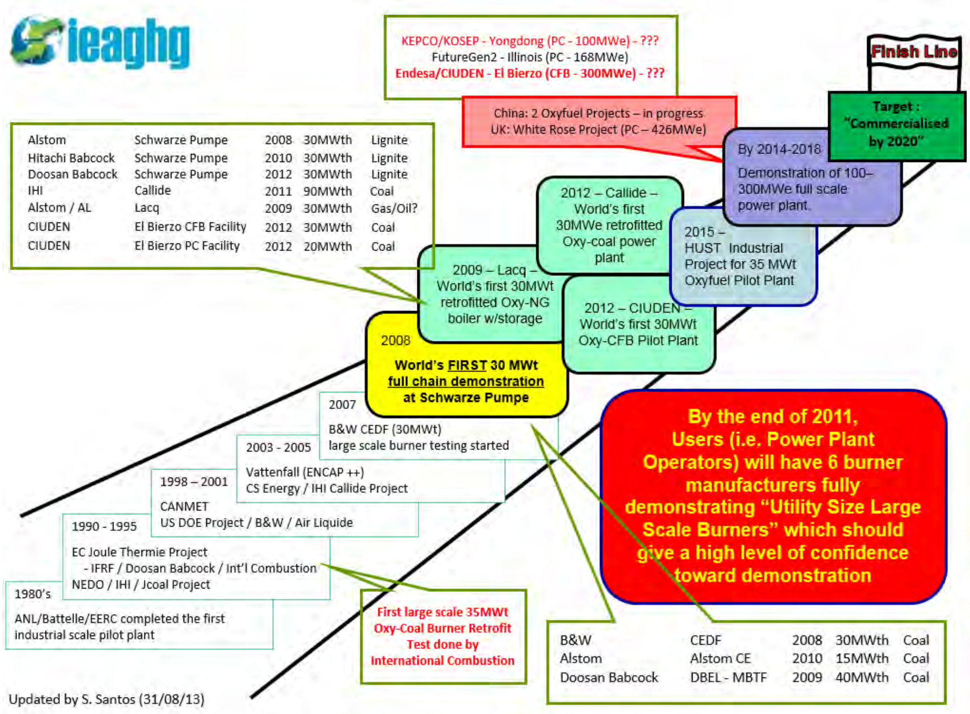

Figure 15 – Oxyfuel Combustion Technology - Timeline to Commercialisation [1, 2]

According to DOE/NETL reports [3-8], OxyCT has the potential to deliver the highest efficiency and lowest cost of CO_2 capture for coal-fired plants. A number of recent pilot and demonstration projects have shown OxyCT offers lower technology risk because the plant components are primarily conventional equipment modified for operation in oxyfuel mode. It can be retrofitted using existing plant and equipment, and output can be increased by heat integration [9-22]. The oxygen production and the CO_2 processing unit contribute to ~50-60% and ~30-40% of the total energy penalty respectively [6-7, 23-24]. Furthermore, this technology has the potential to reach near zero emissions and achieve greater than a 98% CO_2 capture rate [25-30]. One of its benefits over post-combustion capture on coal is that there are no new solvents or chemicals to be used within the power plant; therefore it, does not require low pressure steam extraction for solvent regeneration.

Technology development of Oxyfuel Combustion can be broadly divided into five key areas [2, 9]:

- Fuel preparation (particularly important for lignite to enhance efficiency)
- Boiler design and operation
- Oxygen Production
- Flue Gas Processing
- CO_2 Processing Unit (CO_2 Purification Unit/Gas Processing Unit)

Work done at Vattenfall's Schwarze Pumpe facility [31-41] has demonstrated that all components of this technology could be adapted to any coal fired boilers. Intensive RD&D activities worldwide over the past decade have succeeded in engaging a good number of OEMs that could provide commercial offerings of this technology.[7]

With the Vattenfall experience and the success at the Callide Power Station in Australia (demonstrating an Oxyfuel Boiler at 90MWth / 30MWe) [20-22], it is clear that not only is the technology proven, but it could be retrofitted to just about any coal fired boiler.

Additionally, the demonstration of the largest oxy-CFB boiler (30MWth) at CIUDEN's Technology Development facility expands the range of options for oxyfuel combustion coal fired power plant with CO_2 capture [42-44].

Successes at various large scale pilot facilities worldwide have provided a good basis toward scaling up of this technology to the 100 – 300 MWe scale.

For the new build power plant option, it is preferred to have a demonstration scale at 250-300MWe – as this is the smallest coal-fired boiler that is viable to provide steam at supercritical condition (a pre-requisite for any future plant for 600-1000MWe).

For the retrofit case, the experience from the Callide Oxyfuel Project is an important cornerstone for the demonstration of this technology. This project has proven that this technology could be retrofitted to an existing coal fired power station. Achievement of10,000 operating hours at the Callide Power Plant by 2014 will be a major milestone, as this could be used as a reference to the various components of this technology by the participating OEMs. Work at Callide Power Station will be further enhanced if Young Dong Project in South Korea retrofitting a 125MWe coal fired power plant with oxyfuel combustion technology is implemented.

The next step in the development of oxy-CFB technology would be to demonstrate at a scale of 100-300MWe. This should provide opportunities to demonstrate the modular nature in the design of CFB boilers and its scale up principle which could be applicable to the scaling up of any oxy-CFB boilers. In addition, research work done under the O2Gen project in Europe involving the use of a lower flue gas recycle rate and higher oxygen concentration in the boiler could provide fundamental understanding in the development of next generation oxy-CFB boilers that could potentially reduce capital cost.

[9] Note: there are six boiler manufacturers (Alstom, B&W, Doosan Babcock, Foster Wheeler, Hitachi and IHI) and four industrial gas companies (Air Liquide, Air Products, Linde and Praxair) capable of offering a suite of technologies that could demonstrate oxyfuel technology at the large demonstration scale.

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4.2.1 Development of Oxy-PC and Oxy-CFB Boilers

Development of PF and CFB boilers for coal fired power generation evolves over time from their demonstration to commercialisation (as illustrated in Figures 16 and 17).

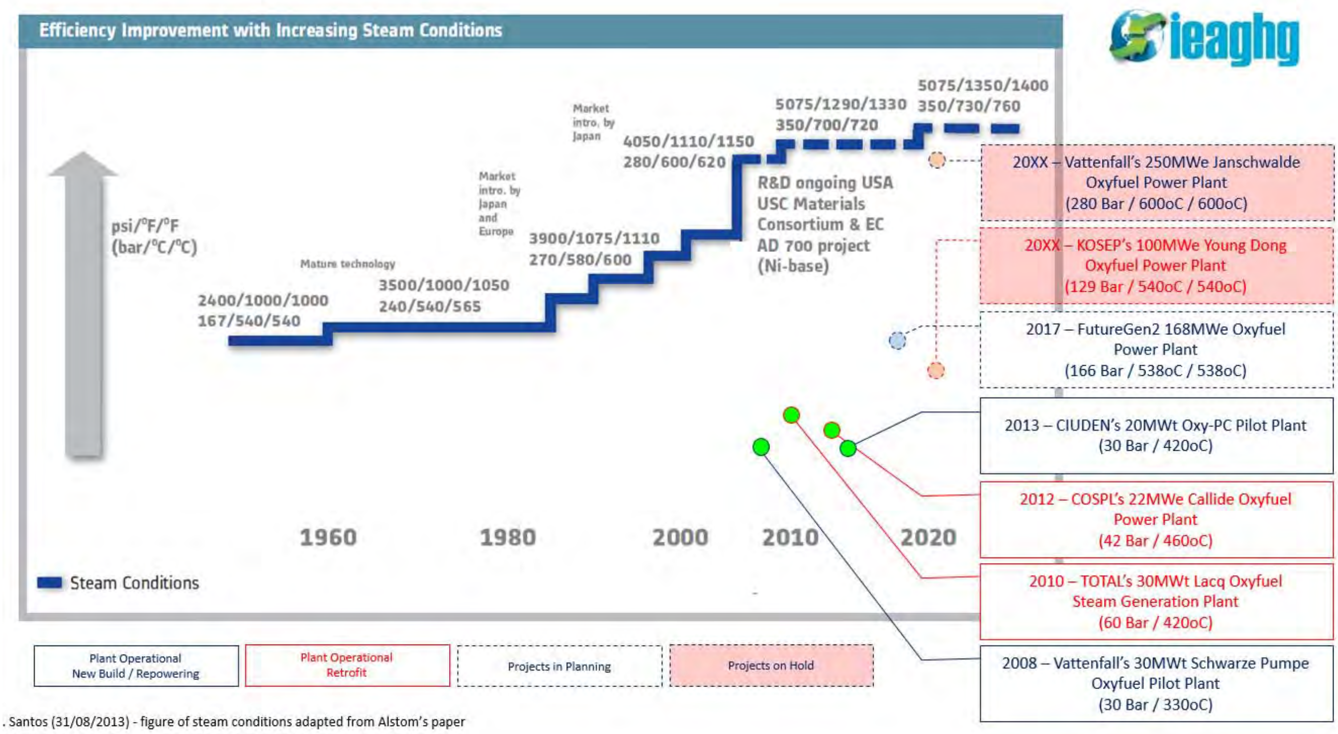

Figure 16 – Development pathway of PF coal-fired boiler – also depicting the current status of oxyfuel combustion boiler development (Figure adapted from [45]).

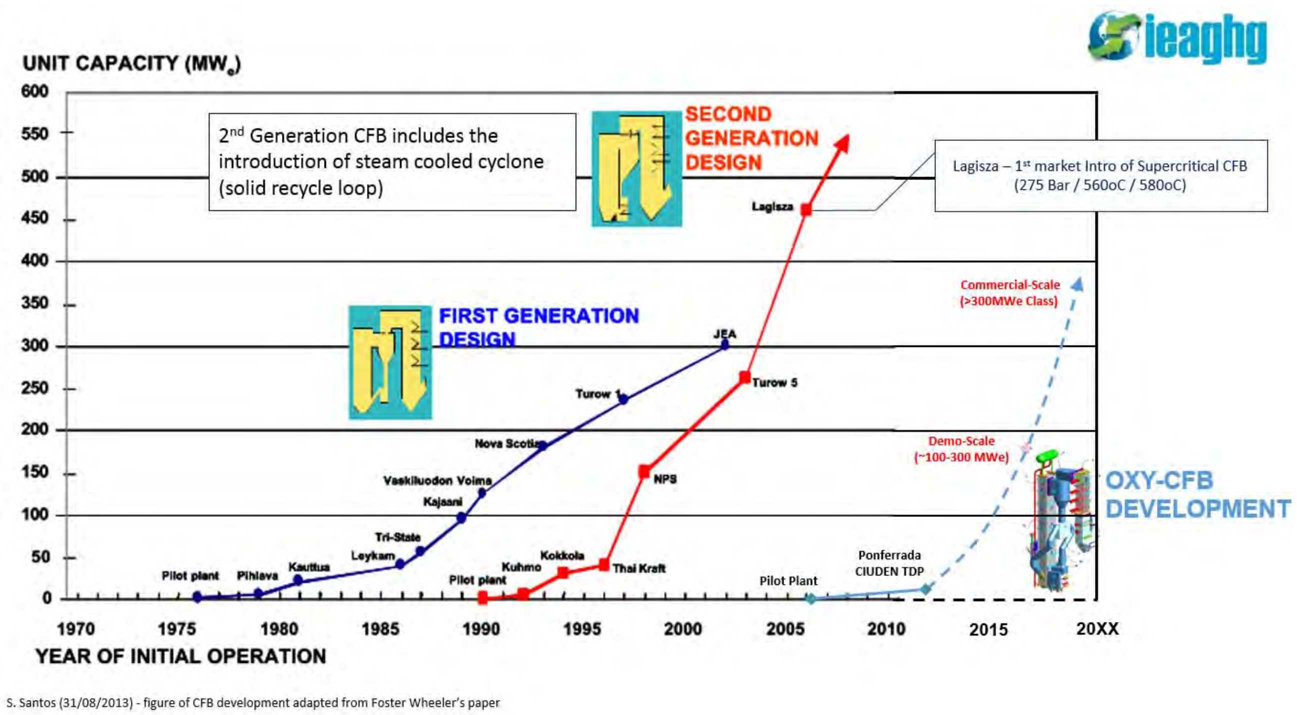

Figure 17 – Development pathway of CFB coal-fired boiler – also depicting the current status of oxy-CFB boiler development (Figure adapted from Foster Wheeler paper) [46].

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It is expected that the development of Oxy-PC and Oxy-CFB will follow a similar development path to their air-fired counterpart. Thus, it is difficult to classify what is second or third generation technology as the overall technology concept is established on a learning by doing trajectory. Likewise, several designs and components used by conventional air-fired PC/CFB boilers are to be adapted to the Oxy-PC/CFB Boilers design and operation.

Figures 16 & 17 also illustrate the current status of the development in both Oxy-PC and Oxy-CFB boilers in relation to the air-fired counterpart. To reach commercialisation, the learning curve is expected to be steep.

Additionally, it should be noted that, unlike other leading capture technologies, development of oxyfuel combustion is “all or nothing”. One cannot just work with a slip stream of flue gas. The whole boiler needs to be changed.

The development pathway will be based on the coal types used resulting in variation to the design of the boiler and downstream flue gas processing units. (i.e. FF/ESP, de-SOx and FGC) [11-13]:

- Lignite (various tests completed via projects at Vattenfall’s Schwarze Pumpe pilot plant)
- Sub-bituminous coal (various tests completed via projects by Alstom at CT, USA; Doosan Babcock at Renfrew; B&W at Ohio)
- Bituminous coal (various tests completed via projects by Vattenfall, Callide, and all the OEMs)
- Semi-anthracite/Anthracite (various tests completed or underway at CIUDEN’s TDP facility)

Areas for future development of this technology (for boiler), where development is always related to and based on a clear understanding of the combustion characteristics of the coal or other solid fuel, include:

- Coal with high Sulphur and Chlorine
- Coal blending
- Co-firing with biomass (from virgin to torrefied class; from easy to difficult)
- Co-firing with petcoke

Controlling the combustion is an important area of continued work. Oxyfuel has opened up several options for controlling the combustion including the control and location of oxygen and flue gas recycle injection, and flame stability at low flue gas oxygen. Use of warm flue gas recycling is another promising area of development as a way of improving efficiency. These are all optimisation issues that offer opportunities for improved performance and reduced maintenance, but by and large they will be vendor specific developments.

In terms of power generation, Vattenfall has reported that Janschwalde’s 250MWe Demonstration Plant could achieve 36% net efficiency – a penalty of ~8% as compared to power plants without capture [47].

Materials

For the first generation of Oxyfuel Combustion technology applied to coal or other solid fuels, the main consideration is the combustion characteristics of the fuel and the optimization of design and operation associated with that fuel [10, 11]. For the demonstration and first generation oxyfuel boilers, it is expected that conservative designs based on known boiler tube materials currently used by their air-fired counterpart will be deployed. Operation of the boiler (i.e. heat extraction rate) will be adjusted according to the dew point temperature of the resulting flue gas. Current development will focus on flue gas processing (of the recycled flue gas) to remove SOx, NOx, halogenated compounds, and water to reduce risk of material failures due to corrosion. It is expected that future generation oxyfuel boilers will merge its development to the development of advanced USC boilers followed by their air-fired counterpart.

One key research areas is related to the development of materials used in advanced USC boilers. This includes research into the reliability of boiler tubes operating under oxyfuel combustion conditions (i.e. with very high concentration of acid components such as NOx, SOx, HCl, in the presence of high water content).

Some laboratory/pilot scale tests [48-51] have indicated that Austenitic steel and Ni-based alloys have experienced high oxidation rate under oxyfuel combustion particularly in the presence of both high Chlorine and SOx (SO_2/SO_3) concentration. Likewise, metal carburisation of the boiler tube is another concern. Several material tests subjected to real or simulated oxyfuel flue gas conditions provided mixed results for both issues. Hence the mechanism that promotes higher oxidation rates or initiates carburisation under oxyfuel conditions seems to remain un-clarified, and understanding these mechanisms is necessary to develop boiler tube materials for advanced USC steam parameters (i.e. 300 bar / 700^{o}C).

Equipment

The main focus of development is in the understanding of the combustion characteristic of the fuel operating under oxyfuel combustion conditions. Equipment (i.e. coal mill, burners, boilers and other auxiliaries) used by current air-fired boilers will be adapted to the operation of oxyfuel combustion. To achieve this, several research activities have been undertaken. Key areas of R&D include the following [9-22]:

- Understanding the coal devolatilisation and char combustion properties. (important for combustion control and flame stability);
- Modeling heat transfer (radiative and convective heat transfer);
- Evaluating the slagging, deposition, fouling propensity of the coal ash;
- Understanding NOx and SOx formation mechanisms;
- Development of low NOx burners (important for reducing CO emissions);
- Evaluating in-furnace SOx removal (i.e. adsorbent injection);
- Understanding the fate of trace elements (essential to establish Hg balance); and
- Development of burner scaling methodology for oxyfuel combustion application.

Many of these issues have been addressed by various R&D activities undertaken in the past ten years [9-22, 31-38]. Understanding of the fundamentals has been achieved with confidence, meaning that this technology is ready for demonstration. Nonetheless, just like any new build, re-powering or retrofit projects for coal-fired power plants; these are very fuel-specific properties which would require continuous evaluation even during the commercialisation of the technology.

Today, there are three large scale facilities that are capable of testing different PC burners at commercial scale (i.e. burner size of 20MWth and above); these include Alstom's CT facility (a platform for tangential firing boilers); the B&W OH facility (for wall fired boilers); and the Doosan Babcock Renfrew facility (for wall-fired boilers) [2, 16-17, 38, 52]. There are two large scale pilot plants (Vattenfall's Schwaze Pumpe; CIUDEN's Ponferrada facilities) demonstrating the full chain oxyfuel combustion technology [30-44]. One small demonstration plant (Callide Power Station) operating a full scale boiler; two trains of ASU; and a train of CPU processing 18% of the CO_2 rich flue gas from the boiler [20-22].

It has been established that the basic principles used in designing conventional coal-fired boilers and burners are also applicable to the design of oxyfuel combustion boilers [9-24]. Future work will follow the development of advanced ultra-supercritical PC-fired boilers to higher temperatures and pressure (i.e. 300 bar / 700^{o}C). Most of this work is related to material development as briefly described in the previous section.

Process Design and Heat Integration

There are several options where flue gas could be recycled to the boiler, dependent on the sulphur content of the coal. It has been suggested that the use of warm recycle of the flue gas contributes to some efficiency gains.

4.2.2 Development of Air Separation Units for Oxyfuel Combustion

The oxygen demand for oxyfuel combustion coal-fired boilers could be the largest among any large oxygen consumers today. Only cryogenic air separation unit could meet such demand. Other oxygen production technologies currently being developed are not mature enough to replace the cryogenic ASU.

The cryogenic air separation unit is considered one of the mature technologies within the CO_2 capture chain. For conventional ASU, it would be difficult to achieve any major improvement to the efficiency of this process. However, ASUs for oxyfuel combustion applications that deliver oxygen with low purity (i.e. 95 – 97% O_2) and low pressure (i.e. 1.2 to 1.8 Bar) have opened up opportunities for a step change improvement in energy efficiency [53-57]. It is expected that advanced ASU cycles using three columns or dual reboilers will be deployed as part of the development pathway.

Key to the development of the air separation unit is the demonstration of a large scale single train ASU (i.e. in the range of 5,000 to 10,000 TPD O_2). Today, the largest operating ASU is 3900 TPD O_2. A contract has recently been awarded to build the largest single train ASU at 5,250 TPD O_2 in India for gasification application. This is expected to be operational by 2015. This kind of commercial deployment will naturally feed into the development of large scale single train ASUs for oxyfuel combustion application, which should help reduce capital and operating costs.

Materials

Cryogenic air separation unit is a mature technology. Therefore, the main focus of the work is related to equipment and process improvement [57].

Nonetheless, development of novel oxygen production is currently on-going. In this area of research, the main focus is on the development of membrane and ceramic materials for high temperature oxygen production [58]. This is being developed in various labs and pilot scale facilities.

Equipment

The main cost and energy penalty of the ASU is the main air compressor (MAC). A 5,000 TPD oxygen plant requires approximately 700,000 Nm3/h of air. Although compressor manufacturers are confident of being able to design and manufacture these large compressors, the long term reliability of an ASU with these large compressors remains to be proven.

Future development will focus on further improvement of the main air compressor's efficiency (i.e. improved impeller design); and capability of wider turndown range for operating flexibility. Current compressors are limited to 75-80% turndown [53, 57].

Some of the key areas of development where improvements to the equipment could potentially provide efficiency gains and reduce capital cost include the following [53, 54, 57]:

- Improvement to the Front End Purification Processes. (i.e. packing selection for Direct Contact After Cooler – that could reduce pressure drop and minimise vessel diameter).
- Improvement to the main heat exchanger (i.e. use of brazed aluminum heat exchanger with larger core sizes and lower pressure drop).
- Improvement of the distillation column (i.e. use of high capacity structured packing that will lead to low pressure drop and smaller diameter).
- Improvement to the reboiler design (i.e. use of improved Thermosyphon reboiler design).

The selection of an appropriate ASU cycle is an important aspect of the delivery of an optimised CAPEX and OPEX air separation unit for oxyfuel combustion application.

Process Design and Heat Integration

Process design and cycle selection of the ASU is an important step in optimising the CAPEX and OPEX of the cryogenic oxygen production [53-57]. Generally, the leading options involve the use of either the three columns cycle or the dual reboilers cycle. In these advanced ASU cycles, energy consumption is achieved by reducing the pressure and the amount of process air needed to be compressed by the MAC.

Heat integration with the power plant is possible. Heat from the air compressor could be used for pre-heating boiler feed water. Published data has indicated that integration of an ASU to the Power Plant could lead to some efficiency gains [59].

Consideration of the use of waste nitrogen is another aspect where potential energy savings could be gained. However, this is a very site specific condition that would require available waste within the site (this could be applicable to industry such as steel mills).

4.2.3 CO_2 Processing Unit (CPU)

The CO_2 processing unit or CPU is the purification of the CO_2-rich flue gas before its delivery to the storage site.

Development of the CPU could be sub-divided into three key areas of research activity, namely [25-30]:

1. Pre-treatment of the CO_2 rich flue gas from the oxyfuel boiler (i.e. removal of SOx, NOx, particulates, Hg and water).
2. Use of an auto-refrigeration cycle using impure CO_2 as refrigerant.
3. Development of the process for additional recovery of CO_2 from the CPU vent.

The main challenge to the development of the CPU is the absence of established specifications for the CO_2. The design of the CPU (process and equipment) is governed by the amount of non-CO_2 components that will be allowed to be co-captured with the CO_2 for transport and storage.

On this basis, the following should be noted:

- CO_2 from the CPU will be expected to be bone dry (from < 1 to 10 ppm) as this is a process requirement for the cryogenic separation (i.e. removal of non-CO_2 components mainly consists of O_2, N_2 and Ar).
- Any NOx and SOx in the CO_2 rich flue gas are removed during the CO_2 compression.

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- The paper published by Air Products [25, 27] recognising the reaction of NOx and SOx in the presence of oxygen and water producing sulphuric acids and nitric acids during compression (i.e. classic lead chamber reaction) is an important development of the previous decade that led to the development of wide variety of processes to remove these acidic components. For the purpose of simplicity, this removal process could be classified as the front end pre-treatment unit of the CPU. Depending on the technology vendors, the design of the NOx and SOx removal unit is also dependent on the design of the Flue Gas Processing Unit (i.e. Flue Gas Desulphurisation and Flue Gas Condenser) of the OxyCT.
- Removal of oxygen governs the overall process design of the cold box (i.e. main CPU cycle). This will be based on the principle of cryogenic separation. For oxyfuel combustion, a range of purity from 95% to 99.999% CO_2 could be designed for. Cost difference between 95% and 99% could be minimal depending on what could be offered by the technology vendors [59].
- Mercury[8] is an operational issue to the cryogenic separation process (i.e. it could cause damage to any aluminium base equipment – BAHX, valves and expanders). It is expected that any forms of mercury are removed down to undetectable limit (i.e. this is analogous to the standards used in NG processing).

Materials

The development of the CPU should follow the same approach to its industrial or food grade CO_2 production counterpart. Therefore, like the ASU, the main focus of work is related to equipment and process improvement.

Equipment

Like the ASU, it is also expected that the CO_2 compressor takes up the majority of the cost and energy penalty of the process.

Unlike the other two leading capture technologies (i.e. post- or pre- combustion CO_2 capture); the CO_2 compressor is an integral part of the CO_2 processing unit. For the CO_2 compressor, centrifugal type compressor is expected to be the leading choice. The compressor used prior to the removal of NOx and/or SOx would require sour service. Ramgen Compression may not be applicable to oxyfuel combustion.

The use of CO_2 as a refrigerant is considered a mature technology. However, engineering data (particularly with the use of impure CO_2) is required. There are several CPU cycle patented by Air Products, Air Liquide, Praxair, Linde and Alstom [15, 25-30, 60-61]. Refrigeration is provided by using JT expansion valves (expanding impure CO_2). However, some OEM suggested the use of Expanders to recover energy during the refrigeration process. This will need further development to reduce capital cost. Demonstration of this technology in large scale operation is necessary.

Oxyfuel combustion technology could be designed to recover greater than 98% of the CO_2 emitted from the power plant [25-30]. This will involve additional equipment capturing CO_2 and/or O_2 from the vent of the CPU.

[8] The removal of mercury is not a major concern for oxyfuel combustion as the majority of the oxides of mercury will be removed by the FF, FGD and FGC. Additional removal of mercury will be expected during the sour compression of the flue gas. Nitric and sulphuric acid are good reagents in capturing both elemental and oxidised mercury. Furthermore, a mercury guard bed will be installed in the CPU. The only problem encountered so far is the credibility of the Hg measurement techniques used conventionally which is significantly affected by the acidic components of the oxyfuel flue gas, resulting in inaccurate readings.

Most of this additional equipment is commercially available and mature, however it would require large scale demonstration. The process used to capture the additional CO_2 is described in the next section.

Process Design and Heat Integration

The process design for the removal of SOx and NOx prior to the cryogenic removal of the inert gases is dependent on the OEM vendors. The main principle in the development of the process is to take advantage of the tendency to convert any NO to NO_2 during compression. NO_2 could act as catalyst for the conversion of SO_2 to form SO_3 in the presence of water and oxygen. There are a number of vendor's approaches[9]:

- Air Products [25, 27, 41, 62] proposes the use of the Sour Compression Process (based on lead chamber reaction) to knock out 99% of the SOx as H_2SO_4 and remove at least 95% of NOx as HNO_3 and HNO_2 during the compression of the CO_2 rich flue gas.
- Linde [28-29, 63] proposes the use of the LICONOX process whereby 99% of the SOx is initially removed at the FGD and/or FGC. The cleaned gas is compressed to 15 Bar to convert NO to NO_2; and then NO_2 is removed using an alkali wash (based on NH_3 water or NaOH). This would result in the removal of at least 95% of NOx as spent salts of nitrite and nitrate. An option to reduce the salt loading is possible by preheating the salt solution to 60°C therefore reducing the spent salt of nitrite to N_2 and H_2O.
- Praxair [30] presented two possible options for pretreatment of the flue gas. The first option uses sulphuric acid wash to recover nitric acid. This would result to a clean gas containing 50-100 ppm SOx and less than 50 ppm NOx. The second option uses activated carbon to adsorb any SOx and NOx resulting to dilute acid during regeneration of the bed; with the resulting cleaned gas consists of less than 10 ppm of NO.

The separation of inert gas and CO_2 requires cryogenic separation. Different CPU cycles have been proposed by various OEM vendors [15, 25-30, 60-61]. The main development is based on an auto-refrigeration cycle using impure CO_2 as refrigerant. The design of the cycle is based on the required final O_2 content in the CO_2. Lower purity would require a simple flash separation column while higher purity requires the use of a distillation column.

The process design for capturing additional CO_2 from the CPU vent is dependent on the technologies developed by different OEM vendors. As discussed earlier, the additional capture would result in a high capture rate of greater than 98% and this also minimises the impact of the air ingress. Some of the processes presented by the different OEM vendors are described below:

- Air Products proposed the use of a CO_2 membrane ("Prism") where the permeate, consisting of CO_2 and O_2, is recycled back to the boiler. It is claimed that with this equipment installed, the oxygen requirement from the ASU could be reduced by 3-5% [25, 27].
- Linde proposed the use of PSA to further recover CO_2 from the vent gas of the CPU. The CO_2-rich gas recovered is recycled back to the dehydration unit of the CPU, while the remaining gas could be fed into the front end purification unit of the ASU. It is claimed that energy consumption of the CPU will increase by 6% as compared to the CPU without PSA installed. However, Linde have not reported the possible savings that could be gained in the ASU [26, 29].

[9] Currently, there is no clear winner among the different technologies proposed by different OEM vendors. Technology is at the pilot stage. The main gap for development requires engineering data for scale up.

- Praxair proposed the use of VPSA to recover CO_2 from the vent of the CPU. The CO_2-rich gas recovered is recycled back to the sour CO_2 compressor just after the FGC. Praxair has yet to report on the performance of this process [30].

Heat integration with the power plant is dependent on the technology choice. For example, Air Products proposes the use of heat from the power plant during the expansion of the vent gas from the CPU to produce electricity, while waste heat from CO_2 compression could be used to pre-heat boiler feed water for the power plant [25].

4.2.4 Impurities and its Tolerance

The handling of impurities is an integral part of the oxyfuel combustion technology.[10] From a holistic point of view, the removal of non-CO_2 components is defined by the following requirements: namely (a) removal of acid components in the flue gas prior to its recycling to the boiler to prevent any issues related to corrosion and carburization; (b) removal of the non-CO_2 components governed by the process requirements of the CPU; and (c) removal of the non-CO_2 components as defined by the requirements of transport and storage.

4.2.5 Environmental Impact Atmospheric Emissions & Water Pollutants

Oxyfuel combustion results in a near zero emission power plant; with regard to atmospheric emissions, CO emission is the only concern for the oxyfuel combustion coal fired power plant. It should be noted that the amount of CO produced is generally lower than its air fired counterpart. But CO concentration at the CPU vent could exceed the current concentration limit set in some jurisdictions; eg the EU Large Combustion Plant Directives. CO could be removed at the CPU vent using Catalytic Converters[11] [64]

As water is removed from the flue gas of the boiler, therefore it is expected that all the trace elements and acid components would end up in the waste water treatment plant of the power station. This is dependent on the technology choice for the flue gas processing unit and CPU.

[10] For Post-Combustion Capture – the main concern related to the allowable O_2 content in the CO_2 (~100 to 300ppm for MEA) has yet to be addressed. For Pre-Combustion Capture – the main concern related to allowable H_2 and H_2S content in CO_2 and will also need to be addressed. Additionally, debate on the acceptable water content limit of the CO_2 is still on-going. Both concerns mentioned above are defined by the requirements of the transport and storage.

[11] CO has similar cryogenic properties to N_2, therefore it will just go straight to the vent. Depending on the regulatory framework regarding CO emissions this could be diluted using waste nitrogen from ASU as the cheapest option.

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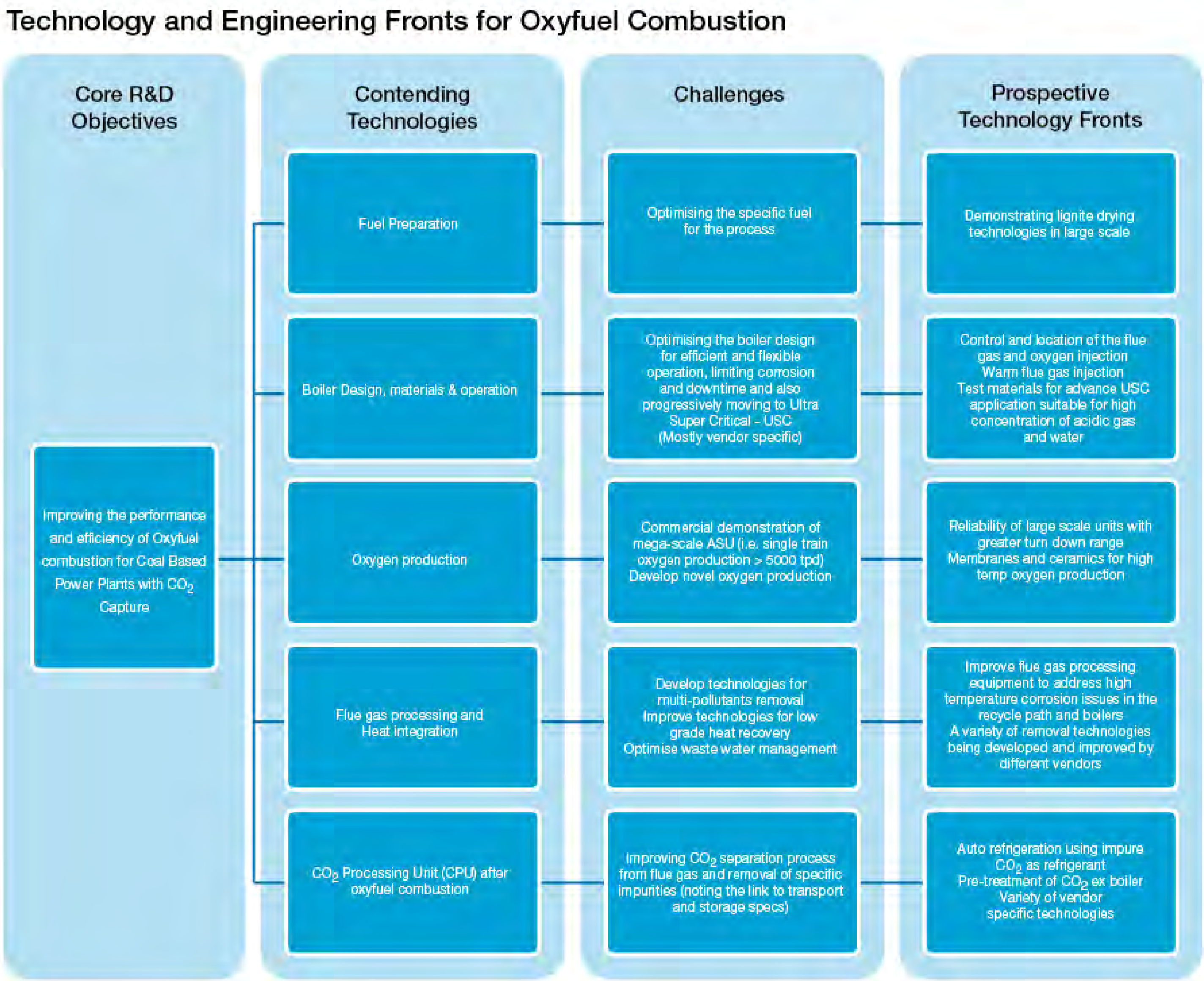

Figure 18 - Technology and Engineering Fronts for Oxyfuel Combustion for coal based Power Plants with CO_2 capture

4.3 Oxyfuel Combustion for Gas-Fired Power Plant

The emergence of shale gas has provided a strong driver for developing oxyfuel combustion technologies for gas-fired power plants.

Typical oxyfuel cycles would have the following features:

- Generally based on close to stoichiometric combustion using nearly pure oxygen mixed with recycled flue gas or steam;
- The working fluid mainly consists of CO_2 or water (or mixtures of both);
- Combustion would require pressurised oxygen between 10 to 300 bars, and oxygen purity ranging from 95 to 98% - depending on the type of GT cycle and the combustor design of the turbo machinery used; and
- If fired with natural gas, the CO_2 processing unit mainly consists of separation of water and CO_2. The amount of NOx present in the flue gas depends on the GT combustor design and the purity of oxygen used. However, if fired with syngas (i.e. coal based oxyfuel combustion), the CO_2 processing unit requires removal of trace compounds such as SOx and NOx.

From the literature, there are several cycles proposed or under development. Examples of oxyfuel cycles using CO_2 as working fluid include the MATIANT [65, 66], Coolenerg [67], COOPERATE [68, 69], and Allam [70] Cycles. On the other hand, cycles using water as working fluid include CES Water [71-74] and Graz cycles [75]. Other hybrid cycles which don't require an ASU for oxygen production include the use of Chemical Looping [76-78] and AZEP cycle [79-80]. Additionally, research using ITM and OTM technologies for oxygen production are being evaluated.

For the purpose of analysing gaps in knowledge, only the oxyfuel cycles with advanced development (i.e. technology maturity toward large scale pilot demonstration) will be assessed and these include the CES Water Cycle and Allam Cycle.

4.3.1 Current State of Development of CES Water Cycle and Allam Cycle

Clean Energy System (CES) Water Cycle [71-74]

The CES Water Cycle was developed using the principles of the rocket engine where the rocket engine's combustor is adapted to provide the main gas generator for the oxyfuel cycle.

Figure 19 shows the combustor/gas generator providing the working fluid to the steam and gas turbines; and Figure 20 presents the simplified process flow diagram of a 200MWe oxyfuel gas-fired power plant.

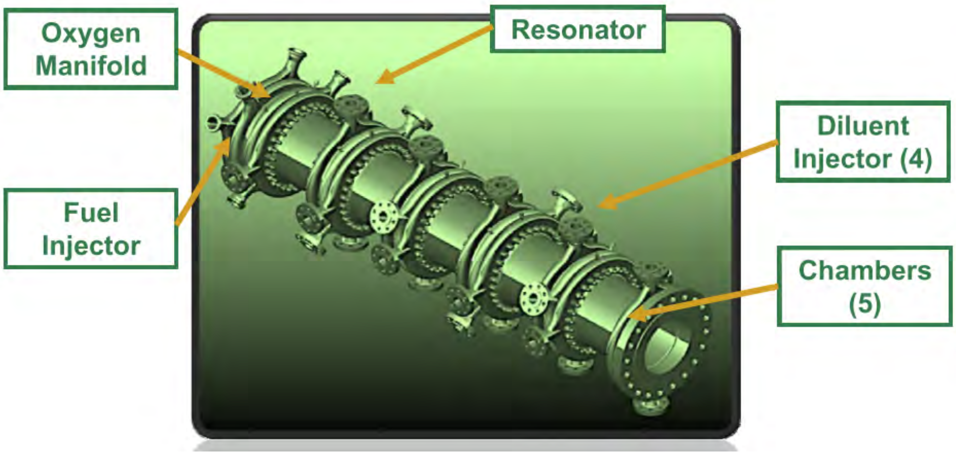

Figure 19 - 200MWth CES Combustor / Gas Generator (GG)

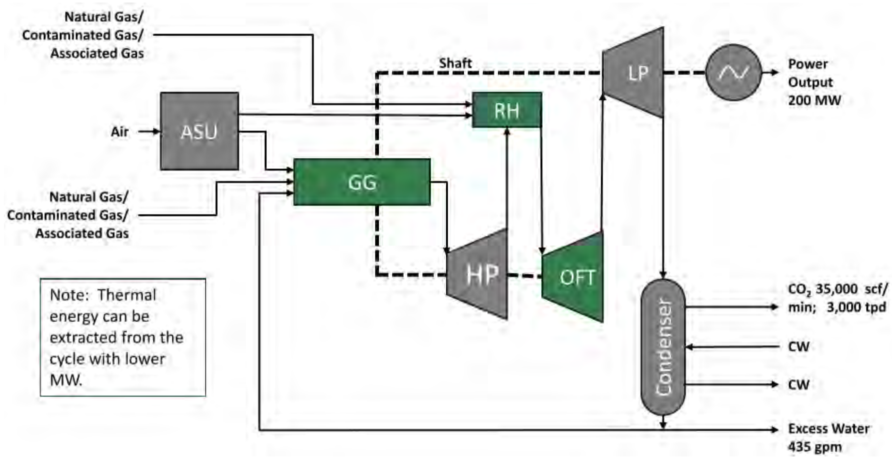

Figure 20 - Process flow diagram of the 200MWe Oxyfuel Gas Fired Power Plant

Typical working fluid generated by the combustor is about 80% water and 20% CO_2. The initial temperature of the combustor (i.e. first chamber) is maintained between 1650 and 1750°C; and the operating pressure is generally in the range of 50 to 100 bar. Temperature is moderated in the cooling chamber downstream of the combustor/gas generator by water or steam injection to match the operating inlet temperature of the high pressure (HP) steam turbine (normally between 500-610°C for current generation steam turbine, and up to 760°C for future generation steam turbine). The pressure ratio of the current generation HP steam turbine is about 5. The working fluid is reheated in an external combustor to provide a working fluid with a turbine inlet temperature (TIT) matching the capabilities of the intermediate pressure (IP) gas turbine or OFT. Typical TIT could be in the range of 700 to 1750°C depending on the operating inlet turbine temperature of the modified gas turbine to be used. The heat from the exhaust of the gas turbine is recovered via HRSG and the steam generated by the HRSG is delivered to the low pressure (LP) steam turbine; or the exhaust of the OFT could be used as the working fluid for the LP steam turbine (if temperature matches the operating temperature of available steam turbine).

CES has successfully developed and demonstrated the gas generator and modified GE J79 aeroderivative gas turbine (also known as OFJ79) providing a nominal power output of 40MWe. The nominal 220MWe is also demonstrated based on the modified Siemens SGT900 (also known at OFT900 or SXT150) gas turbine.

Future development of this technology includes (but not limited to) the following:

- Having demonstrated all the main components from 12 to 42 to 220MWe, the technology has reached the early commercial stage. The next step would be to demonstrate and validate its economic feasibility based on a large scale full chain power plant with CO_2 capture (having its own PPA).
- The potential to improve the efficiency of the CES Water Cycle technology depends solely on the development of two main components namely: development of the HP steam turbine operating at 760°C and the oxyfuel gas turbine with operating parameters similar to the H and J class gas turbine (i.e. with TIT at 1500°C). This should be followed by development of the gas turbine that could operate at TIT of 1760°C.
- Demonstration of this technology using gaseous fuel other than NG. This should benefit industrial users that could use low BTU off-gases or coal-based systems using gasifiers to produce syngas.

Allam Cycle [70]

The Allam cycle was developed using supercritical CO_2 as the working fluid and capturing the waste heat from the main air compressors of the air separation unit. This technology is based on a simple cycle and therefore has the potential to reduce CAPEX. Figure 21 presents the Zeus combustor and modified gas turbine to be used. Figure 22 presents the simplified process flow diagram of the oxyfuel cycle for gas-fired power plant.

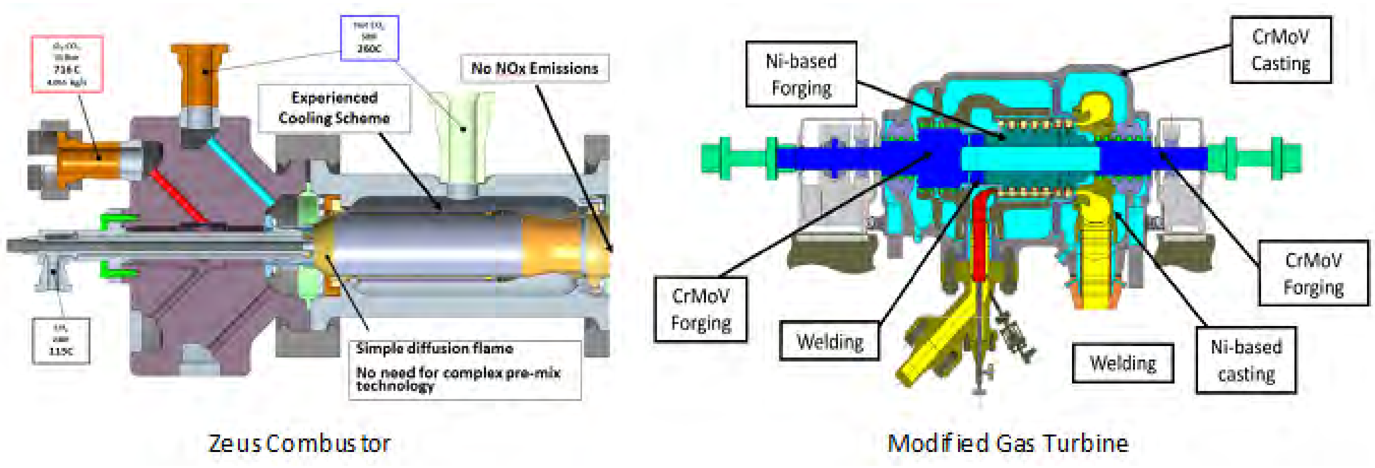

Figure 21 - 50MWth Combustor and Gas Turbine for Allam Cycle

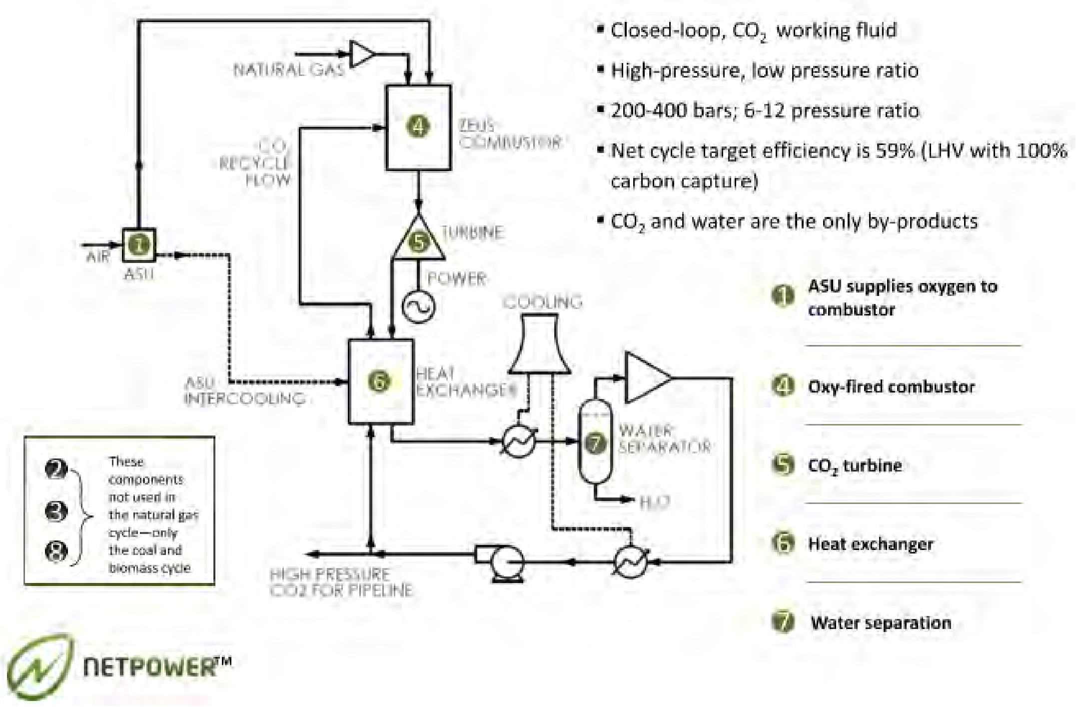

Figure 22 - Simplified Process Flow Diagram of the Allam Cycle

The typical working fluid generated by the combustor is about 75-80% CO_2 and 15-20% H_2O (and the balance mainly consists of Ar). By working with supercritical CO_2, this has provided an additional benefit of producing CO_2 as a by-product, with quality and pressure suitable for CO_2 transport and storage.

The working fluid is produced by preheating the oxidant, a mixture of oxygen and recycled CO_2, to 700°C before combustion. A can-type combustor based on single cell diffusion burner will be used[12]. The combustion temperature will be maintained in the range of 1100 to 1200°C and operating pressure is in the range of 20 to 300 bar. NOx will be minimised to nearly zero by using oxygen with nitrogen content of less than 10 ppm (i.e. O_2 purity is at least 98%). The working fluid will be expanded in a modified gas turbine with outlet pressure and temperature of about 20 bar and 700°C. Heat will be recovered from the turbine exhaust by preheating the recycled CO_2. Additional heat will be recovered by preheating the oxygen and recycled CO_2 from the ASU's main air compressor (i.e. using adiabatic compressors).

The Allam cycle will be developed in partnership with Toshiba – providing the combustor and turbine. A 50MWth demonstration is in planning. It is projected that this demonstration will be operational by 2015.

The current challenge of this technology requires the successful adaptation and demonstration of the modified gas turbine to be used in the Allam cycle. Near term development of this technology lies in the successful

[12] N.B. current burners used in state of the art gas turbines are based on an annular arrangement using lean pre-mix burner technology. The use of a can-type combustor based on diffusion burner technology simplifies and remove the complexity of the burner design.

development of the combustor and gas turbine using supercritical CO_2 as working fluid. Important to the turbine development is the success of using cold CO_2 as a cooling medium for the turbo machinery[13].

4.3.2 Oxygen Production

In the near term, it is expected that cryogenic ASU would be the only option to meet the demand of the oxygen required by the oxyfuel combustion NG fired power plant with CO_2 capture (for 220MWe using CES water cycle would require ~4600TPD O_2). For the CES Water Cycle, oxygen is delivered at pressure between 50 to 100 bar with O_2 purity ranging from 95 – 99% depending on the specification of the CO_2 to be delivered for transport and storage. On the other hand, Allam Cycle would need the oxygen delivered at 300 bar and at least 98% O_2 purity. This is pretty much governed by the reduction of NOx emission of the diffusion burner.

Consequently, ASU technology used in coal-based oxyfuel combustion power plant is not the same as the ASU technology to be used by the gas-based oxyfuel combustion power plant. The overall energy consumption is strongly dependent on the delivery pressure of the oxygen.

To improve efficiency of the oxygen production delivered by the ASU, the use of pumped LOX (PLOX) technology is required to deliver the oxygen at the pressure required by the process. Scaling up the LOX pumps to reduce cost is important to the development of the ASU for gas-based oxyfuel combustion power plants. Currently, the largest pump can only deliver up to 800 tpd.

4.3.3 CO_2 Processing Unit

For NG gas-fired oxyfuel combustion power plants, the CO_2 processing unit (CPU) is determined by the CO_2 specification required for transport and storage. Primarily, the main process consists of the dehydration of the CO_2 rich flue gas. However, one of the main factors that will govern the final design of the CPU will be the limits to oxygen and other inert gases (primarily Ar) in the CO_2 content. Given that operation of the gas-fired oxyfuel combustion power plant is nearly stoichiometric, it is feasible to remove residual oxygen content by catalytic combustion using hydrogen. This means that cryogenic separation of the inert gases may not be necessary. However, if there is a stringent requirement to remove Ar, the trade-off between the removal of Ar by using a cryogenic CPU process and the use of high purity O_2 should be evaluated.

For integrated coal gasification-based gas-fired oxyfuel combustion power plant, the CPU would require an additional pre-treatment process to remove trace elements such as NOx and SOx. The trade-off between removing sulphur compounds (as H_2S, COS, etc) in the syngas vs. its removal (as SOx) at the CPU pre-treatment processes is a necessary evaluation step. Likewise, it is expected that removal of Hg would be done by pre-treatment of the syngas using sulphur impregnated activated carbon.

In general, the only environmental concern with respect to atmospheric emission will be related to the allowable CO emissions. This is strongly dependent on the operation of the burner of the combustor. Addressing this issue would be similar to how CO is removed in coal based oxyfuel combustion power plant.

[13] Current gas turbines use steam or air as a cooling medium for the turbo machinery (in addition to thermal barrier coatings). Using the convective cooling capacity of CO_2 is a novel development.

Key Observations and Recommendations to CSLF on Oxyfuel Combustion

1. For Oxyfuel coal combustion the technology is mature; large scale (100-300MWe) plants are required to get both full scale up knowledge and also reduced costs from “learning- by-doing”.
2. Oxyfuel combustion of natural gas is an important new field that may well play a big part in CCS beyond 2030; improved turbine design is an important development dimension.
3. Air separation units are available to produce the oxygen required for both coal and natural gas combustion, but reducing the cost of oxygen production would have a major effect on overall Oxyfuel technology cost reduction.

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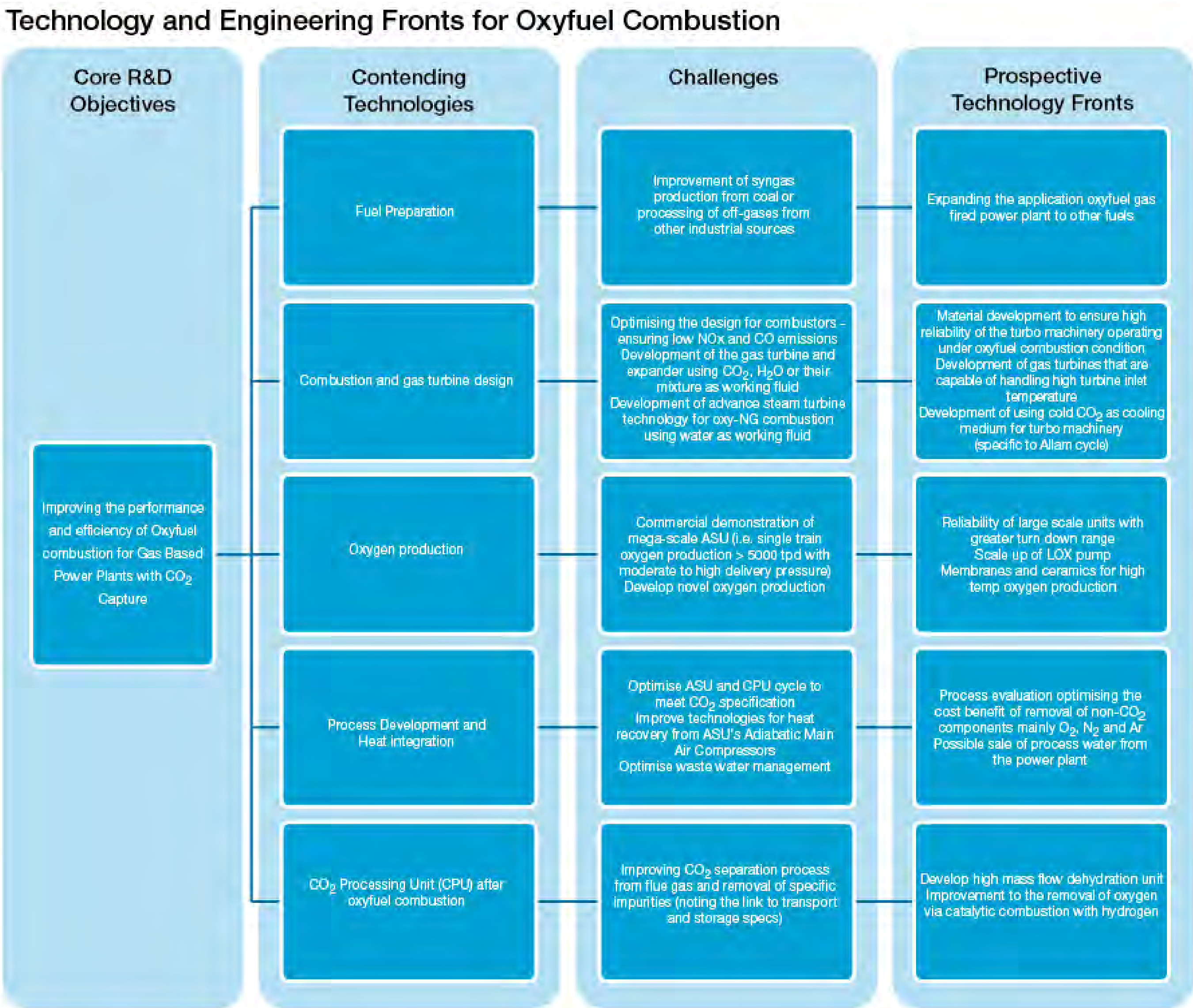

Figure 23 - Technology and Engineering Fronts for Oxyfuel Combustion for gas based Power Plants with CO_2 capture

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5. CO_2 Transport Technologies

There have been a number of recent reports describing the status of transport technology for CO_2. The general overview is that the transportation of CO_2 is a mature technology:

5.1. Pipelines

In the US there are around 6500 km of onshore pipelines, representing 36 pipelines, transporting 48 – 58 Mtpa of mainly naturally sourced CO_2 for enhanced oil recovery purposes (GCSSI 2012). The first CO_2 pipeline built in the US was in 1964; over 40 years of operational experience has been gained (Energy Institute 2010). The longest CO_2 pipeline built in the US is the Cortez Pipeline at 800 km long and with a capacity of 20 Mt/yr (Demofonti & Spinelli, 2011)

The only offshore pipeline for CO_2 is part of the Snøhvit project in Norway. The pipeline is 153 km long and has been operational since 2008 (GCSSI 2012). The CO_2 is removed from natural gas streams and re-injected into the gas reservoir.

5.2. Road Tanker

CO_2 transportation by road tanker has been standard practice for over 40 years Each tanker can hold up to 20 tonnes of CO_2 (Energy Institute 2010).

5.3. Ship

LPG and LNG have been shipped around the world in tankers and it has been argued that there will be very little difference in transporting CO_2 this way (A.Verder). There are six ships, with capabilities in the range of 8,500 m^3 to 10,000 m^3, certified for carrying industrial and food grade CO_2 at optimum pressure and temperature for highest transport efficiency. This transport has led to the development and operation of a ship logistics system in Europe over the last twenty years. As an example of the industry's safety performance it has been estimated that more than 5,000 ship years have already been performed without a cargo related accident (Energy Institute 2010). These statistics go some way in highlighting that CO_2 transport via ship is a proven technology[14]. Ship transport may be important in an initial market where trunk pipelines are not in place. Ships may also play a role in CO_2-EOR if CO_2 is needed for a limited time only. Preliminary designs have been suggested for up-scaled CO_2 tankers.

Preliminary feasibility studies on CO_2 shuttle shipping with direct injection of CO_2 from the ship (Chiyoda Corporation 2011) have shown promise as a technology that could offer shorter lead times for transport and storage of CO_2. There could be potential for this direct injection from the ship in areas that have multiple CO_2

[14] For ship transport, post-combustion capture will be penalised most as this would require external refrigeration for liquefaction. For pre-combustion, Selexol will be disadvantaged compared to Rectisol. Oxyfuel Combustion and the Rectisol process will be the most favourable for capture technology when ship transport is involved.

sources along the coast, such as Japan, and in areas where there are multiple smaller scale geological storage sites offshore.

5.4. Issues

CO_2 transport has been associated with pure or natural CO_2 that has been used for EOR. Transport of anthropogenic CO_2 (e.g. from Power Plants) will contain co-products not previously transported. Typical impurities generated from capture technologies not covered by EOR pipeline specifications include CO, NOx, SOx, H_2 and Ar. Other impurities that need to be considered are H_2S, N_2, CH_4, O_2 and the water content. These impurities affect the behaviour of the dense phase fluid, the preferred form of CO_2 for long distance transportation. The fluid's behaviour is described by equations of state which need improving for specific CCS applications.

Transport of CO_2 has been from single point source to single point-use/storage. For CCS pipelines the CO_2, whether from a single source or collected from a hub, may have a differing composition over time which would need to be controlled to an agreed fluid composition.

Anthropogenic CO_2 will contain impurities and be captured from a variety of sources. This may cause problems with composition and flow rate control and care will be required to avoid circumstances that could produce operational and safety problems.

All but one existing pipeline are onshore, and the majority of those onshore pipelines run through remote areas with a low population density. Pipelines running through more populated regions will have tighter safety requirements governing pipeline integrity.

Up-scaling of the infrastructure and transport technology required for large-scale, commercial projects. There are 6,000 km of CO_2 pipelines in the US compared to 490,000 km of natural gas pipelines (Energy Institute 2010). In Europe some estimates for the up-scaling required for CO_2 transport is between 30,000km – 150,000 km of pipeline, more than a 10-fold increase in pipeline lengths compared to current world wide installations (Energy Institute 2010). The infrastructure required for the transport of CO_2 will vary significantly between each CCS project, but research is underway to optimise the efficiency of these networks by clustering hubs of CO_2 emissions sources and developing CO_2 transport networks utilising existing pipeline routes or infrastructure corridors in Northern Europe and the North Sea (SCCS 2012) and Australia (Geoscience Australia 2013)

There needs to be a legal framework for the design, operation and maintenance of dense phase CO_2 pipelines, and other transport modes, which will set technical constraints.

In Australia, the Standard AS2885.1 Pipelines: Gas and liquid petroleum - Design and Construction, 2012 has an informative appendix covering CO_2 pipelines. However, there is some research indicates a need to improve the understanding of the safe and efficient design and operation of CO_2 pipelines. This relates to the prediction of CO_2 dispersion from potential leaks and to the equations of state for the range of compositions encountered.

Largely because of the public's unfamiliarity with CO_2 pipelines there may be challenges with public acceptance, which requires detailed work at the route selection stage of a project

5.5. Major International Research Programs on CO_2 Pipelines

EUROPE

European Commission Research Fund for Coal and Steel (RFCS) project: Requirements for safe and reliable CO_2 transportation pipeline (SARCO2)

- Project partners: CSM (Italy), CMFG (Germany), Europipe (Germany), Salzgitter Mannesmann Line Pipe (Germany), V&M Deutschland (Germany), Corinth Pipeworks (Greece), eni S.p.A (Italy), GDF Suez (France), National Grid (UK).
- Co-funded by the European Pipeline Research Group
- Project aim: develop specific requirements and design criteria of steel pipes for anthropogenic CO_2 transportation pipeline systems (including also crack arrestors and composite reinforced pipes) and create the basis for proposing European Guidelines for safe design and operation of anthropogenic CO_2 pipeline networks.
- Specific goals
- Definition of toughness requirements of base material to control running ductile fracture propagation
- Definition of requirements to control crack initiation event also considering corrosion and stress corrosion cracking phenomena
- Collect experimental data related to the release of CO_2 during a pipeline failure

Materials for Next Generation CO_2 Transport Systems (MATTRAN) project

- Newcastle, Nottingham, University College London (UCL), Leeds and Cranfield Universities
- Funded by the Engineering and Physical Sciences Research Council (EPSRC)and E. ON

IEA Greenhouse Gas R&D Programme, UK: COSHER (Carbon Dioxide, safety, Health, Environment and Risks)

- A Statoil/Gasunie initiative to establish a collaboration of European stakeholders to carry out a large scale CO_2 release experiments and measurements program to obtain data that can be used to improve and validate safety models for CO_2 pipelines

COOLTRANS (Dense Phase CO_2 PipeLine TRANSportation) consortium

- National Grid (UK) funded project, started 2008 and about 50% complete
- £8 million
- Aim: establish and demonstrate the requirements for the safe design, construction, operation and maintenance of dense phase CO_2 pipelines to allow the development of a comprehensive safety justification for the onshore pipeline transportation of dense phase CO_2
- Project has 6 work streams:
    - Thermodynamic and flow characteristics of dense phase CO_2
    - Fracture control
    - Quantitative risk assessment

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- o Pipeline design and integrity
- o Environmental and social impact studies
- o Application of research findings

INTERNATIONAL

CO2PIPEHAZ Research Program: Quantitative Failure Consequence Hazard Assessment for Next Generation CO_2 Pipelines

- UCL, Leeds University, UK Health and Safety Executive (HSE), National Research Centre of Physical Sciences (Greece), Dalian University (China), INERIS (France) and GEXCON (Norway)
- Funded by the European 7th Framework

CO2PIPETRANS Joint Industry Project (JIP)

- Coordinated by DNV
- 15 international partners including operators, suppliers and regulators
- Aim is to close significant knowledge gaps through the collection of data mainly from experimental work and to then incorporate this into an update to the existing Recommended Practice for the Design and Operation of CP2 pipelines DNV-RP-J202

USA AND CANADA

Pipeline Research Council International (PRCI) [US based pipeline research group which is connected to the Energy Pipelines CRC] project on shock tube testing of dense phase CO_2 at the TransCanada Gas Dynamic Test Facility in Canada. This work was funded by a consortium including the Energy Pipelines CRC.

AUSTRALIA

Energy Pipelines CRC CO_2 Pipelines Research

- Funded by the Department of Resources, Energy and Tourism
- $1.636m over 3 years
- Work being done by the University of Wollongong, Monash University, ANU, Acil Tasman and the consultants Peter Tuft and Phil Venton
- Developed the Appendix to AS2885 incorporated into the Standard in 2012
- Research projects with the aim of developing and filling gaps to allow a CO_2 pipeline to be designed and operated to AS2885:
  - o Equations of state
  - o Pipeline decompression
  - o Modelling CO_2 dispersion
  - o Determine limits for water content in CO_2 mixtures for safe transport in carbon steel pipe
  - o Public safety, community consultation and organisational requirements for CO_2 pipelines

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- o Cost – benefit study of the application of the results of the research

Key Observations and Recommendations to CSLF on Transport

1. Transport pipeline technology is mature and available.
2. Large scale transport of CO_2 by ship offers promise and needs to be demonstrated at scale.
3. Fine tuning technology fronts include: managing and designing for variations in CO_2 composition in multiple source hubs (includes understanding equations of state and operational implications), fracture propagation control and CO_2 dispersion modelling for safety case and risk assessment purposes.
4. Experience is needed in planning, designing and implementation of large-scale CO_2 transport networks, including hubs and multiple points of capture.

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6. CO_2 Storage Technologies

CO_2 storage technologies are underpinned by well-established technologies used by the oil and gas industry. Fundamental research over many decades on the formation, movement and extraction of oil and gas has created an outstanding body of deep-seated knowledge. This has been applied and refined by industry around the world. Continued significant investment in next generation technologies has resulted in an oil and gas industry utilising very sophisticated technology that is continually evolving. This is the starting point for understanding and developing the technology associated with carbon storage (Benson and Cook, 2005; Ambrose et al, 2008).

The fundamental research in oil and gas behaviour in the subsurface is strongly informing the essential research and associated laboratory work in CCS. CO_2 has different properties to oil and gas and rather than extracting large volumes, the focus is on injecting significant volumes, this has implications for storage site selection, including understanding storage capacity, injectivity and containment potential at each site. A significant amounts of knowledge related to CO_2 can be gained from the science and technology associated with the injection and monitoring of CO_2 and other gases and liquids in enhanced oil recovery (Kaldi and Gibson-Poole, 2008). As in all operations, safety issues are reliant on specific parameters; in CO_2 storage these may be different to those conventionally used in the oil and gas industry.

This rapidly growing body of knowledge in the oil and gas industry, combined with the emerging laboratory and pilot scale studies in CO_2 storage (as well operating projects) gives immense confidence in the ability to safely store very large volumes of CO_2 in the world's sedimentary basins[15]. There is a strong consensus that safe CO_2 storage is possible today based on current technologies. This is reinforced by that fact that there are eight projects in operation globally and nine in the execution phase (GCCSI, 2013), noting that many of these are EOR projects.

There are however aspects where research and operational experience can optimise exploration regulatory and operational outcomes. This section looks at both the fundamental laboratory and pilot scale work on the behaviour of CO_2 in the subsurface (Fundamental knowledge in Table 2) that is underpinning the emerging technology of carbon storage, but also the application of large scale assessment, operations and monitoring (Applied Knowledge in Table 2). Large scale operations are creating both new knowledge in the applied space but will also define fundamental research needs to further improve operational deployment of CCS in the future. These are the typical dynamics of continuous improvement that occur in all large industrial processes.

[15] It is to be noted that this report recognises that CO_2 storage in unconventional storage systems, such as basalts, shales, mudstones and carbonates is a research front. However, due to the very site specific nature of the geological storage of CO_2 within these unconventional systems and the long time frame for research and development of these sites, the report focuses on the more near-term research fronts in deep saline aquifers and depleted hydrocarbon reservoirs.

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Fundamental Storage R&D	Applied Storage R&D				
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Storage Geology • Top seal characterisation • Fault seal characterisation • Discontinuities & heterogeneity • Upscaling for large sites • Rock characterisation – caprocks & reservoirs • Saline aquifers/ depleted O&G reservoirs	• Optimising storage resource • Managing imperfect data • Size of storage complex – resource conflict	• Storage limits characterisation • Managing high uncertainty • Assessing structural traps vs stratigraphic traps • Hydrostratigraphy • Faults as trapping mechanisms • understanding confined and laterally unconfined aquifers	• High permeability thief zones and profile modification • Operating relative to seal limits • Well bore orientation to optimise efficiency • Optimisation (number of wells, capacity & permeability)	• Modelling release of trace elements • Induced seismicity risk	• Appropriate / fit for purpose data acquisition for characterisation • Reduction of MMV surface footprint • Detection versus quantification of leakage and how accurate it is possible to be.
Subsurface CO_2 Behaviour • Appropriate modelling • Temporal / spatial changes in chemistry, pressure, stress prediction • Residual & solution trapping effectiveness • Geomechanical and hydrodynamic	• Analytical solutions for fluid flow • Impacts outside storage complex • Dynamic capacity • quantify connectivity and continuity of intraformational baffles & seals- Hydraulic monitoring	• Risk and uncertainty based modelling • Along fault leakage • Impacts of Mineral Associated Trapping (MAT)	• Storage Management: - Optimising pore space resource - Optimising injection rates and maintaining reservoir integrity • E factor for storage efficiency • Leak-off Tests (LOT) to optimise injection	• Pressure relief / management modelling • Geoengineering/ 'plume steering' • Monitoring for brine displacement • Subsurface intervention	• performance verification • MMV-based long term model forecast calibration • understanding the amount and saturation of CO_2 relative to geological parameters to visualise/recognise the plume.
MMV Technologies • Seismic & EM • CO_2 sensors atmosphere • Other geophysical • Tracers	• Effective large scale assurance monitoring • Hydrodynamics • Methods for monitoring groundwater resources that command general consent	• Effective baseline duration	• Effective performance monitoring • Far field effect MMV • Lack of injectivity software	• Above zone monitoring • Well integrity evaluation • Marine monitoring • Data sets for leakage models (natural systems) • Determing the origin of potential leakage • Data sets to calibrate & test behaviour of tracer / CO_2 in lab and field.	• Developing continuous, high resolution low cost, low impact subsurface monitoring • Technology and methodologies for offshore (sub marine) & land surface MMV • calibrating M&V with controlled releases

Table 2: CCS Storage R&D Gaps/Opportunities: fundamental and applied technology

Table 2 sets outs three key areas in fundamental storage research where opportunities for improvement in understanding have been identified:

- Understanding the geological basis and constraints for CO_2 storage
- Understanding CO_2 behaviour in the subsurface. This is relevant to both reservoir scale and basin scale issues associated with carbon storage (see Figures 24 and 25 for the prospective associated research fronts).
- Optimising and adapting current MMV techniques and developing new techniques specifically for CO_2 storage

The growing knowledge base from these three areas and the deep knowledge base from the oil and gas industry are the underpinnings of the applied technology required for carbon storage. The framework of applied stages of CO_2 storage project discovery and operation used in this report are:

- Basin Scale Assessment
- Site Selection and Characterisation
- Injectivity and Operations
- Management and Risk Assessment
- Measurement, Monitoring & Verification (MMV)

6.1. Fundamental laboratory and bench scale research on storage

This work is mainly associated with understanding CO_2 at the micro scale (interaction with pores and minerals in the reservoirs and seals – Ferer et al, 2002) which in turn is used to interpret CO_2 movement and behaviour at the core/log scale, the storage site scale and ultimately the basin scale. This fundamental understanding is essential for the proper prediction of CO_2 movement and stablisation over both the short periods of time necessary for efficient operational management but also the longer periods of time in defining and delivering final safe storage.

The main areas of laboratory and pilot scale research and development are:

- Understanding CO_2 movement and fluid flow, geochemical and geomechanical interactions from the pore to basin scale, (including pressure effects) and applying these to commercial scale projects (see Michael et al, (2009), Michael and Underschultz, (2009) and Allinson et al, (2010) for summary reviews).
- Upscaling of CO_2 simulations e.g. upscaling of solubility, residual gas trapping, convective mixing or of vertical migration of CO_2 (see Ennis-King and Paterson, 2000).
- Defining geochemical and mineralogical interactions with rock and pore fluid; see Knauss et al, (2005); Kirste et al(2010).

All of the above have fundamental theory and micro modeling research fronts and rely on the underpinning data sets of phase interactions, chemical equilibria, and the kinetics of CO_2 mineral interactions. Often, data sets that have been developed for the oil and gas industry are used but they may lack specificity to CO_2 related research, or they may be restricted to areas of oil and gas exploration, and do not include areas where hydrocarbons are not present but which may have potential for CO_2 storage

6.1.1 CO_2 movement and fluid flow and geomechanical effects

This covers laboratory work on the interaction of CO_2 with pores and conduits in the rock, as this is vital to understanding safe storage and injection strategies. Key areas are:

- Understanding geomechanical effects of pressure and volume changes on the integrity of seal and reservoir rocks (eg Perkins and Gonzales, 1985; Hawkes et al, 2005; Zoback, 2007; Rutquist et al, 2008; Kvamme et al, 2009);
- Developing data sets to test geomechanical models for the risk of fault reactivation (can known faults be deliberately reactivated to test models….perhaps by using water rather than carbon dioxide).

6.1.2 Geochemical research and reaction modelling

Geochemical modeling is sufficiently well developed to enable speciation and saturation index calculation for complex aqueous solution compositions and their reaction with many mineral phases. More experimental and field data for single- and multi-mineral phase-aqueous solution systems are required to ensure reaction path models are representative of natural systems. Incorporation of kinetics of reactions introduces significant uncertainty because of the number of variables required to adequately represent the controls on rates and the reaction mechanisms (Kirste et al, 2010). However, the geochemical modeling of experimental, field and natural analogue data is being carried out and the uncertainty is recognised and can be addressed.

Critical research gaps, opportunities and prospective technology fronts include:

- Developing robust data sets to test models for convection of dissolved carbon dioxide reactions on large time scales (beyond what is possible in demonstration projects), based on analogues from natural systems and extrapolation.
- Developing detailed conceptual models of the geochemical system involving CO_2. Choices of reactant and product phases are often the product of the numerical model rather than experimental and observational data.
- Fine tuning mineral dissolution or precipitation thermodynamics (processes and rates are largely unknown in CO_2-brine-rock systems in real time). However, reviews of geological analog studies (eg Schacht, 2008, Wilkinson et al, 2009) may provide insights into these aspects.
- Develop models that consider convergent flow (partial penetration/skin effects), dissolution of CO_2 in brine, precipitation of carbonate minerals or drying effects.
- Produce more thermodynamic data, especially for Pitzer equation, formulation are required for saline solutions.
- Improving the understanding of the thermodynamic properties of mixed mineral phases (solid solutions) and poorly defined mineral phases like clays that are not well constrained.
- More experimental data sets associated with surface processes like adsorption and exchange that can act as a significant buffer to pH changes and can be repositories for cations that may be involved in mineral trapping. Many modeling codes include the ability to simulate adsorption and ion exchange making sensitivity analysis possible.
- Develop refined kinetic rate parameters for critical mineral phases, especially mixed mineral phases and poorly defined mineral phases such as clays. Dawsonite precipitation kinetics need to be investigated as this is one of the most common product phases of numerical simulations and yet is not a common phase observed in natural analogues or experiments (Duan et al, 2005).

- Reactive surface area – determination, calculation, estimation. The most common difficulty described in the recent literature is the selection of a value for the reactive surface area to include in rate equations.
- Surface reaction mechanisms and how they influence the rates of reaction is poorly understood and difficult to model.
- Precipitation nucleation and degree of supersaturation required for precipitation for many important phases is not well known.
- Upscaling of reaction kinetics from the mineral surface to the continuum scale of reactive transport modeling is poorly constrained.

For carbonate reservoirs there are some specialist geochemical considerations:

- Assessing the significance of carbonate mineral dissolution.
- Determining the risk of liberation of contaminants when or if carbonate dissolution occurs.
- Researching the potential of a chemical equilibrium developing between CO_2 & carbonate reservoirs.
- Improving the understanding of the impacts of migration associated trapping (MAT) for evaluating capacity

Key observations and recommendations on fundamental storage science and laboratory work

1. It is important to continue research, laboratory work and data gathering on physical and chemical parameters underpinning the detailed modelling of CO_2 fluid flow behaviour, chemical reactions with minerals and geophysical responses. This includes up-scaling simulations of solubility, residual gas trapping and fluid mixing. More precise fundamental metrics and algorithms are vital to large scale predictive models and hence robust modelling predictions.

6.2. Integrating fundamental research into site and basin scale models of CO_2 behaviour

A significant shortcoming relates to the lack of integrated fluid flow and sub-surface models which also bring together geochemistry and geomechanical dimensions of modeling. It is expected that, as the underpinning science and modeling improves, the application of CCS behaviour knowledge will be much more efficient and useful to operators and regulators alike (Bachu, 2008).

Critical issues include:

- The ability to more accurately model plume movement and plume stabilisation in laterally unconstrained saline aquifers, taking into account residual trapping dissolution of CO_2 and eventual sinking of heavy CO_2 charged water and mineralisation.
- More efficient models of fluid flow through complex strata stacks with varying permeabilities and intermediate partial seals at reservoir and basin scale. Today there is a limitation on the number of blocks (or grid) components in the models for computational reasons. The larger the blocks of rock in the models the more assumptions have to be made about the flux of CO_2 (rate and volume) though each block.

6.2.1 Basin Scale Assessment

Basin Scale Assessment is conducted as a high level assessment to evaluate a basin's potential for CO_2 storage. There are two dimensions of this, one is the assessment of the basin for specific storage sites, and the other is for regulators who need to consider optimising the use of the basin in the long term for CO_2 storage. This is relevant, for example in the North Sea, where a significant quantity of Northern Europe's CO_2 could be stored for centuries if the use of the basin is properly planned. Similarly, assessment of the Gippsland Basin of Australia (Gibson-Poole et al, 2006, 2007), has demonstrated that this basin could store most of Australia's emissions. This then influences the allocation of storage rights, the order of injection into different individual storage sites and, last but not least, the impacts on other commodities such as oil and gas extraction and potable water aquifers.

Many of the techniques and skills used by the hydrocarbon industry will be used for basin scale planning and assessment for a CO_2 storage project. However, there are new dimensions that are substantially different from the oil and gas industry. The eventual scale of injection is formidable and the associated pressure effects and resource conflict issues are not very often present in the oil and gas business, which is mostly about extraction and the drop in pressure. There are thus a number of new challenges involved when conducting a basin scale assessment and planning for large volumes of CO_2 storage.

Critical research gaps, opportunities and prospective technology fronts include:

- Optimise use of natural resources and determine the impact of a storage project in regard to current and future hydrocarbon projects and ground water interactions to avoid resource conflict in the subsurface.
- Improvements in hydraulic modelling and monitoring will be required to quantify the connectivity and continuity of intraformational seals and baffles at basin scale. Basin scale modelling will require high level assessment of the interplay between the petrophysical, geomechanical, hydrodynamic and geochemical properties of caprocks and faults (Kaldi and Gibson-Poole, 2008). Background data on this will often be lacking or will consist of old seismic data and wells from oil and gas activity.
- Models are needed to understand the interaction of basin-scale hydrodynamics with CO_2 migration.

- The ability to populate basin scale models with synthetic data is used by the oil and gas industry but needs to be improved for CO_2 storage. The data sets are improved and ground-truthed as more hard information becomes available from wells, seismic interpretation and interpretation of other geophysical data such as gravity and aeromagnetics (Spencer et al, 2010). One of the research fronts is to get better probabilistic determinations and confidence levels on specific sequences of rock that may act as seals, fluid flow or unintended migration pathways. This will aid in the selection of new wells or seismic surveys to improve confidence levels of key sequences likely to be used for storage.
- There also needs to be work on the best way to use or access data-sets not commonly acquired through standard petroleum industry acquisition methods in basin-scale assessment, but which may already exist or be more cheaply acquired than new seismic data. Airborne gravity and magnetics are examples that have occasionally been used by the oil and gas industry.
- Faults in the subsurface create special problems and sometimes opportunities. They need to be mapped and properly defined to establish whether they could act as migration pathways for CO_2 or as trapping mechanisms. More research and studies on the containment-enhancing role of faults need to be provided to the CCS community so that proponents, regulatory agencies and the public are aware that faults in a potential CO_2 reservoir could be beneficial.
- Incorporating tenement allocations into basin scale assessment for CO_2 storage projects so as to avoid possible conflicts of interest between proponents, regulatory agencies and the public. Basin modelling will also assist government agencies in the allocation of tenements.

Key Recommendations to CSLF on basin scale modelling

1. CO_2 modelling would benefit from the move towards integrated dynamic models of fluid flow, geochemistry and geomechanics (computational fluid dynamics is already well established in designing many complex industrial processes).
2. More work is required on the ability to build robust basin scale fluid flow models; this is an important basis for operators and regulators as well as for governments involved in resource allocation and resource conflict issues.

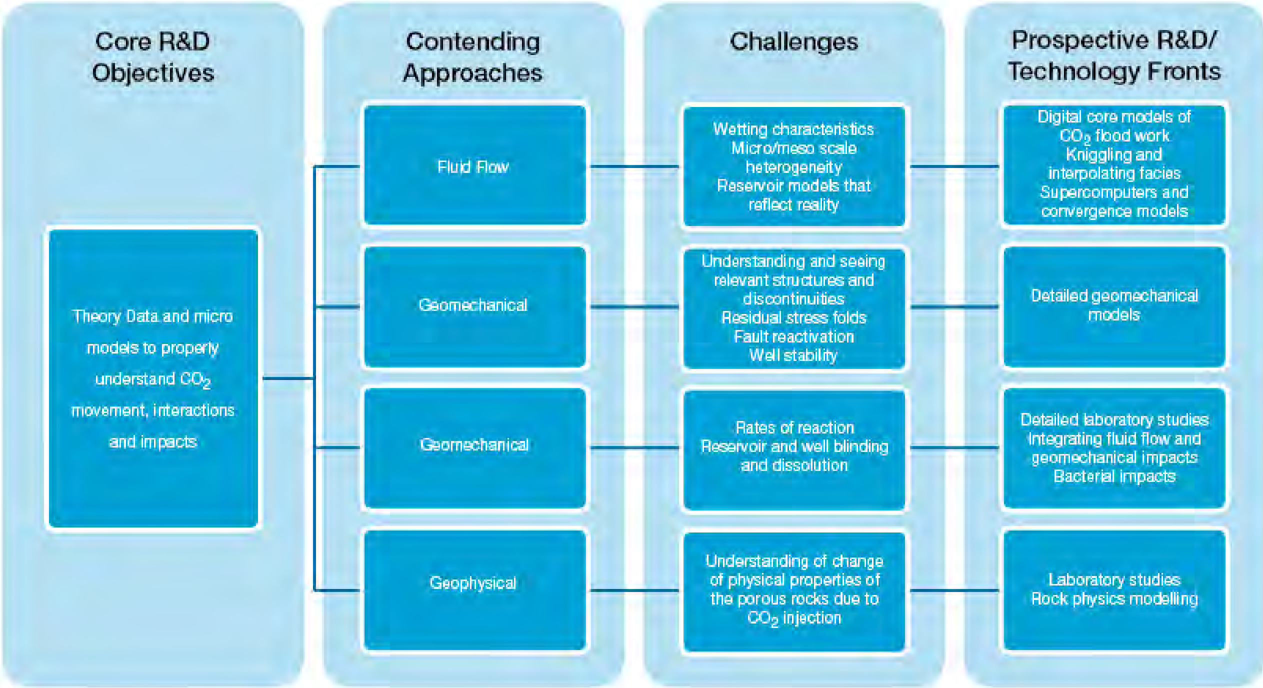

Figure 24 - Prospective Technology Fronts for Understanding CO_2 Behaviour in the Subsurface

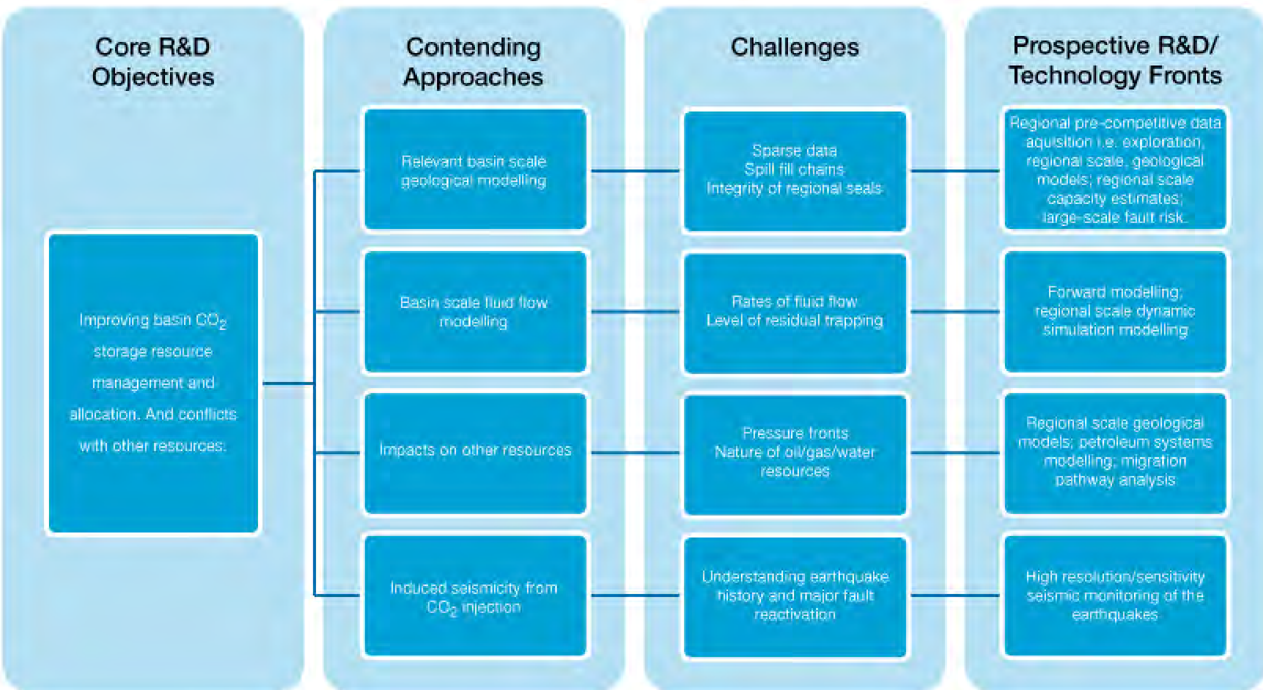

Figure 25 - Prospective Technology Fronts for Understanding CO_2 Behaviour & Impacts at Basin Scale.

6.3 Site Characterisation & Operation

6.3.1. Site Selection & Characterisation

The selection of storage sites suitable for significant volumes of CO_2 comprises mainly geological evaluation of the applicable storage system (e.g. saline formations, depleted or near depleted oil and gas reservoirs and/or coal systems) at various levels of detail. CO_2 site characterisation taps into a vast array of expertise in reservoir engineering, structural geology, sedimentology, stratigraphy, hydrogeology and geological modelling. Site characterisation requires greater detail than basin-scale assessment investigations and may involve re-evaluation of regional geology, generation of new data and/or updating of existing static geologic and seismic data, dynamic engineering data and numerical flow simulation models (Kaldi and Gibson Poole, 2008). An important aspect of site characterisation is the determination of acceptable versus unacceptable levels of uncertainty in order to determine the amount of risk associated with the site and the amount and type of additional data required to reduce the uncertainty (Vendrig et al, 2003; Bowden and Rigg, 2004; Streit and Watson, 2004). Three key factors that require further detailed evaluation at each specific storage site are: containment, capacity, and injectivity. These three factors encompass the fundamental elements needed to characterise any potential CO_2 geological storage site and are described in more detail below.

For greater understanding of the site selection and characterisation process, several opportunities for improvement of knowledge are:

- Researching and assessing the value of the different characterisation techniques for shallow and deep reservoirs to determine if different technologies are required or the same can be applied to both types of reservoir.
- Determining the optimum size of the characterisation “footprint” for site selection, i.e. how far away from the proposed storage zone will new data and deeper insights in geology be required.
- Evaluating the limitations of baseline surveys for characterising potential sites and determining when further detailed site characterisation will be required.
- Evaluating the significance of hydro-stratigraphy in site selection and characterisation.
- Comparing the significance of the evaluation of seal properties to the evaluation of reservoir properties for capacity and injectivity.

6.3.2 Capacity

Defining capacity of a storage site is a vital issue in CCS (Bachu et al, 2007; Bradshaw et al, 2007; Kaldi and Gibson Poole, 2008; Spencer et al, 2010). It is required in the initial work to determine if the injection volumes contemplated for “bankable” projects are realistic, so as to provide confidence (minimise risk) to operators, investors and regulators. The pore space is where the CO_2 is to be stored and so it becomes a resource; therefore calculating this space becomes an accounting issue. Much of the existing methodologies that address storage capacity estimation are based on the oil and gas industry’s Petroleum Resource Management System (PRMS) guidelines. *Storage capacity* is considered a resource, and as in petroleum accumulations and mineral deposits, categorised based on levels of certainty of resource availability (Allinson et al, 2010).

Because of uncertainties inherent in subsurface evaluation, exact quantification of geological properties is not possible and therefore storage capacity is always, at best, an approximation of the amount of pore space into which CO_2 can be injected. Hence, the likelihood of contingent and prospective storage volumes achieving commerciality is determined probabilistically, utilising high, low and best estimates.

All levels of capacity assessment involve mainly technical issues and, as the methodologies for estimation of capacity for CCS are still nascent, there are many opportunities to improve knowledge in certain key areas:

- Determining if different assessment methods are required to characterise depleted fields versus virgin saline formations.
- Distinguishing between the different assessment methods required in structural traps (folds and fault) versus stratigraphic traps.
- Developing a consistent methodology to define an Efficiency factor (E) for capacity estimation at various sites.
- Evaluating the suitability and effectiveness of the Petroleum Resource Management System (PRMS) of capacity estimation to be used as the standard methodology applied to all sites. This works on a net present value approach to the viability of a site and may need to take into account:
    - Incorporating lease boundary constraints and competing resource constraints into capacity estimations.
    - Improving understanding of scales in order to make capacity estimates for basins or regions.
    - Including source-sink matching in capacity estimates.

6.3.3. Containment

6.3.3.1 Hydrodynamics

The impact of hydrodynamics on the sealing capacity of top seals and faults has been discussed in the literature only with respect to hydrocarbon migration. With respect to CO_2 geological storage, little research has been published on this issue, though the IEAGHG report on *Pressurization and Brine Displacement Issues for Deep Saline Formation CO_2 Storage* (IEAGHG, 2010) as well as papers by Michael and Underschultz (2009) and Cavanagh and Wildgust (2011) have begun to address this gap.

Critical research gaps, opportunities and prospective technology fronts include:

- The most critical knowledge gap on this topic is the absence of data to calibrate analytical and numerical models and to quantify the impact of seal properties on reservoir pressure and capacity calculations.

6.3.3.2 Geochemistry

Chemical interaction between CO_2 and caprock may affect the mechanical strength and transport properties of the sealing formation, possibly inducing slip along currently sealing faults or creating pathways, allowing carbon dioxide seepage (Kaldi et al, 2011). However, very few studies attempt to couple chemical and mechanical processes occurring within the caprock as a result of CO_2 injection.

Critical research gaps, opportunities and prospective technology fronts include:

- Modelling of the hydraulic integrity of the reservoirs to quantify connectivity between the systems and continuity of intraformational seals and barriers is lacking. Collected data can then be integrated in predictive models of caprock integrity.
- Petrophysical, geomechanical, hydrodynamic and geochemical properties of both the reservoir and caprock are important to determine whether multiple reservoir/caprock and/or single reservoir/caprock systems can be utilised for safe, long-term storage. Very little work has been done towards

understanding the interplay between the combined effects of these properties on caprocks and faults for CO_2 systems.

6.3.4. Injectivity and Operational Issues

Injectivity refers to the rate at which CO_2 can be injected into a given reservoir interval and the ability of the subsequent CO_2 plume to migrate away from the injection well (Cook, 2012). For low permeability formations, numerical simulations show that there will be large pressure gradients near the wellbore, which will restrict the injectivity. Low injectivity potential for an interval might result in a site with otherwise excellent capacity and containment characteristics turning out to be uneconomic and therefore unsuitable for CO_2 storage. An example of this is the ZeroGen Project in Queensland, Australia (James et al, 2012). During CO_2 injection into a reservoir, the injectivity and nature of plume migration will depend on parameters such as the viscosity ratio, injection rate, permeability and relative permeability. These parameters will in turn depend on variables such as depositional environment and reservoir heterogeneity, stratigraphic architecture, post-depositional diagenetic alteration, structural dip, fault distribution and fault seal capacity, pressure distribution and the nature of the formation fluids (Kaldi and Gibson Poole, 2008).

Other critical operational issues relate to the ability to take the feedback and data from the early part of an operation and feed it back into the projected models for the future plume movement, pressure effects and related possible geomechanical impacts at the reservoir scale and the on seal stability. These kind of feedback processes are already well established in oil and gas industry practice and in geothermal energy but there will be considerable lessons that come from the early storage projects. These lessons will be vital to scale up to the multi-million tonne per annum operations that will be the next generation of storage projects starting in the late 2020s.

Critical research gaps, opportunities and prospective technology fronts include:

- The development of a low cost downhole solid state CO_2 detection method.
- Construction of a database for calibrating optimum wellbore parameters (e.g. diameter; perf zone) for injection into formations of various permeabilities, and thereby determining permeability cut-offs for injectivity.
- Managing high permeability intervals (“thief zones”) via profile modification.
- Establishing the parameters that control optimum wellbore orientation (vertical vs horizontal vs slant).
- Determining the relationship of optimal number and orientation of wells, capacity outcomes and permeability to optimise injectivity.
- Modelling injection-related pressure buildups and the effects of near-well boundary and far-field transients.
- Determining optimal injection rates to prevent blow-out (surface or subsurface).
- Lab-test the effects of injecting CO_2 with impurities (SOx, NOx, CO, and other exotic species) into the reservoir.
- Injectivity modelling is limited by software required versus software available and the inability to upscale from lab to field scale.

There is a lack of understanding of the full effects of pressure. There is a need to:

- Optimise injection rates while maintaining reservoir integrity.

- Optimise injection planning by calculating how and when to run Leak-off tests (LOT) and Extended leak-off tests (XLOT).
- Research the extent of pressure effects (near well-bore vs far field effects).
- Undertake research and calculations concerning the effect of pressure on induced seismicity.

6.3.5. Induced Seismicity

Seismicity can be induced by any industry that is injecting volumes of fluid or gas into the subsurface (e.g., CCS, geothermal and waste water disposal; Gerstenberger, et. al., 2013, Zoback and Gorelick, 2012; Avouac, 2012; Deichmann & Giardini, 2009; Holland, 2013; van der Elst, et al., 2013). Few induced earthquakes have been associated with CCS or other CO_2 storage sites, and those that have been recorded are small (i.e. micro-seismicity of M≤2.0; Gerstenberger, et al, 2013); however, the volumes of CO_2 injected have typically been small compared to what will be required for commercial scale CCS. Examples such as the Basel, Switzerland enhanced geothermal (EGS) project, which induced a magnitude 3.4 event, caused damage to the city and halted the EGS project (Deichmann & Giardini, 2009), indicate that appropriate mitigation and planning is required for a successful CCS industry. A key step in reducing the risk is appropriate selection of well characterised sites including understanding the response of the reservoir to injection. In addition, detailed monitoring of induced seismicity is an important mitigation measure and can also be used for understanding the behaviour of the subsurface and tracking the migration of the CO_2.

The understanding of the relationship between fluid injection and induced seismicity is in its infancy but some basic relationships such as a positive correlation between injected volume and maximum magnitude have been seen. Statistical predictive modelling tools are currently being developed and may prove to be useful in assisting mitigation of induced seismicity. Physics based numerical models are being developed in concert with the larger seismological community, but as of yet lack the necessary validation against observations. In the future, both types of modelling will likely be useful tools for reducing the risk of induced events.

While the available evidence indicates that the probability of inducing a large and damaging event is likely to be low, smaller non-damaging events may be detrimental to the reputation of the industry. Some key steps and knowledge gaps that can help reduce this risk are (Gerstenberger, et al, 2013):

- Availability of an across-industry induced seismicity catalogue.
- Understanding of fundamental induced seismicity relations.
- Realistic physics based modelling.
- Understanding of the impacts of scaling from pilot to production projects.
- A CCS Induced Seismicity Risk Management Protocol.
- Collaboration across industries including the wider seismological community.

Key Recommendations on Site Characterisation and Operation

1. Continue to build on oil and gas industry knowledge and integrate with emerging CO_2 storage data and concepts to develop internationally consistent:
    - storage site characterisation methodologies;
    - storage efficiency factor; and
    - capacity estimation and reporting standards.

2. Improving modelling strategies associated with the hydraulic integrity of intra-formational seals (this affects the interplay between reservoir and caprock qualities and the need for multiple or single caprocks in a given geological situation).
3. The industry needs to develop a downhole solid state CO_2 detection technology.
4. Development of methodologies to manage high permeability thief zones and differential pressure effects that can reduce efficient reservoir use.
5. Integrating modelling and operational experience to develop strategies to optimise drill patterns and angles for injection and also for pressure management, avoiding blow outs and induced seismicity.

6.4. Managing and Avoiding Migration Variance

Although there is now significant confidence in the science and technology associated with injecting large quantities of CO_2, consideration needs to be given to situations where some intervention is required to ensure that CO_2 is retained in the subsurface zones agreed with regulators. Ensuring well integrity is important, both for old wells in the plume area and for any new wells. Wells can be fixed and there is again considerable experience in the oil and gas industry on this.

The other dimension of managing and avoiding migration variance is where the plume moves in ways not predicted in the initial modeling. More work is required to build a knowledge base around working with or managing the CO_2 plume movement when there is significant variance to the projected models (Michael and Underschultz, 2009).

6.4.1. Wellbore Integrity

Slow, low-rate leakage is unlikely from injection wells as they will be managed with CO_2 interaction in mind, but leakage could happen from existing wells if they are not properly assessed and managed (Watson, 2009). The largest uncertainties and risks are old abandoned wells in the area of review as the state of completion may not be known (DOE/NETL 2013). The risk profile for projects should reflect the potential for long-term deterioration of wells and the movement of plumes to encounter leaking wells. Cement is key to reducing wellbore integrity issues – if the cementing is good (in terms of the role of centralisers and in design, quality and placement), the well is most likely to perform as expected. Certain cements have the ability to self-heal (in some circumstances).

Research gaps, opportunities and prospective technology fronts include:

- Wellbore integrity is mainly related to the long term risk profile, associated with the breakdown of materials such as cement stability in CO_2 and steel corrosion. Therefore there is a case for more research into the design of CO_2-resistant cements, best practices in well completions, well abandonment practices, detailed modeling of fluid-wellbore interactions, field-scale modeling of wellbore performance and remediation technologies.
- Better characterisation and simulation of CO_2 leakage rates through wellbore cement, to arrive at a better assessment of the overall risk of well leakage.

6.4.2. Migration (including unintended migration and leakage)

Unintended migration or movement of the injected CO_2 plume away from the injection zone and through the reservoir is a potential risk for storage projects. High permeability formations allow relatively fast migration of CO_2, lowering the proportion of the injected CO_2 plume trapped by structural, stratigraphic or migration associated trapping (MAT) mechanisms such as solution, mineral or capillary trapping (Macminn, et al, 2010). Thus higher permeability is ideal near the wellbore to increase injectivity, lower permeability is desirable outside the radius of influence of the wellbore to increase residence times and encourage the rate of residual trapping, dissolution and mineral trapping.

Research gaps, opportunities and prospective technology fronts include:

- Leakage needs to be defined;
  - Is "leakage" any movement of the injected CO_2 out of the intended target storage formation (ie movement from a regulated zone in the subsurface to a shallower non-regulated zone)?
  - Or is it movement through the seal?
  - Or is it appearance at the surface or in sensitive receptors such as potable aquifers?
  - Should leakage/unintended migration refer not only to CO_2, but also to any brines displaced by injection of CO_2?
  - Should the potential impact of leakage be defined?
  - Can the leakage be classified as "detectable" (but without major impact) or "significant" (having major impact)?

Some of the areas for further work in addressing the uncertainties include:

- Data sets are required to test leakage models, perhaps in natural systems.
- Better simulations of fault leakage rates of CO_2 and CO_2/gas mixtures to the surface (involving liquid to gas transitions, as well as characterisation of the fault properties etc).
- Integration of CO_2 leakage to the ocean floor with prediction of CO_2 migration in the ocean (along with predictions on how to monitor it).
- Data sets to calibrate and test reactive transport models.
- How can leakage be attributed and accounted (in terms of liability and impact on carbon credits)?
- Attribution (from interpretation of monitoring data) is not adequately understood;
  - integration of diverse data sets may be necessary, as is determining the source of the leakage, such as through wells, fractures, caprock, spills and migration.

6.4.3. Mitigation

There is little experience in developing and testing mitigation technologies. Theoretically, there are various potential solutions to the key risk associated with storage: the unintended migration of CO_2, including leakage to surface or to sensitive receptors (including water, oil, gas, coal or other resources). Barlet-Gouédard et al (2006) discuss mitigation options for wellbore leakage; and Kuuskraa (2007) considers the subsurface storage system and suggests options such as reducing the pressure in the storage reservoir from which the leak is occurring; increasing the pressure in the storage formation (generally a shallower reservoir) into which the leak is occurring; or intercepting the CO_2 plume and extracting it from the reservoir. However, all of these potential mitigation methodologies are untested and must therefore be considered knowledge gaps.

Research gaps, opportunities and prospective technology fronts include:

- Can pressure management and geoengineering ("plume steering") by changing the flow direction by selective water production and/or injection be implemented under real reservoir conditions?
- Is it possible to change interfacial tensions (hence relative permeabilities by using chemical treatments, such as surfactants, biofilms etc)?
- If "thief zones" (preferential permeability pathways) occur in the reservoir due to channels or fractures, can these be preferentially plugged via profile modification using foams or other blocking agents?
- What are the cost/benefit ratios for all of these technologies?

6.4.4. Risk Assessment

Risk assessment is a critical activity as part of the selection and characterisation of sites for long-term storage of CO_2 and, in particular, for the development of a risk management strategy. While geologic uncertainties or risks are highly site-specific, the main perceived risks are of potential leakage, induced seismicity and ground displacement, and their potential impact on health, environment, resources, and value (GCCSI, 2013). Risks associated with storage that may affect project feasibility are the timely identification of a suitable storage site, its adequate characterisation and public acceptance.

Storage-related risk assessments and risk management processes have matured as more projects approach final investment decisions. Projects in development have benefited significantly from knowledge dissemination of risk management plans and MMV programs from operational or near-operational projects, such as Sleipner, the IEAGHG Weyburn–Midale CO_2 Storage and Monitoring Project, In Salah, and the Gorgon Injection Project (GCCSI, 2013). It is notable that many of the smaller demonstration and R&D projects, e.g. the CO2CRC Otway Project, Frio, Nagaoka, Lacq-Rousse, Ketzin, Cranfield, and a number of tests in the US Regional CO_2 Partnership program, have all contributed to monitoring knowledge through trialling a wide array of technologies.

Research gaps, opportunities and prospective technology fronts include:

- There are multiple risk assessment tools in the market place (eg Bow-tie; Tesla; RISQUE; BBN), but few equitable comparisons have been made concerning which tool is best.
- Although regulators are conversant with risk management, there may be some benefit in educating regulators about risk assessment in CO_2 storage.
- The application of risk assessment to site selection during the various stages of site selection and characterisation; i.e. what constitutes the boundary condition to permanently reject a particular prospective site?

6.5 Key Observation and Recommendations on Managing and Avoiding Migration Variance

- Risk management of potential leakage has matured as more projects are approved or move through to financial investment decision.
- More work is required on:

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- o Developing stronger models and underpinning data sets on possible migration pathways (fault, seal, strata/structure), to enhance risk management.
- o Well integrity including developing CO_2-resistant well cement and simulation modelling of leakage through wells.
- o Mitigation strategies, such as pressure management, and profile modification.
- o The attribution of leaked CO_2 and associated accounting issues.
- o Strategies to underpin the proof of 99% storage (IPCC definition) are required.

Key Recommendations to CSLF on Storage

1. Modelling CO_2 behaviour is a vital element of storage research and technology integration; developments required include :
   - Fundamental research, laboratory work and data gathering on physical and chemical parameters to better underpin detailed modelling of fluid flow behaviour, chemical reactions and geomechanical outcomes.
   - More integrated dynamic models of fluid flow, geochemistry and geomechanics running on very large computers.
   - The ability to build robust basin scale fluid flow models for operators, regulators and governments involved in resource allocation and resource conflict resolution.
   - Modelling and strategies associated with the hydraulic integrity of intra-formational seals and faults and the number and thickness of caprock required.
   - Developing stronger models and underpinning data sets on possible migration pathways (fault, seal, strata/structure) to enhance risk management.
2. Improvements to optimise operational effectiveness and storage efficiency, including:
   - Developing strategies to optimise drill patterns and angles for CO_2 injection and pressure management to avoiding blow outs.
   - Understanding induced seismicity and developing pressure management strategies to avoid minor induced seismic events and potential compromise of caprocks.
   - Approaches to enhance residual trapping, in-situ mineral trapping and mineralisation and also injection strategies for storage in lower permeability rocks.
   - Developing methodologies to manage high permeability thief zones and differential pressure effects that can reduce efficient reservoir use.
   - Understanding fines migration, subsurface erosion and precipitation and the effects of subsurface microbes that could compromise operational effectiveness.
3. Develop (based on oil and gas industry practice) internationally consistent standards:
   - Storage site characterisation methodologies.
   - Storage efficiency factors.
   - Capacity estimation and reporting standards.

4. More work is also required on technology and risk management strategies to mitigate or manage unintended CO_2 migration:
   - Well integrity, including developing CO_2 resistant well cement and simulation modelling of migration through wells.
   - Mitigation strategies, such as pressure management, and profile modification.
   - The attribution of leaked CO_2 and associated measuring and accounting issues.
   - Strategies to give even greater confidence in long term storage.

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7. Measuring, Monitoring, Verifying (MMV) and accounting

7.1 Key Issues in MMV

Much knowledge has been developed and tested with respect to measuring, monitoring and verifying (MMV) in both oil and gas projects as well as in active CCS demonstration projects. A very wide range of techniques is available for MMV, covering many types of geophysical investigation and environmental monitoring. A comprehensive recent summary is given in the IEAGHG report (Korre 2012). A useful distinction is between conformance monitoring – essentially checking and updating models of CO_2 migration – and compliance monitoring, demonstrating compliance with regulatory and societal requirements. The former is relatively unproblematic and builds on decades of related experience in hydrocarbon extraction. The latter is more complex and revolves around the issue of “no leakage” or “no impact”. While many monitoring tools are available, probably the key issue is the integration of monitoring and risk assessment, and the associated issues of regulatory consent and social license.

Feasible monitoring programs will have to be focused on agreed risks in a precise way, not attempting to prove ”no leakage” but rather accepting that this is the conclusion that remains when a number of specific leakage mechanisms have been ruled out (Jenkins, C., 2013 IJGGC). Measurements of CO_2 and its effects in the near-surface and atmosphere need particularly careful handling in this context. Because CO_2 is so intimately bound up with ecosystem processes, there are large variations in the measurements that are unrelated to leakage of anthropogenic CO_2. Unless monitoring programs are carefully designed, with an agreed understanding between stakeholders about the sensitivity of the measurements to leakages and the likelihood of false alarms, such programs could become a focus of contention rather than reassurance.

The outstanding research problem in this area concerns the monitoring of ground water. This is an increasingly critical resource, often occurring at depths where measurements are difficult, boreholes expensive, and models limited in their application. Leakage into aquifers, although unlikely, might go undetected for a long time with currently feasible monitoring methods, and breakthroughs in this area would be important.

As global assessment of storage capacity continues it is clear that a significant quantity of the world’s storage potential is in the offshore environment. Although this domain has been pushed to the limits for oil and gas extraction, there are some issues relating to MMV of offshore CO_2 storage that would benefit from more work. Specifically there is a need to understand and plan for monitoring CO_2 in the marine environment, where complex ocean currents and seasonal variation make MMV more complex. The establishment of the approaches to baseline studies in the marine environment, and then leak detection and finally accounting, will all be necessary. A number of projects around the world have started on this, particularly in the North Sea, a loch in Scotland and in offshore Australia, Korea and Japan.

In both onshore and offshore areas MMV research increasingly needs to understand the whole package of geology between the storage reservoir and the surface. The modelling referred to in earlier sections will be vital to allowing modelling of both the modes of movement through the above reservoir package and how quickly CO_2 can move through it. Such models can then be used to inform the design of MMV strategies, both at the outset of a project and also for any refinements that might be necessary as experience with the particular storage site situation develops over years of injection experience and history matching.

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7.2 Developing Sensing Technologies for CO_2

7.2.1 Seismic:

Time-lapse seismic is an established but rapidly evolving technology for monitoring subsurface changes caused by hydrocarbon production (Johnston, 2013). Compared to other geophysical methods, seismic has by far the highest spatial resolution and thus is the technology of choice for monitoring subsurface changes caused CO_2 injection (Lumley, 2010). Effectiveness of seismic monitoring depends on the ability to detect and interpret (qualitatively and quantitatively) the time-lapse seismic signal on the background of time-lapse noise. As such, the main challenges in the use of time lapse seismic monitoring are related to (1) understanding the time lapse signal; (2) ability to extract useful information (qualitative and quantitative) from it and (3) understanding and minimizing time lapse noise. Additionally, in petroleum industry, time-lapse seismic monitoring is usually accomplished through acquisition of repeated 3D seismic surveys at regular intervals (usually 6 to 12 months). In CCS context, the need for early detection of CO_2 leakage will likely require continuous monitoring over many years, which will need to be optimised with respect to cost and land impact.

Critical research gaps, opportunities and prospective technology fronts include:

1) The quantitative interpretation of 4D seismic data for CO_2 storage, including, 4D inversion (deterministic, stochastic, etc) and 4D full-waveform inversion. The utilisation of the changes in seismic attenuation and seismic anisotropy of the rocks

   Currently the analysis of time-lapse seismic data is mainly based on the comparison of 3D images acquired at different times. This might not be the optimal method as each image contains its own artefacts. More promising are approaches that explicitly uitlise the fact that many parameters of the subsurface remain unchanged, such as deterministic or stochastic constrained 4D inversion (Sirgue et al., 2010; Johnston 2013). Furthermore, the seismic inversion technology requires a number of simplifying assumptions (such an ideally elastic and isotropic earth). Thus it is important to explore other promising seismic attributes, such as the changes in seismic anisotropy and attenuation caused by geomechanical changes in the reservoir (Herwanger et al. 2011). Improving time-lapse signal sensitivity can also be achieved through the development of the new data analysis algorithms such as virtual source method (Bakulin et al. 2007; Dellinger and Yu, 2009), diffraction imaging (Alonaizi et al. 2013), etc.

2) The integration of the reservoir and seismic modelling with 4D seismic into the closed loop prediction/correction workflow.

   The principal objective of seismic monitoring is to verify and improve the predictions of CO_2 migration obtained from dynamic reservoir modelling (flow simulations). To this end, the time-lapse seismic modelling and inversion workflows need to be integrated with reservoir simulations. In such integrated workflow, the results of the seismic time-lapse analysis need to be compared with the seismic response obtained from reservoir simulation, and any observed differences be used to amend the reservoir model. Such close-loop workflows are known as seismic history matching and are still in their infancy (Johnston 2013, Pevzner et al. 2013).

3) Development of continuous (24/7) low-cost continuous seismic monitoring technologies.

   As mentioned earlier, the deployment of time-lapse seismic monitoring of CO_2 storage will likely require continuous monitoring over the time of the project. This emerging technology can be achieved through the deployment of massive buried seismic receiver arrays, both downhole and near-surface. The use of permanent seismic receiver (buried underground or installed on the ocean floor) do not only allow for continuous recording but will also greatly improve the repeatability of the seismic signal (reduce the time-lapse noise) (Bakulin et al. 2012, Berron et al. 2012, Dellinger et al., 2013; Shulakova et al. 2013). Furthermore, while capital expenses may be significant, in the long-term the permanent installations are likely to be cost-effective (Johnston, 2013). Further improvements in both coverage and cost are likely with the use of new developments in the sensing technology (e.g. iDAS) and deployment of fibre optic cables that can detect seismic waves (Daley et al. 2013).

Continuous monitoring will likely benefit from the development of permanently installed seismic sources (Meunier et al., 2001).Examples of permanent land seismic sources include SeisMovie developed by CGG and ACROSS developed by University of Tokyo (Kasahara et al., 2013). However monitoring of industrial size CCS projects will require a large number of permanent sources and hence substantial improvement of the technology as well as cost reduction.

Deployment of permanent receiver arrays opens the possibility of integrating active seismic monitoring with passive monitoring. Passive monitoring may include recording microseismic events caused by geomechanical changes in the subsurface, and the use of external noise sources for monitoring changes in the subsurface (e.g., using multi-channel analysis of surface waves - MASW) (Park et al., 2007; Delinger and Yu, 2009)

Continuous seismic monitoring is an emerging technology and will require development of novel processing algorithms directly benefiting from proper sampling along the 'slow time' axis.

4) Using rock physics data and models to enhance the fundamental understanding of CO_2-injection related changes in the rock properties for the different reservoir types (through both theoretical and laboratory research).

Successful geophysical monitoring of CO_2 sequestration is underpinned by the effect of CO_2 on physical properties of rocks. Thus, understanding of this effect is essential. While theoretical models of the effect of CO_2 saturation on rock properties are known, they need to be calibrated and validated using laboratory measurements (Wang and Nur, 1989; Shi et al., 2007, Lebedev et al., 2013). The standard ultrasonic measurements of elastic properties do not adequately represent the real seismic experiment due to differences in frequency, stress and/or temperature conditions. Thus the current challenge is in the advancement of the methods of measuring elastic properties of rocks at seismic frequencies and at in-situ P-T conditions. Such experiments are particularly important for situations where basic assumptions of standard theoretical relationships are invalid, for instance, for carbonate lithologies, where CO_2 may react chemically with the rock matrix. Furthermore, since laboratory measurements can only be performed on small core samples, theories need to be further developed to upscale the laboratory results to the reservoir scale.

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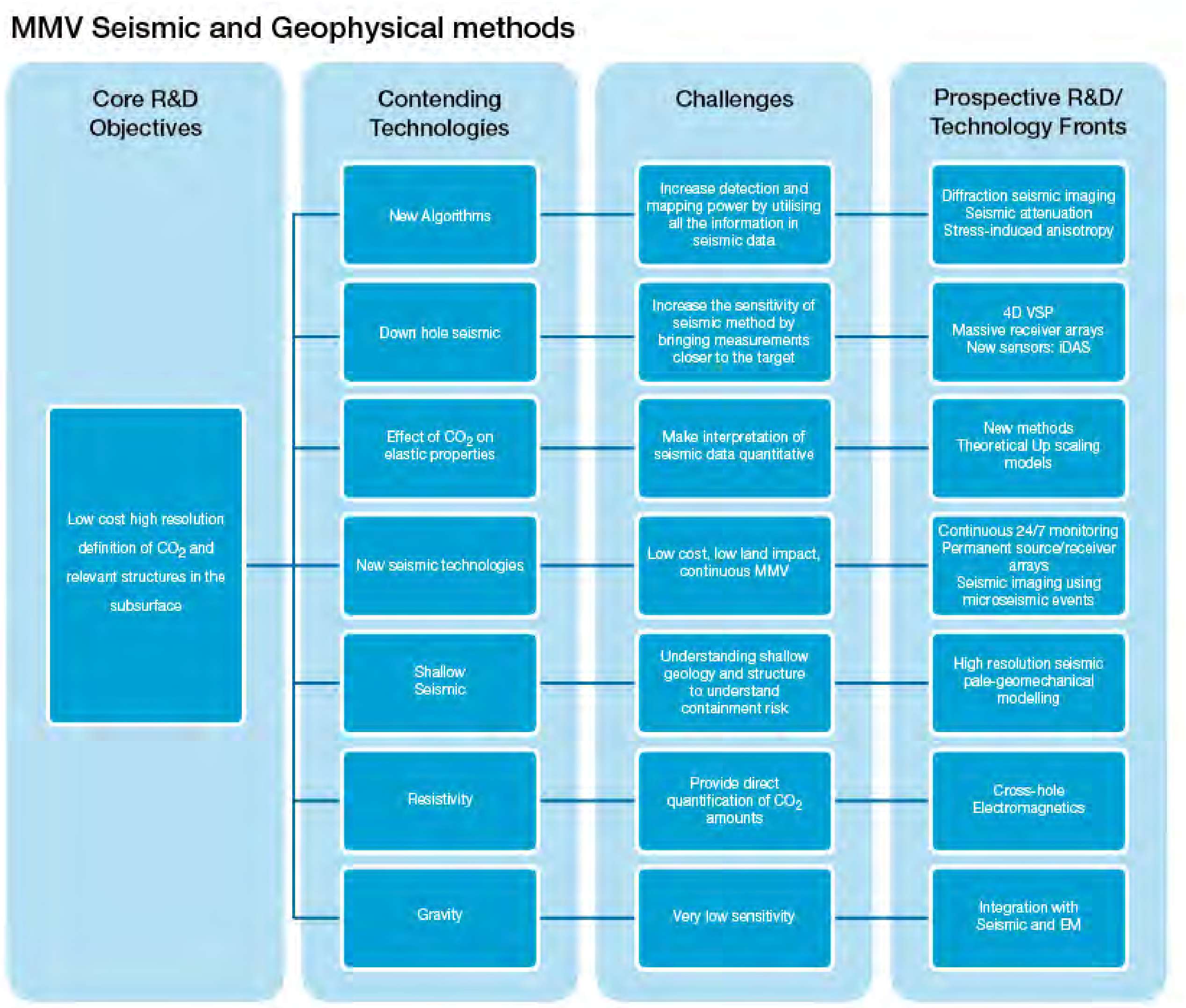

Figure 26 - Prospective Technological Fronts for Seismic and Geophysical MMV methodologies

7.2.2 Electromagnetic Methods

Electromagnetic (EM) methods are used to map electrical resistivity distribution of subsurface rocks. They are used in mineral and petroleum geophysics in borehole mode (resistivity logs), cross hole and surface modes. EM methods are attractive for CO_2 monitoring because CO_2 is electrically resistive compared to subsurface brines. That is, CO_2 injection into saline aquifers is typically accompanied by substantial changes in resistivity distribution. However, surface EM methods can suffer from low spatial resolution. Conversely, resistivity logs provide information only in the immediate vicinity of the wellbore. Thus for many circumstances cross-hole EM methods are the most promising for CO_2 monitoring (Harris and Pethick 2011, Swanepoel et al., 2012 Fabriol et al., 2011, Carcione et al., 2012). Pilot cross-hole EM studies have been conducted in a number of CCS projects: Ketzin, Nagaoka, Frio, Cranfield. One challenge is that wide spatial coverage of cross hole EM methods requires a number of suitably spaced wells. Another challenge of diffusive EM methods is their rapid loss of spatial resolution with distance between transmitter and receiver. However, results from time lapse EM monitoring can be significantly improved by integration with seismic methods, such as joint or cooperative seismic/EM inversion. This integration can be particularly useful as seismic can provide the structure while EM methods can be used to quantify saturation within a detailed seismically determined structural framework (Hoversten et al., 2003).

7.2.3 Gravity

Gravity methods are designed to map density of subsurface rocks, and are used mainly in mineral geophysics. These methods are attractive for CO_2 monitoring because density is linearly related to saturation. However, gravity has very low sensitivity, and thus is likely to be useful for monitoring only in downhole mode. A pilot study on the use of borehole gravity for CO_2 monitoring was conducted at Cranfield and produced promising results (Dodds et al., 2013). Due to the sparse nature of such observations, these methods will require integration with other geophysical methods, such as seismic and EM.

7.2.4 Down Hole Techniques

Wells for injection and pressure relief can provide access to the subsurface in or near CO_2 storage that can be used for pressure and temperature measurement as well as down hole seismic, electrical geophysics and even gravity detection. The value of these techniques is that they are in or close to the CO_2 and can thus give higher resolution and hence insights into early unanticipated CO_2 movement. They also offer the opportunity for integration of data sets (or inversion of data) to provide more detailed insights into the disposition of CO_2 plumes in the subsurface.

In addition to the above there are also refinements to the traditional down hole wire-line techniques developed by the oil and gas industry.

An important technique developed for CO_2 storage has been the down hole capturing of reservoir fluid to follow plume breakthrough from one hole to another for example. A valuable contribution to the field of CO_2 storage has been the development of solid state CO_2 detection methods[16] that can be integrated with other down hole monitoring devices cemented into wells behind the casing for continuous longer term subsurface

[16] E.g. Intelligent Optical Systems, Inc. (IOS) has developed an aqueous CO_2 monitoring system for deployment in water wells over long periods of time and a broad range of depths. Data are relayed in real time via network to a remote laboratory. This sensor has advantages over traditional CO_2 sampling, which requires transport of samples to the lab and increases potential for error and cost.

monitoring. Development here concerns ensuring that they can withstand the subsurface conditions for long periods of time.

7.2.5 Atmospheric Monitoring Techniques

The measurement and interpretation of atmospheric CO_2 concentrations and fluxes is a well-developed area of scientific research, especially for ecosystem studies. The difficulty for leakage detection is the large variations in the CO_2 background, because of the role of surrounding ecosystems in producing and consuming CO_2. Signals are also strongly diluted by atmospheric dispersion. With the current state of the art, atmospheric methods are useful for detecting leakages from small spatial areas, at ranges of a few hundred meters. Tracers are sometimes helpful in these cases but are expensive on industrial scales. A key advance would be a reduction in the cost of high-end measurement systems by a factor of 10.

Critical research gaps, opportunities and prospective technology fronts include:

- Improving and lowering the cost of C-14 detection, a natural tracer which is potentially important for monitoring CO_2. “Fossil” CO_2, resulting from burning fossil fuels, has essentially no C-14, whereas the isotope is naturally present in the atmosphere (it is created by cosmic rays). Currently the detection of C-14 in atmospheric samples is slow and very expensive, and a portable, affordable sensor would be a game-changer.

7.3 Key Research Issues in MMV

Research gaps, opportunities and prospective technology fronts include:

- Development of cheap, panoramic surface assurance techniques.
- Developing data sets to test and calibrate tracer/ CO_2 behaviour in lab and field.
- Better simulations of tracer effects in CO_2, especially density effects due to accumulation of relatively insoluble tracers at the front.
- Methods for monitoring groundwater resources that command general consent.
- Continuing to calibrate M&V methods with controlled releases.
- Determining how much atmospheric monitoring is required for commercial scale projects and which techniques are likely to provide the most consistent results.
- Quantifying the appropriate monitoring of leakage; including uncertainty associated with off-shore monitoring methods and approaches.
- Monitoring at depth, while expensive, may allow remediation before impacts occur in the shallow subsurface.
- Improve understanding of the amount and saturation of CO_2 relative to geological parameters to provide the ability to visualise/recognise the plume.
- Develop methodologies to determine the origin of potential leakage where complex interactions between CO_2, brine and mobilised hydrocarbons takes place (e.g. EOR projects).
- Develop new theoretical and analytical methods of attributing leakage.
- Detection versus quantification of leakage and how accurate it is possible to be; there may also be non-quantitative key indicators as precursors to escape from the storage reservoir.

- Assembling knowledge gained from controlled release sites will be essential to calibrating monitoring tools; these have not yet started to be incorporated into projects.
- Other needs include determining the variability of aquifer response to CO_2 – passage of plumes, pressure fronts, buffering capacity with respect to metals and understanding how a laboratory characterisation of potable aquifers is likely to be impacted by CO_2.
- Improve understanding of the differences between confined and laterally unconfined aquifers, as well as development of methods that can monitor large areas effectively. In the reservoir the plume may not be where predicted (as true reservoir complexity is rarely able to be accurately modelled).
- Improve understanding of physical and chemical transport processes (e.g. if secondary pooling were to occur, seismic could be effective for leakage monitoring). While there is no generic solution, it would be useful to compile information from existing projects to see how each have adjusted monitoring plans to suit site-specific conditions.

Key Observation and Recommendations on MMV Technology to CSLF

MMV continues to be a vital part of the CCS technology development, as it underpins operational decisions as well as the relationship with regulators and the community. Some of the key observations and recommendations are:

1. Establish technologies and methodologies for offshore (sub marine) MMV, as a significant portion of global storage capacity is offshore.
2. Improving onshore and offshore MMV technology and model:
    a. the whole package of geology between the storage reservoir and the surface, to assess the timing and possible modes of potential CO_2 movement and to inform remediation and mitigation strategies,
    b. CO_2 plumes in the subsurface, particularly with respect to the relationship between CO_2 saturation and plume resolution,
    c. MMV in aquifers which cover large areas, where specific plume movement may be more difficult to precisely predict, particularly in horizontally unconfined aquifers.
3. Continuing work on controlled release calibration and natural analogues are important fronts for CO_2 detection and accounting research.
4. Develop an agreed methodology and language for dealing what will be the principal result of most monitoring – a null result.
5. Continue the rapidly evolving trend to continuous, high resolution, low cost, low impact subsurface monitoring.[17]
6. Continue to develop new seismic interpretation and inversion techniques for enhanced CO_2 detection including:

[17] The extent to which this is required on any specific project will depend on the cost, the proponent's needs, the stage and status of their project and the relationship to regulators and local communities.

a. Quantitative interpretation of 4D seismic, including, 4D inversion (deterministic, stochastic, etc) and 4D full-waveform inversion,
b. Using changes in seismic attenuation and seismic anisotropy of the rocks,
c. Integrating reservoir & seismic modelling with 4D seismic into the closed loop prediction/correction workflow and improving signal sensitivity with new data analysis algorithms,
d. Using rock physics data and models to enhance in fundamental understanding of CO_2-injection related changes in the rock properties,
e. The deployment of permanent sources, massive buried receiver arrays,
f. Combining active as well as passive seismic methods and novel processing algorithms.

7. The following detectors either need further development or enhancement to be valuable to storage monitoring:

   a. Improving subsurface (down well) solid state detectors for CO_2 to be robust for long term down hole usage.

   b. A portable low cost C-14 detection system (CO_2 from fossil fuels has no C-14 content).

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MMV Methods within the reservoir

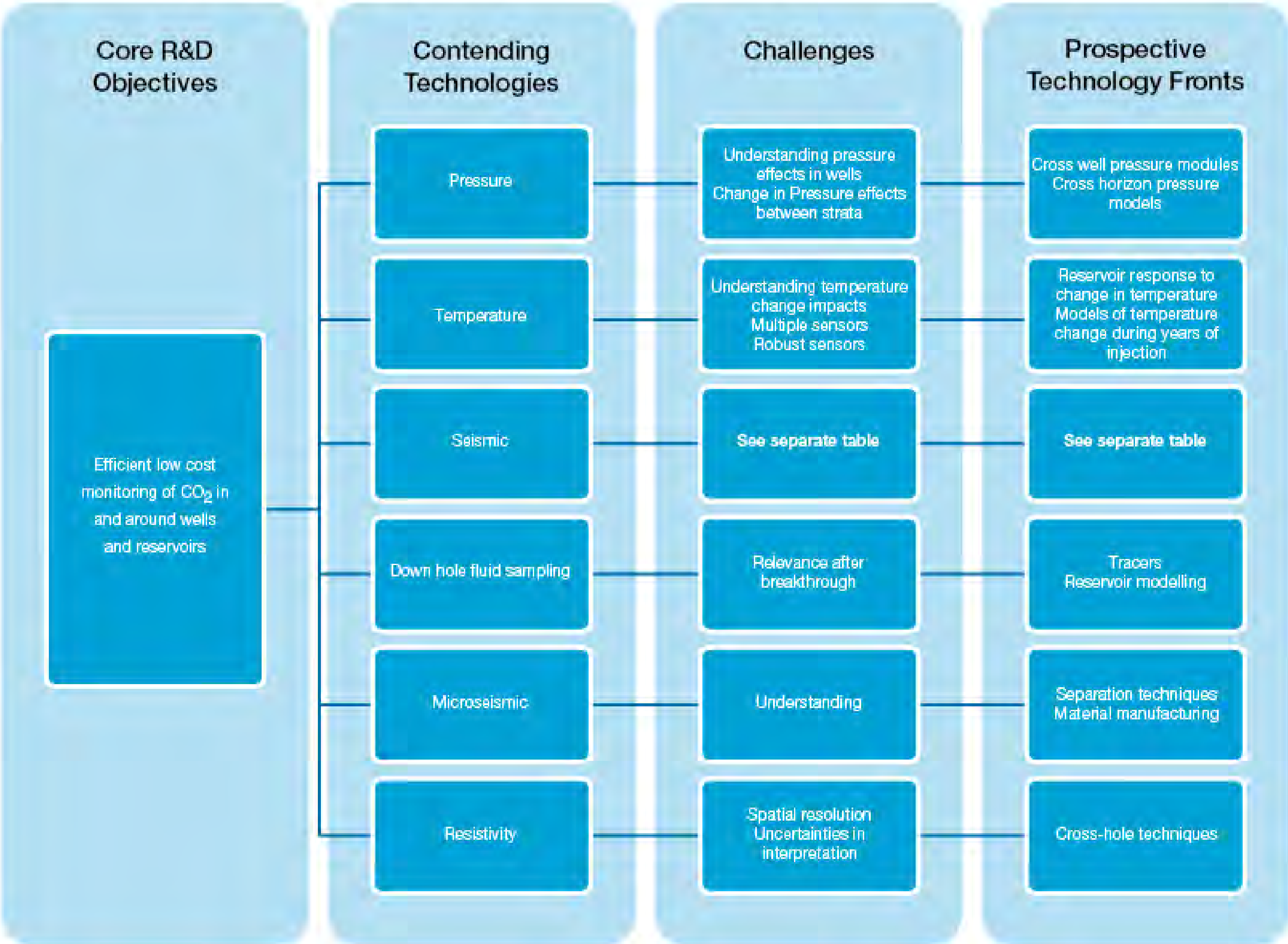

Figure 27 - Prospective technology fronts for MMV within the reservoir

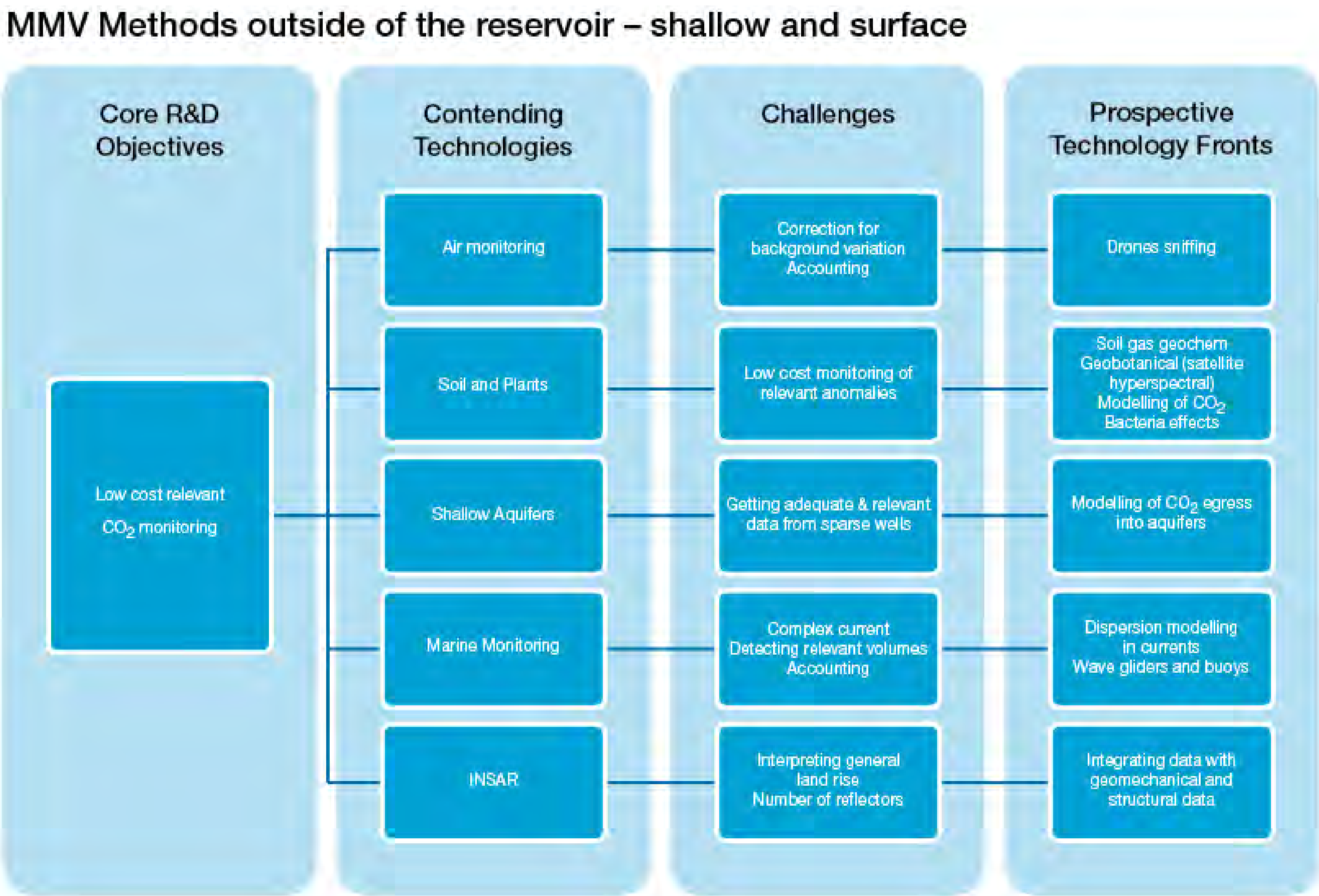

Figure 28 - Prospective technology fronts for MMV outside of the reservoir

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8. The role of Government in Technology Development, Exploration and CCS Industry Dynamics

8.1 Introduction

This chapter looks at some of the ancillary factors related to CCS technology development that require action if the global community is to meet 2050 targets with lowest costs and efficient outcomes. Although CCS technology is readily available and proven, the technology needs to be refined and costs driven down to ensure that CCS can reach its full potential. The research fronts identified in the earlier chapters of this document will continue to evolve as long as the drivers are there for the evolution of the technology.

Over the last ten years there has been a significant growth in CCS technology development; however the lack of global coherence and commitment to climate change action raises some questions about the future trajectory for the technology. Looking at the state of the technology and the associated industry dynamics, there is a need to:

- Deploy and fine tune the current (1st generation) technologies to get progressive learning and improvement by building larger scale pilots and demonstrations and fine tuning the technology from one project to another.
- Drive policies for stronger pull through to commercialisation of the 2nd and 3rd generation technologies to ensure that the benefit of these are realised in the future.
- Start significant regional exploration, discovery and characterisation of large capacity storage sites, factoring in the long lead times.
- Improve international collaboration to get better global outcomes from expenditure.

A variety of studies have shown that the prize associated with CCS deployment is huge in economic terms. However, the cost of climate change mitigation will double in the UK without CCS, adding £30 billion per year by 2050 to the cost of energy for the UK economy (ETI 2013). Furthermore, the cost of delaying CCS deployment will add a further £4 billion for every five year delay. These economic costs highlight the importance of continuing to drive the technology forward; starting the exploration for storage sites is essential.

8.2 Improving the Current Viable (1st Generation) Technologies

For the 1st generation technologies to get the benefit of learning by doing, more projects are required. The technology will only progress to lower unit costs if the cumulative investment or level of deployment progresses. It is thus essential to have incentives and policies to drive industry and/or governments to invest in more plants.

The early scale demonstration projects (see GCCSI 2012) and pilot projects (see Appendices in this document) have demonstrated that CCS technology to capture and store CO_2 is viable. The larger projects are deploying current off the shelf technologies and in the process identifying opportunities to reduce costs for subsequent plants. The aspirations for a planned roll out of CCS, as in many of the recent roadmaps (IEA, CSLF, UK), would see the 1st generation technologies following the incremental pathway seen in Figure 29.

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This learning by doing is a well-established and understood pathway for technology development. It is however in stark contrast to the early phases of the search for breakthrough technologies, also seen in Figure 29.

For both pathways, there must be incentives and/or funding, or the technology progress will slowly falter or stop on its development path. If a significant lull in investment is sustained the technology can in some cases go backwards as industry knowledge is lost. In summary, to drive down the cost of the current batch of market available technologies, governments are advised to create the incentives and funding to drive more large scale CCS projects.

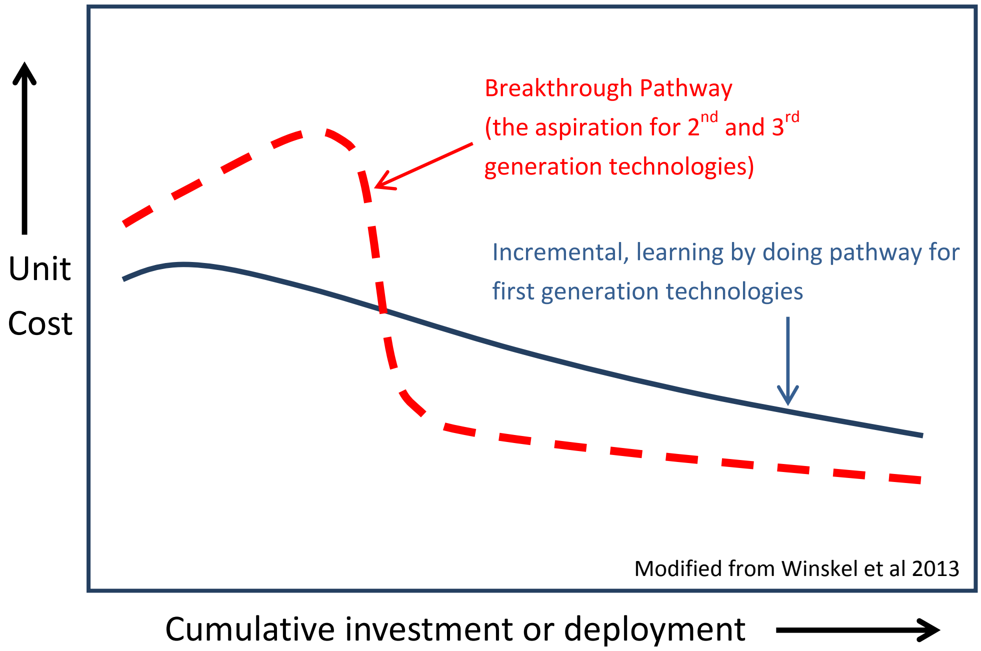

Figure 29 - Learning Curves for Incremental and breakthrough technologies

8.3. Drivers to Lower Costs Through 2nd and 3rd Generation Technologies

For the 2nd and 3rd generation technologies, that have the potential for much lower costs or greater efficiencies, longer lead times are required to bring the technology to the market place. It is also necessary to have the market or policy environment to drive these technologies forward. However, while there is a situation where there is no systematic price on carbon or sense of direction then there will be little incentive for the private sector to invest in the high risk, long term technology development associated with next generation technologies.

In the course of writing this report and talking to organisations that would normally develop and bring energy related technology to markets, it is clear that there is a reluctance to invest whilst there is little or no certainty in the policy environment; i.e. there is currently little or no market pull for the technology. Some companies have spent significant amounts on developing the first generation technologies for the market, only to find that there is virtually no market yet established that requires CCS. The result is that there has been little or no return on their initial investments and there is little appetite for further investment in second generation technologies with long lead times until the policy environment changes.

The technology push for next generation technologies is largely being driven by governments, where the comparatively low cost of the early phase of 2nd and 3rd generation technologies is moderate. Again, without the market incentives or significant investment by governments to pull these next generation technologies through to commercialisation, the technologies will struggle to get to the widespread pilot and demonstration phase and hence into the market. The current absence of strong global policy and market settings will slow down or negate the full and timely realisation of the next generation of low cost capture and storage technology that we will be needed in the 2030s and 2040s.

8.4. Exploration and Technology Development Dynamics

There is a significant body of rapidly evolving exploration technology in the oil and gas industry and this can be easily adapted to exploring for and defining carbon storage capacity. The oil and gas industry is also well acquainted with the exploration risks and timeframes, where exploration investment dynamics are fine-tuned around the rewards, risks and costs associated with exploration.

One of the most pressing problems for global CCS deployment at scale is getting the requisite amount of exploration started, when there is no price on carbon, to justify the exploration risk. Typically large scale carbon storage projects will take some 7-10 years or more from the time of the initial intent to explore, through to the discovery, definition, characterisation and approvals. There is little commercial incentive to start the design and construction of a major capture facility until the storage is well defined. Thus the lead times from initiating exploration through approvals and construction to getting CO_2 into the ground will often be as long as 10-15 years. This has implications for the degree to which CCS can contribute to 2050 targets. Figure 30 below shows the lead time effects of ramping up storage to 100Mtpa in a particular country or state; at a global scale the number will need to be an order of magnitude more than this.

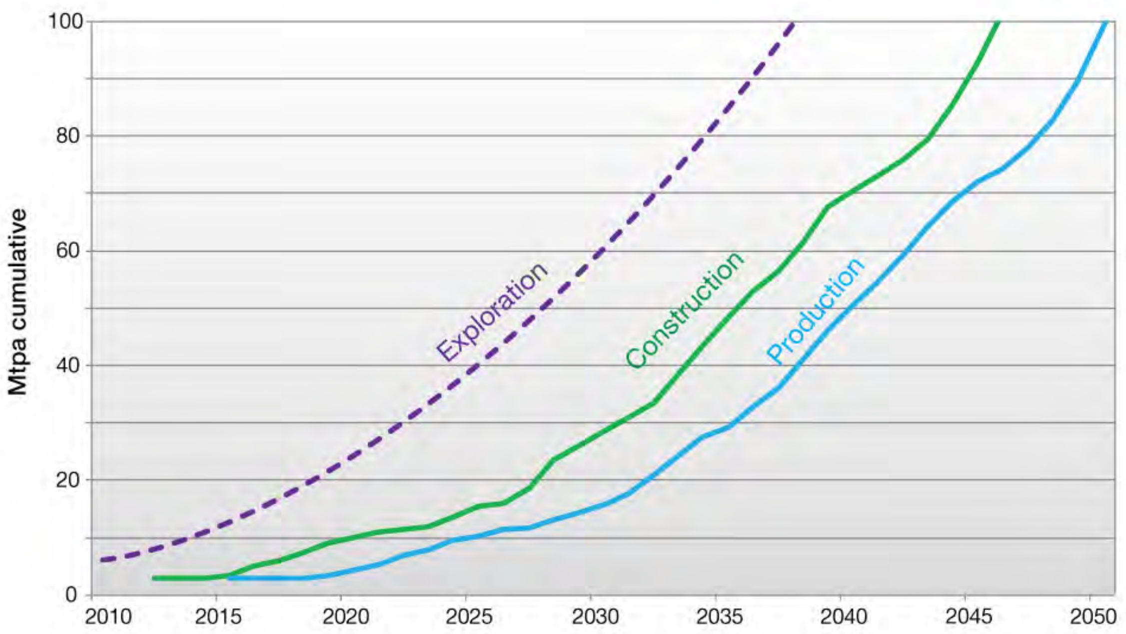

Figure 30 - Schematic diagram of exploration and production timing to reach 100 Mtpa by 2050

This “exploration dynamics” issue is one of the most important outstanding drivers for CCS deployment and it also has indirect links to technology development. The definition and characterisation of a large scale CCS storage site can also cost several hundred million dollars (Chevron 2012). To make a decision to start exploration and discovery for any government or company is a big step. To get CCS deployment on a large scale requires industry to be incentivised and to have a clear idea of the forward trajectory for profitability. It is required at a scale that can be more easily driven by the private sector as many governments will not be able to summon the required skills, risk appetite and funds to underwrite the level of activity that is required. They would be better to create the market forces that will incentivise the private sector.

In a world where the incentives for carbon storage exploration are lacking and the market pull for technologies is weak or non-existent, the potential delays to technology development are significant. If exploration is slow, large scale deployment will be slow, which will in turn slow learning by doing for current technologies. Conversely, if governments are prepared to incentivise the market to act, with carbon prices, taxes or mandates, the result will be synergistic for both exploration and discovery of storage capacity and also for technology development, resulting in lower costs, which will in turn drive the market dynamics more strongly (see Figure 31).

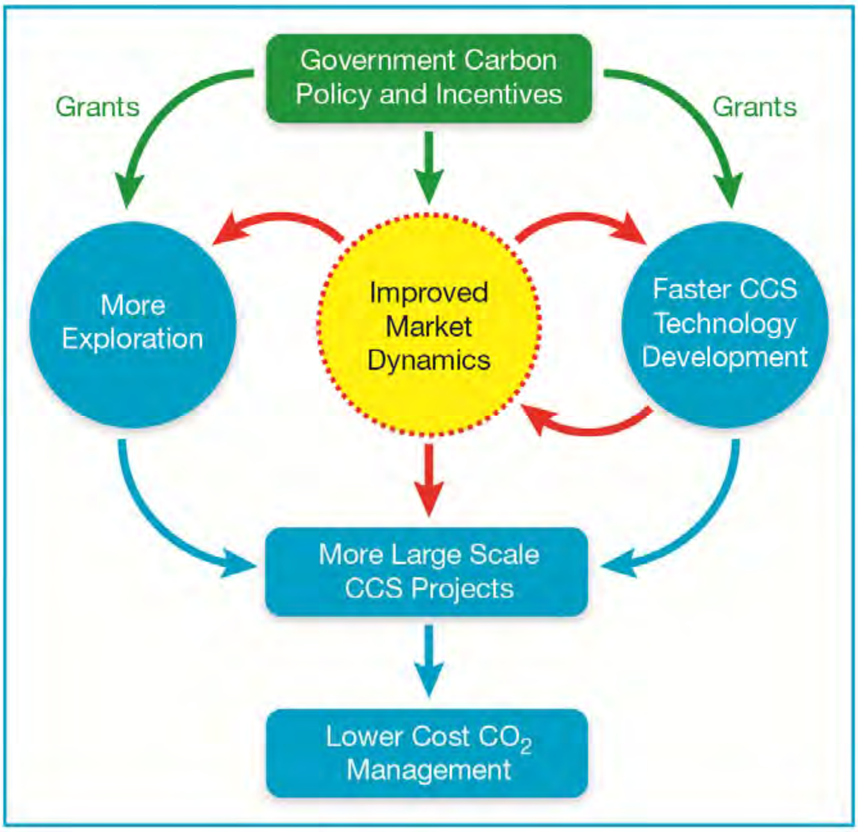

Figure 31 - System dynamics diagram showing the role of market dynamics driving exploration and technology development for CCS

In summary, governments around the world have a technology at their fingertips that can be deployed to manage carbon emissions, but the rate of take up needs to be incentivised. In this context it is useful to look at the role played by governments in the development of the nuclear industry in the US, the development and deployment of SO_2 scrubbing and also the global LNG industry. In all these cases the role of government, with long term vision and technology incentives, brought new technology into play, in a way that could not be achieved by the private sector in anything like the required timeframes (Rai, Victor and Thurber 2010). These authors concluded that “in these industries, governments played a decisive role in the development of the technologies… and the diffusion of these technologies beyond the early demonstration and niche projects hinged on the credibility of incentives for industry to invest in commercial scale projects."

8.5. International Collaboration

The logic behind enhanced international collaboration on CCS technology is compelling. There are consistent calls for global collaboration and some jurisdictions are actively encouraging it. de Conick et al (2009), set out the key justification for this and the IEA Technology Road Map (2013) and CSLF Technology Roadmap (2013) both call for more collaboration. Some of the key reasons underpinning international collaboration are that it can:

a. Provide a strong basis for accelerated learning,
b. Share the cost of learning, particularly where large or unique demonstration or operation facilities are available for technology development and learning,
c. Drive globalisation of the learning, including to developing countries,
d. Expand community and social awareness by leveraging knowledge and demonstration internationally,
e. Assist in underpinning consistency in regulation and safety/environmental outcomes.

Some jurisdictions are actively encouraging their researchers to collaborate internationally; not only with travel funds but also by providing funds for a financial stake in international consortia working on particular trials or demonstrations. Many senior researchers have a natural network of international researchers by virtue of the field in which they operate. Collaboration can be a natural extension of this if the funds are available.

Collaboration is easier on the storage projects, but is more difficult for capture technologies where Intellectual Property (IP) issues can create difficulties, especially once the technology has reached a certain point on its development path and the IP has some incipient value. Collaboration on 2nd and 3rd generation technologies that are earlier in the development phase is easier.

Governments are encouraged to stimulate international collaboration by providing funds for:

a. Researchers to travel and share their learning, insights and aspirations,
b. Joining smaller scale projects, involving exchange of researchers and possibly complimentary work programs,
c. Contributing to, or buying a stake in important consortia of international parties around larger projects where particular teams can bring a unique or complimentary set of skills to a research or demonstration project,
d. Encouraging industry, government and researchers to collaborate around key projects, where the collaboration brings a range of commercial and technical perspectives to the research and technology development paths at hand.

International collaboration is considered to be a valuable approach to furthering the technology of CCS.

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8.6. References

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Abbreviations and Acronyms

2DS	IEA ETP 2012 2°C scenario
Ar	Argon
ASU	Air Separation Unit
BAHX	Braised Aluminium Heat Exchanger
BTU	British thermal unit
CAPEX	Capital expenditure
CCS	Carbon Capture and Storage
CFB	Circulating fluidized bed
CH_4	Methane
CLC	Chemical Looping Combustion
CLR	Chemical Looping Reforming
CPU	CO_2 Processing Unit
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO2CRC	Cooperative Research Centre for Greenhouse Gas Technologies
COS	Carbonyl Sulphide
CSLF	Carbon Sequestration Leadership Forum
DCC	Direct contact cooler
DOE	Department of Energy (USA)
EM	Electromagnetic
EOR	Enhanced Oil Recovery
ESP	Electrostatic precipitator
ETIS	Energy Technology Innovation Scheme (Australia)
FF	Fabric Filter
FGC	Flue Gas Condenser
FGD	Flue Gas Desulphurisation
GPU	Gas Permeability Unit
GT	Gas turbine
H_2S	Hydrogen Sulphide
HCl	Hydrogen Chloride
Hg	Mercury
HHV	Higher Heating Value
HI	Heat Integration
HP	High Pressure
HRSG	Heat Recovery Steam Generator
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas Research & Development Program
InSAR	Inferometric synthetic aperture radar
IP	Intermediate Pressure
IPCC	Intergovernmental Panel on Climate Change
ITM	Ion transport membrane
JT	Joule-Thompson
kPa	Kilopascal
LCA	Life cycle assessment
LCOE	Levelised cost of electricity
LNG	Liquefied Natural Gas
LP	Low Pressure

LPG	Liquefied Petroleum Gas
LOT	Leak off test
LOX	Liquid oxygen pumps
MAC	Main Air Compressor
MAT	Migration associated trapping
MEA	Monoethanolamine
MMV	Measurement, Monitoring and Verification
Mtpa	Million tonnes per annum
MTR	Membrane Technology & Research
MW	Megawatt
MWe	Megawatt electrical
MWth	Megawatt thermal
N_2	Nitrogen
NaOH	Sodium Hydroxide
NETL	National Energy Technology Laboratory (USA)
NG	Natural Gas
NOx	Nitrogen oxides
OEMs	Original equipment manufacturers
OFT	Oxy-Fuelled Turbine
OPEX	Operating expenses
OTM	Oxygen transport membrane
OxyCT	Oxyfuel Combustion Technology
PC	Pulverised coal
PF	Pulverised fuel
PIMs	Polymers of intrinsic microporosity
PLOX	Portable liquid oxygen pumps
PRMS	Petroleum Resource Management System
PSA	Pressure Swing Adsorption
RA	Risk assessment
RRRR&E	Reservoir, Rock Physics, Resolution, Repeatability & Economics
SER	Sorption Enhanced Reforming
SOA	State of Art
SOFC	Solid oxide fuel cell
SOx	Sulphur oxides
TIT	Turbine inlet temperature
TPD	Tonnes per day
TRM	Technology Road Map
TSA	Temperature Swing Adsorption
USC	Ultra super critical
VSA	Vacuum Swing Adsorption
XLOT	Extended leak off test

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APPENDIX A: Table 1 – Pilot Plant Facilities Demonstrating CCS

Name	Name of Facility	Location	Company	Pilot MWe	Pilot t CO_2/d	Source	Key Research	Key Innovation	Key Learnings	Year of First Test
Solvents										
Akermin	National Carbon Capture Center, Plant Gaston	Alabama, USA	Akermin	0.01		Coal	Enzyme-catalyzed Potassium Carbonate	Biocatalyst delivery system		2012
Boundary Dam Pilot (1)	Boundary Dam Power Station		SaskPower		4		MEA, RS-2			2000
Castor (2)	Dong Energy	Esbjerg, Denmark	European Commission Funded, IFP-run	3	24	Coal PCC	Piperazine	MEA, proprietary solvents such as CASTOR-2	Solvent degradation	2008
CATO-2 CO_2 Catcher (3)	CATO-2 CO_2 Catcher	Rotterdam, Netherlands		0.4		Coal PCC	Amines			2008
CO_2 Capture Plant Project / CSIRO (4)	Tarong	Tarong, Australia	CSIRO	0.1	2	Black Coal PCC	Advanced amines / piperazine	High rate of absorption		2008
CO_2 Capture Plant Project - University of Texas(5)	SRO	University of Texas, USA	U. of Texas	0.1 to 0.5		Prepared flue gas	Advanced amines / piperazine	High rate of absorption		2010
CO_2 Capture Plant Project – Southern Company/US DOE (6)	National Carbon Test Center, Plant Gaston	National Carbon Test Center, Alabama, USA	Southern Company / USDOE	0.5	10	Coal PCC	Multiple Technologies – solvents, sorbents, membranes	Technology dependent		2010
CO2CRC (7)	Hazelwood Power Station	Latrobe Valley, Australia	CO2CRC	2		Brown Coal PCC	Amino acids, potassium carbonate	Lower energy Impurity tolerance		2008
CO2CRC UNO MK 3 (8)	Hazelwood Power Station	Latrobe Valley, Australia	CO2CRC	0.05	1	Brown Coal PCC	Precipitating Process	Lower energy Impurity tolerance		2012

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Name	Name of Facility	Location	Company	Pilot MWe	Pilot t CO_2/d	Source	Key Research	Key Innovation	Key Learnings	Year of First Test
CSIRO (9)	Loy Yang Power Station	Latrobe Valley, Australia	CSIRO		1	Brown Coal PCC	Conventional amine			2008
CSIRO (10)	Delta Electricity Munmorah Power Station	Munmorah, Australia	CSIRO		3	Black Coal PCC	Ammonia	Lower energy		2009
CSIRO (11)	Huaneng Beijing Cogeneration Plant	Beijing, China	CSIRO		3	Black Coal PCC	Conventional amine			2008
Dow Chemicals (12)	South Charleston	West Virginia, USA	Dow	0.5		Coal PCC	Amines			2009
Elcogas (13)	Elcogas Puertollano	Puertollano, Spain	Elcogas	5		Coal and Petcoke IGCC	Physical and Chemical Solvents			2010
ENEL (14)	Brindisi Power Plant	Cortemaggiore, Italy	ENEL	1.5		Coal PCC	Amines			2009
ERTF (15)	ERTF				1		MEA, RS-2			
First Energy (16)	Burger Plant	Shadyside, OH, USA	First Energy	1		Coal PCC	Ammonia	Lower energy		2008
Hitachi (17)	Tokyo Electric Power Station	Yokosuka, Japan	Hitachi	<1			MEA and advanced amines			1990s
ITC (18)	International Test Centre for CO_2 Capture	University of Regina, Canada			1	Steam boiler	MEA and advanced solvents (including Econamine)			2000
KoSol Process for CO_2 Capture (KPCC)	Boryeong Thermal Power Plant	Republic of Korea	KEPCO	0.1	2	Coal PCC	Advanced Amines	Low energy demand Less corrosion & degradation	Low energy demand	2010
KoSol Process for CO_2 Capture (KPCC)	Boryeong Thermal Power Plant	Republic of Korea	KEPCO	10	200	Coal PCC	Advanced Amines	Low energy demand Less corrosion & degradation		2013

Name	Name of Facility	Location	Company	Pilot MWe	Pilot t CO_2/d	Source	Key Research	Key Innovation	Key Learnings	Year of First Test
MHI (19)	MHI Hiroshima R&D	Hiroshima, Japan	MHI		1	Coal PCC	Impurities testing on MHI's solvents such as KS1			2004
MHI (19)	Matsushima Thermal Power Station	Nagasaki, Japan	MHI		0.8	Coal PCC	MHI's solvents and process			2006
MHI (19)	Nanko Natural Gas	Osaka, Japan	MHI	0.1			MHI's solvents and process			1991
NETL (6)	National Carbon Test Center, Plant Gaston	National Carbon Test Center, Alabama, USA	NETL, Linde, BASF	1		Coal PCC	Advanced Amines	Lower energy demand, equipment integration		Beyond 2013
Neumann Systems Group	Colorado Springs Utilities Drake #7	Colorado Springs, CO, USA	Neumann Systems Group	0.5		Coal PCC	Absorber design/piperazine	Lower energy demand, lower footprint, lower cost		2014
Nuon (20)	Nuon Buggenum	Buggenum, Netherlands	Nuon			Coal and Biomass IGCC	Physical and Chemical solvents			2010
PGE (21)	Bechatow Power Station	Bechatow, Poland	PGE	20		Coal PCC	Amine			2014
Siemens (22)	E. ON's Power Station	Staudinger, Germany	Siemens	<1		Coal PCC	Amino acid salts	Low environmental impact Low energy demand		2009
Southern Company Services	Plant Barry	Alabama, USA	Southern Company Services, MHI	25		Coal PCC	Amine, Heat integration	Lower energy demand		2011
Technology Centre Mongstad, TCM (23)	Mongstad Cogen Pilot	Mongstad, Norway	Statoil	15		NG PCC	Chilled ammonia, amines			2012

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Name	Name of Facility	Location	Company	Pilot MWe	Pilot t CO_2/d	Source	Key Research	Key Innovation	Key Learnings	Year of First Test
University of Kentucky Research Foundation	E.W. Brown Generating Station	Kentucky, USA	University of Kentucky, Hitachi	0.7	15	Coal PCC	Two-stage stripping, integrated cooling tower, Hitachi amine solvent	Lower energy demand		2014
Membranes										
Air Liquide (24)			Air Liquide	0.1	2		MEDAL hollow fibre membrane units	Sub ambient membrane operation		2011
CO2CRC (7)	Hazelwood Power Station	Latrobe Valley, Australia	CO2CRC							
Hybrid Membrane Absorption Process (25)	Midwest Generation Joliet Power Station	Illinois	GTI, Porogen, Aker	0.025	0.5		Porous PEEK membranes	Membrane contactors with carbonate and MEA solvents		2013
Media and Process Technology, Inc.	National Carbon Capture Center	Alabama, USA, Plant Gaston	Media and Process Technology, Inc.		50 lb/hr	IGCC	Membrane	Integrated WGS-membrane reactor		
MTR Polaris (26)	APS Cholla	Arizona, USA	MTR Incorporated	0.05	1	Brown Coal PCC	8” Polaris Modules	Spiral wound design with air sweep, novel polymers	Membrane retains performance in presence of SOx, NOx	2010
MTR Polaris (26)	National Carbon Capture Centre (NCCC)	Wilsonville, Alabama	MTR Incorporated	0.05	1	Coal PCC	9” Polaris Modules	Spiral wound design with air sweep, novel polymers		2011

Name	Name of Facility	Location	Company	Pilot MWe	Pilot t CO_2/d	Source	Key Research	Key Innovation	Key Learnings	Year of First Test
MTR Polaris (26)	National Carbon Capture Centre (NCCC)	Wilsonville, Alabama	MTR Incorporated	1	20	Coal PCC	Full scale Polaris Modules	Spiral wound and Plate and Frame Design		2013
MTR Proteus (26)	National Carbon Capture Centre (NCCC)	Wilsonville, Alabama	MTR Incorporated	500 lb/hrv		IGCC	Proteus Membrane Module	Spiral wound design, lower energy demand		2012 (smaller membranes tested in 2010 and 2011)
Nanoglowa (27)	Sines	Portugal		?	30 m3/hr	Coal PCC	Fixed site carrier membranes			
Nanoglowa (27)	Rutenberg	Israel		?	?	Coal PCC	Parker PPO hollow fibres			
Nanoglowa (27)	Scholven	Germany		?	?	Coal PCC				
Adsorbents										
ADA-ES	Plant Miller	Alabama, USA	ADA-ES	1	20	Coal-fired power plant slipstream	Solid sorbent, reactor design	Novel sorbent, lower energy demand		2014
CO2CRC (7)	Hazelwood Power Station	Latrobe Valley, Australia	CO2CRC	0.15	3	Coal fired power plant slip stream	3 BED VSA, Feed 1.3 atm, 75% CO_2 purity, 70% recovery, wet flue gas handled	Multi-layered beds removed need for pretreatment and drying	Effect of HCl on feed blower, need for proper front end cleaning, need low pressure drop materials	2010

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Name	Name of Facility	Location	Company	Pilot MWe	Pilot t CO_2/d	Source	Key Research	Key Innovation	Key Learnings	Year of First Test
Chubu Electric Power Co (28)	Not disclosed	Japan	Takamura	Not disclosed	7.44 Nm3/h.	boiler exhaust gas	4-bed, 8-step PSA; Feed: 13% CO_2 CO_2 purity 59% CO_2 Recovery 91.6%	Evaluated NaA/NaX combination in 2 bed VSA; 1.2atm feed, 10kPa vacuum		2001
ECUST Plant (29)	Not disclosed	China	East China University of Science and Technology	?	50 Nm3/h	Coal fired power plant slip stream	3 bed VPSA; 80% CO_2 purity with 80% recovery. Energy of 1.7-2 MJ/kg CO_2, vacuum level 7kPa	Have used a variety of cycles with 13X APG and 5A adsorbents from UOP	Front end water removal needed	2012
0.5 MW Dry Regenerable Sorbent Process (32, 33, 34)	KOSPO, Hadong Thermal Power Station	Hadong, Republic of Korea	KEPCO (solid sorbent) KIER, (process)	0.5	10	Coal PCC	KEP-CO2P (K_2CO_3 based-solid sorbents) and Dual fluidised-bed process	Solid sorbent CO_2 Capture Process	Much less environmental impact (no volatile, less waste water & corrosion) and high thermal stability of sorbent	2010
10 MW Dry Regenerable Sorbent Process (35)	KOSPO, Hadong Thermal Power Station	Hadong, Republic of Korea	KEPCO (solid sorbent) KIER, (process)	10	200	Coal PCC	KEP-CO2P (K_2CO_3 based-solid sorbents) and Dual fluidised-bed process	Solid sorbent CO_2 Capture Process		2013
NUS	Not disclosed	Singapore	National University of Singapore	0.15	3 TPD	Coal fired power plant slip stream	Not yet disclosed	Commissioning underway	Commissioning underway	2013

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Name	Name of Facility	Location	Company	Pilot MWe	Pilot t CO_2/d	Source	Key Research	Key Innovation	Key Learnings	Year of First Test
TDA/ADA (30)	Not disclosed	USA	TDA Research, Inc., ADA Environmental Solutions	1kW slipstream	5 ACFM	Coal fired power plant slip stream	Circulating fluidized bed flow contactor, 90% CO_2 recovery, low purity.	Uses low grade steam at 1.08atm and 110°C to regenerate – pilot used electrical heating though	Amine tethered materials best for this application due to low regeneration energy	2011
TEPCO (31)	Yokosuka Thermal Power Station	Japan	Ishibashi	Not disclosed	1000 Nm3/h	Coal fired power plant slip stream	2000 hours; PTSA; CO_2 purity 99%, 90% recovery; power 560kWh/t CO_2	CaX zeolite used, 3 stages: dehumidification stage, PTSA stage, PSA stage	Process performance extremely sensitive to CO_2 level in the feed; alumina needed to remove SOx	1996

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APPENDIX B:

Table 1: CO_2 Storage Projects

Project Name	Project Owner	Location	Project Size	Storage Reservoir	Current Status	Year of First Injection	CO_2 Source	Total Injection (Tonnes)	Injection Rate	Injection Depth
BSCSP Basalt	Montana State	Pasco, Walla Walla County, Washington, USA	<100,000t	Basalt	Planned	2013	food grade	907	To be determined	2700-2900ft
Callide Oxyfuel Project	CS Energy	Gladstone, Queensland, Australia	<100,000t	SA or DOG	Planned	Not yet known	Callide A Oxyfuel Plant	60000	Approx 10,000 tpa	To be determined
Carbfix	Reykjavik Energy	Reykjavik, Iceland	<100,000t	Basalt	Operational	2012	Magmatic	2000 (through July 2012)	2200 tpa	400-800m
CarbonNet	VIC Gov department of Primary Industries	Gippsland Basin, Victoria, Australia	<100,000t	SA	Planned	2020	Coal Fired PP	To be determined	To be determined	To be determined
CO2CRC Otway (Stage I)	CO2CRC	Victoria	<100,000t	DOG	Injection Complete	2007	Geologic	65000	150 tpd	2000m

Project Name	Project Owner	Location	Project Size	Storage Reservoir	Current Status	Year of First Injection	CO_2 Source	Total Injection (Tonnes)	Injection Rate	Injection Depth
CO2CRC Otway Project (Stage 2A,B)	CO2CRC	Victoria, Australia	<100,000t	SA	Injection Complete	2010	Geologic	150	600 tonnes (150 CO_2 & 450 formation water) injected over 5 days4	1400m
Frio, Texas	LBNL/Utexas	Houston, TX, USA	<100,000t	SA	Injection complete	2004	Purchased (Praxair)	1600	160 tpd	1500m
K12B (CO_2 Injection at K12B)	GDF/CATO	150km NW Amsterdam, Offshore Netherlands	<100,000t	DOG	Operational	2004	Gas processing	70000	45 tpd	3800m
Ketzin	German Research Centre for Geosciences (GFZ)	Berlin, Germany	<100,000t	SA	Injection Complete	2008	Food Grade (Linde AG)	53000	45 tpd	650m
Masdar/ADCO Pilot project	Masdar, ADCO	Abu Dhabi, United Arab Emirates	<100,000t	EOR	Injection Complete	2009	Commercial	22000	60 tpd	2895m
MGSC loudon Field EOR Phase II	MGSC	Fayette County, Illinois, USA	<100,000t	EOR	Injection Complete	2007	Commercial	39	5-10 tpd	457m

Project Name	Project Owner	Location	Project Size	Storage Reservoir	Current Status	Year of First Injection	CO_2 Source	Total Injection (Tonnes)	Injection Rate	Injection Depth
MGSC Mumford Hills EOR Phase II	MGSC	Indiana, USA	<100,000t	EOR	Injection Complete	2009	Commercial	6260	20-35 tpd	585m
MGSC Sugar Creek EOR Phase II	MGSC	Kentucky, USA	<100,000t	EOR	Injection Complete	2009	Commercial	6623	18-27 tpd	600m
MRCSP Appalachian Basin (Burger) Phase II	MRCSP	Shadyside, Ohio, USA	<100,000t	SA	Injection Complete	2008	Commercial Source	Less than 50 tonnes	8-49 tpd	6500ft
MRCSP Cincinnati Arch (East Bend) Phase II	MRCSP	Rabbit Hash, KY, USA	<100,000t	SA	Injection Complete	2009	Commercial Source	1000	Varied. Max reached 1200 tpd	3200ft
MRCSP Michigan Basin Phase II	MRCSP	Otsego, MI, USA	<100,000t	SA	Injection Complete	2008	Gas Processing	60000 (10,000 and 50,000)	400-600 tpd	3200ft
Mountaineer	American Electric Power service corporation	New haven, WV	<100,000t	SA	Injection Complete	2009	Coal Fired PP	37403.3	50-100 tpd	2469m

Project Name	Project Owner	Location	Project Size	Storage Reservoir	Current Status	Year of First Injection	CO_2 Source	Total Injection (Tonnes)	Injection Rate	Injection Depth
Nagaoka Pilot CO_2 Storage Project	RITE	Nagaoka, Japan	<100,000t	SA	Injection Complete	2003	Food Grade	10400	20-40 tpd	1100m
PCOR Williston Basin -Phase 11 (N E Mcgregor Field)	PCOR	Williams County, North Dakota, USA	<100,000t	EOR (carbonates)	Injection Complete	2009	Commercial	400	313 tpd	2450m
PennWest Energy EOR Project	Pennwest	Alberta, Canada	<100,000t	EOR	Injection Complete	2005	Gas Processing	56749	50 tpd	1650m
SECARB Stacked Storage Project Cranfield Phase II	SECARB	Natchez, MS, USA	<100,000t	DOG	Injection Complete	2008	Geologic	50000	2750 tpd	10300ft
SECARB-Mississippi Saline Reservoir Test Phase II	SECARB	Escatawpa, Jackson County, Missisipi, USA	<100,000t	SA	Injection Complete	2008	Geologic	3020	100 tpd	2895m
South West Hub (Collie South West Hub) (pilot)	WA Department of Mines and Petroleum	South of Perth, Western Australia	<100,000t	SA	Planned	2015	Industrial source from Collie area	To be determined initially small scale	Not yet known	2000-3000m

Project Name	Project Owner	Location	Project Size	Storage Reservoir	Current Status	Year of First Injection	CO_2 Source	Total Injection (Tonnes)	Injection Rate	Injection Depth
South-central Kansas CO_2 Project - Wellington Field	Kansas Geological Survey	Sumner County, Kansas, USA	<100,000t	SA	Operational	2011	Abenogoa Bioenergy Plant	70000	To be determined	>5000 ft
Surat Basin CCS Project (Previously Wandoan) (Pilot)	Xstrata	Approx 300km NW of Brisbane Queensland, Australia	<100,000t	SA	Planned	Not yet known	Not yet identified	To be determined	To be determined	To be determined
Tomakomai CCS Demonstration Project	Japan CCS Co. Ltd.	Tomakomai, Hokkaido, Japan	<100,000t	SA	Planned	2015	Gas Processing	To be determined	To be determined	2400-3000m, and 1100-1200m
Total Lacq	Total	Pau, France	<100,000t	DOG	Operational	2010	Oxy boiler	43000	92 tpd	4500m
West Pearl Queen	Sandia Nat Labs	Hobbs, NM, USA	<100,000t	DOG	Injection Complete	2002	Commercial	2090 (over 2 mths)	70 tpd	1372m
Western Kentucky	KGS	Hancock County, KY, USA	<100,000t	SA	Injection Complete	2009	Commercial food grade	626		1115m & 1535m

Project Name	Project Owner	Location	Project Size	Storage Reservoir	Current Status	Year of First Injection	CO_2 Source	Total Injection (Tonnes)	Injection Rate	Injection Depth
Aquistore project	SASKPOWER	Southeastern Saskatchewan, Canada	>100000t	SA	Planned	2013	(Boundary dam) Coal PP		2000tpd	
Allison Unit	US DoE	San Juan County, NM, USA	>100000t	ECBM	Injection Complete	1995	Commercial	300000	100000-150000 t/yr	2865m
MGSC Decatur	MGSC (DOE/NETL)	Decatur, IL, USA	>100000t	SA	Operational	2011	Ethanol	999000	900 tpd	2100m
PCOR Zama	PCOR/EERC	Zama City, Alberta, Canada	>100000t	SA	Operational	2006	Acid Gas Injection	281160	55 tpd	5000ft
SECARB Anthropogenic - Citronelle	SECARB	Citronelle, AL, USA	>100000t	SA	Operational	Planned:2012	Plant Barry Coal PP	300000	100000-150000 t/yr	2865m

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TECHNICAL GROUP

Final Report by the CSLF Task Force on Technical Challenges in the Conversion of CO_2-EOR Projects to CO_2 Storage Projects

Background

At the September 2011 CSLF Ministerial Meeting in Beijing, a Task Force was formed to investigate Technical Challenges in the Conversion of CO_2-EOR Projects to CO_2 Storage Projects. The task force mandate was to review, compile and report on technical challenges that may constitute a barrier to the broad use of CO_2 for EOR and to the conversion of CO_2-EOR operations to CCS operations. This document is the Final Report from the Task Force and concludes the Task Force's activities.

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Carbon Sequestration Leadership Forum
www.cslforum.org

Technical Challenges in the Conversion of CO_2-EOR Projects to CO_2 Storage Projects

Report Prepared for the CSLF Technical Group
by the CSLF Task Force on
Technical Challenges in the Transition from CO_2-EOR to CCS

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September 2013

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EXECUTIVE SUMMARY

The 40 years of experience and the current number of CO_2-EOR operations currently active in the world indicate that there is sufficient operational and regulatory experience for this technology to be considered as being mature, with an associated storage rate of 90-95 % of the purchased CO_2. Application of CO_2-EOR for CO_2 storage has a number of advantages: 1) it enables CCS technology improvement and cost reduction; 2) it improves the business case for CCS demonstration and early movers; 3) it supports the development of CO_2 transportation networks; 4) it may provide significant CO_2 storage capacity in the short-to-medium-term, particularly if residual oil zones (ROZ) are produced; 5) it enables knowledge transfer, bridging the experience gap and building and sustaining a skilled CCS workforce; and 6) it helps gaining public and policy-makers acceptance.

The current number of CO_2-EOR operations in the world is negligible compared with the number of oil pools in the world, and the main reason CO_2-EOR is not applied on larger scale is the unavailability of high-purity CO_2 in the amounts and at the cost needed for this technology to be deployed on a large scale. The potential for CO_2 storage and incremental oil recovery through CO_2-EOR is significant, particularly if residual oil zones (ROZ) and hybrid CO_2-EOR/CCS operations are considered. Besides the main impediment in the adoption and deployment of this technology of the unavailability of CO_2 at economic prices, the absence of infrastructure to both capture the CO_2 and transport it from CO_2 sources to oil fields suitable for CO_2-EOR is also a key reason for the lack of large scale deployment of CO_2-EOR.

There are a number of commonalities between CO_2-EOR and pure CO_2 storage operations, both at the operational and regulatory levels, which create a good basis for transitioning from CO_2-EOR to CO_2 storage in oil fields. However, currently there are a significant number of differences between the two types of operations that can be grouped in seven broad categories: 1) operational, including CO_2 purity and quality; 2) objectives and economics; 3) supply and demand; 4) legal and regulatory; 5) assurance of well integrity; 6) long term CO_2 monitoring requirements; and 7) industry's experience.

The analysis presented in this report indicates that there are no specific technological barriers or challenges *per se* in transitioning and converting a pure CO_2-EOR operation into a CO_2 storage operation. The main differences between the two types of operations stem from legal, regulatory and economic differences between the two. While the legal and regulatory framework for CO_2-EOR, where it is practiced, it is well established, the legal and regulatory framework for CO_2 storage is being refined and is still evolving. Nevertheless, it is clear that CO_2 storage operations will likely require more monitoring and reporting 1) of a wider range of parameters, 2) outside the oil reservoir itself, and 3) on a wider area, and for a longer period of time than oil production. Because of this, pure CO_2 storage will impose additional costs on the operator. A challenge for CO_2-EOR operations which may, in the future, convert to CO_2 storage operations is the lack of baseline data for monitoring, besides wellhead and production monitoring, for which there is a wealth of data.

In order to facilitate the transition of a pure CO_2-EOR operation to CO_2 storage, operators and policy makers have to address a series of legal, regulatory and economic issues in the absence of which this transition can not take place. These should include:

1. Clarification of the policy and regulatory framework for CO_2 storage in oil reservoirs, including incidental and transitioned storage CO_2-EOR operations. This framework

should take into account the significant differences between CO_2 storage in deep saline aquifers, which has been the focus of regulatory efforts to date, and CO_2 storage in oil and gas reservoirs, with particular attention to the special case of CO_2-EOR operations.

2. Clarification if CO_2-EOR operations transitioning to CO_2 storage operations should be tenured and permitted under mineral/oil & gas legislation or under CO_2 storage legislation.
3. Clarification of any long-term liability for CO_2 storage in CO_2-EOR operations that have transitioned to CO_2 storage, notwithstanding the CO_2 stored during the previous phase of pure CO_2-EOR.
4. Clarification of the monitoring and well status requirements for oil and gas reservoirs, particularly for CO_2-EOR, including baseline conditions for CO_2 storage.
5. Addressing the issue of jurisdictional responsibility for pure CO_2 storage in oil and gas reservoirs, both in regard to national-subnational jurisdiction in federal countries, and to organizational jurisdiction (environment versus development ministries/departments).
6. Examination of the need to assist with the economics, particularly the cost of CO_2 and the infrastructure to bring anthropogenic CO_2 to oil fields.

The Policy Group should take note of these issues and establish ways to address them within CSLF, and make appropriate recommendations to the governments of its members.

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1. INTRODUCTION

1.1 CSLF PURPOSE

The Carbon Sequestration Leadership Forum (CSLF) is a Ministerial-level international climate change initiative that is focused on providing a government-level framework for international cooperation in research, development, demonstration and commercialization of improved cost-effective technologies for the separation, capture, transportation, utilization and storage of carbon dioxide (CO_2). The mission of the CSLF is to facilitate the development and deployment of such technologies via collaborative efforts that address key technical, economic, and environmental obstacles. The CSLF also promotes awareness and champions legal, regulatory, financial, and institutional environments conducive to such technologies. The CSLF seeks to realize the promise of CO_2 capture, utilization and storage (CCUS) over the coming decades, and to ensure that CCUS is both commercially competitive and environmentally safe.

The CSLF comprises 25 members, including 24 countries and the European Commission. CSLF member countries represent over 3.5 billion people, or approximately 60% of the world's population.

The CSLF seeks to:

1. Identify key obstacles to achieving improved technological capacity;
2. Identify potential areas of multilateral collaborations on carbon separation, capture, transport and storage technologies;
3. Foster collaborative research, development, and demonstration (RD&D) projects reflecting Members' priorities;
4. Identify potential issues relating to the treatment of intellectual property;
5. Establish guidelines for the collaborations and reporting of their results;
6. Assess regularly the progress of collaborative R&D projects and make recommendations on the direction of such projects;
7. Establish and regularly assess an inventory of the potential areas of needed research;
8. Organize collaboration with all sectors of the international research community, including industry, academia, government and non-government organizations; the CSLF is also intended to complement ongoing international cooperation in this area;
9. Disseminate information and foster knowledge-sharing, in particular among Members' projects;
10. Build capacity of Members;
11. Consult with and consider the views and needs of stakeholders in the activities of the CSLF;
12. Develop strategies to address issues of public perception; and
13. Initiate and support international efforts to explain the value of CCUS, in developing legal and regulatory frameworks and markets, and promote broad-based adoption of CCUS; and
14. Support international efforts to promote RD&D and capacity building projects in developing countries.

The Carbon Sequestration Leadership Forum comprises a Policy Group and a Technical Group. The Policy Group governs the overall framework and policies of the CSLF, and focuses mainly on policy, legal, regulatory, financial, economic and capacity building issues. The Technical

Group reports to the Policy Group and focusses on technical issues related to CCUS and CCUS projects in member countries.

The Technical Group has the mandate to identify key technical, economic, environmental and other issues related to the achievement of improved technological capacity, and establish and regularly assess and inventory of the potential areas in need of research.

At the CSLF Ministerial meeting held in Beijing, P.R. China in September 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.

1.2 TASK FORCE MANDATE

At the same meeting in Beijing in 2011, the Technical Group has identified the following twelve Action Plan items:

1) Technology Gaps Closure
2) Energy Penalty Reduction
3) CCS with Industrial Emissions Sources
4) Best-Practice Knowledge Sharing
5) Risk and Liability
6) CO_2 Transport and Compression
7) Monitoring for Commercial Projects
8) Technical Challenges for Conversion of CO_2-EOR to CCS
9) Competition of CCS with Other Resources
10) Life Cycle Assessment and Environmental Footprint of CCS
11) Carbon-neutral and Carbon-negative CCS
12) CO_2 Utilization Options

Canada volunteered to take the lead on “Technical Challenges for Conversion of CO_2 EOR to CCS” (EOR stands for enhanced oil recovery), the US volunteered to take the lead on “CO_2 Utilization Options” (this would cover all forms of CO_2 utilization except for CO_2 enhanced oil recovery), Australia volunteered to take the lead on “Technology Gaps Closure” and Norway volunteered to take the lead on “Monitoring for Commercial Projects”. CSLF Task Forces were created to address these four themes.

The action on “Risk and Liability” is being covered by a new Joint Policy and Technical Group Task Force on this topic, while the International Energy Agency Greenhouse Gas Programme (IEA-GHG) is addressing the “Competition of CCS with Other Resources”. Also, the Clean Energy Ministerial (CEM) and the International Energy Agency (IEA) are addressing how industrial emissions relate to CCS, and this would relate to the action on “CCS with Industrial Emissions Sources”. The United Kingdom’s Department of Energy and Climate Change (DECC) already is completing a report on “Energy Penalty Reduction”. Finally, the Global CCS Institute (GCCSI) is already heavily involved in Best Practices Knowledge Sharing, but the CSLF Project Interaction and Review Team (PIRT) will also undertake this action for CSLF-recognized projects. Thus, nine out of the twelve actions in the Action Plan developed at the CSLF Ministerial-level meeting in Beijing in 2011 are being acted on one way or another.

Since its inception in 2003, the Technical Group 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. Although deep saline formations have been assessed as having the largest storage potential (IPCC, 2005), 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, but it is widely recognized that all CO_2-EOR projects store a significant amount of the purchased and injected CO_2 by various trapping mechanisms.

On the geological-storage side, the focus of CO_2 Utilization is on the use of CO_2 in CO_2-EOR operations. A task force to implement Action Plan #8 was approved by the Technical Group at the Ministerial-level meeting in Beijing in 2011, chaired by Canada and with membership from Brazil, P.R. China, Mexico, Norway, Saudi Arabia and United States.

Oil and gas reservoirs have long been considered to be likely the most advantageous sites for CO_2 storage because they have demonstrated confinement (sealing) properties in regard to buoyant fluids, they are well known and characterised, and in most cases access infrastructure is already in place. Carbon dioxide can be stored in hydrocarbon reservoirs after abandonment (at depletion), or can be stored while hydrocarbons are still being produced, during EOR operations. The latter option provides the advantage that some of the CCS costs will be offset, or, most likely, an economic profit will be realized as a result of incremental oil production. CO_2-EOR is a growing industry but has not yet found wide application outside of the Permian basin in west Texas and other locations in the United States where CO_2 is produced on a large scale and at a very affordable cost from several natural CO_2 reservoirs and a few gas processing, ammonia, ethylene and fertilizer plants, and coal gasification plants. The high capital costs of CO_2 capture and transport, along with cyclic oil prices tend to keep most areas from implementing CO_2-EOR.

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 or dual oil production/ CO_2 storage operations. There are recognized economic and policy barriers and 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 "concurrent" or "incidental" 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.

1.3 HISTORY OF CO_2-EOR AND CCS

Enhanced oil recovery (EOR) refers to the introduction of heat, chemicals, and/or gases to stimulate the production of oil unrecovered during primary and secondary oil production. Oil pockets not accessible to secondary methods of recovery (such as water/steam floods) can be recovered using miscible CO_2-EOR, when the injected CO_2 becomes miscible with crude oil. In reservoirs where the injected CO_2 and oil are immiscible with each other, oil production may be enhanced by swelling and thinning the crude oil. The recovery of oil up to 10-12% of the original oil in place (OOIP) extends the productive life of the flooded oilfields. The first patent on the use of CO_2 to recover oil was granted in 1952 (Whorton et al., 1952). CO_2-EOR was first tested on a large scale in the Permian Basin of west Texas and southeastern New Mexico. A successful small field-scale CO_2-EOR pilot test was conducted in the Mead Strawn field, Jones County, TX in 1964 (Meyer, 2007). The Scurry Area Canyon Reef Operators Committee (SACROC) flood in Scurry County, TX (January 1972) and the North Crossett flood in Crane and Upton Counties, TX (April 1972) were the first commercial CO_2-EOR projects (Melzer, 2011). CO_2 for the early commercial tests was sourced from the Val Verde natural gas processing plants. Oil production from CO_2-EOR increased incrementally over the next five to ten years with additional CO_2 flood projects. The discovery of large, natural CO_2 source fields such as Sheep Mountain, McElmo Dome (Colorado), Jackson Dome (Mississippi), and Bravo Dome (New Mexico), and the construction of pipelines in the 1980's connecting CO_2 sources to Permian Basin oilfields led to an expansion in U.S. CO_2-EOR production (Melzer, 2011). For example, current EOR operations at the SACROC field store ~6.5 million metric tonnes (MT) of CO_2/year (NETL, 2008). Currently, the SACROC field (49,900 acres) is operated by Kinder Morgan, and contains 503 CO_2 injection wells and 390 oil producing wells (Koottungal, 2012). It is estimated that about 55 MT CO_2 has been stored in the SACROC unit from 1972 to 2005 (Han et al., 2010). The growth in world, U.S., and Permian Basin CO_2-EOR production is represented in Figure 1.

Figure 1 indicates that a North American CO_2-EOR production is a major fraction of world CO_2-EOR production. The Permian Basin was historically the major focus of CO_2-EOR operations due to the availability of relatively pure natural CO_2 sources connected to oil fields via pipeline infrastructure. CO_2-EOR projects are fairly long-term, the first CO_2 floods at the SACROC and Crossett fields are producing 1 million barrels of oil/year currently (Melzer, 2012). It is estimated that CO_2-EOR production in the Permian Basin contributed to 18% of its total oil production (Melzer, 2012). Analysts point to a tightening of CO_2 supply for the Permian Basin, and projects in other regions in the United States (Rocky Mountains, Midwest/Mississippi/Gulf Coast, Mid-continent) also have contributed significantly to CO_2-EOR production growth in the past decade.

Future growth in North American CO_2-EOR production is expected in the Permian Basin, Rocky Mountains, Midwest/Mississippi/Gulf Coast, Mid-continent regions and Canada. The volume of CO_2 used for EOR in North America grew from approximately 110 million standard cubic feet per day (MMSCFPD) in 1983 to 3380 MMSCFPD (~65 MT/y) in 2011, and is estimated to reach 6500 MMSCFPD by 2018 (Murrell and Melzer, 2012).

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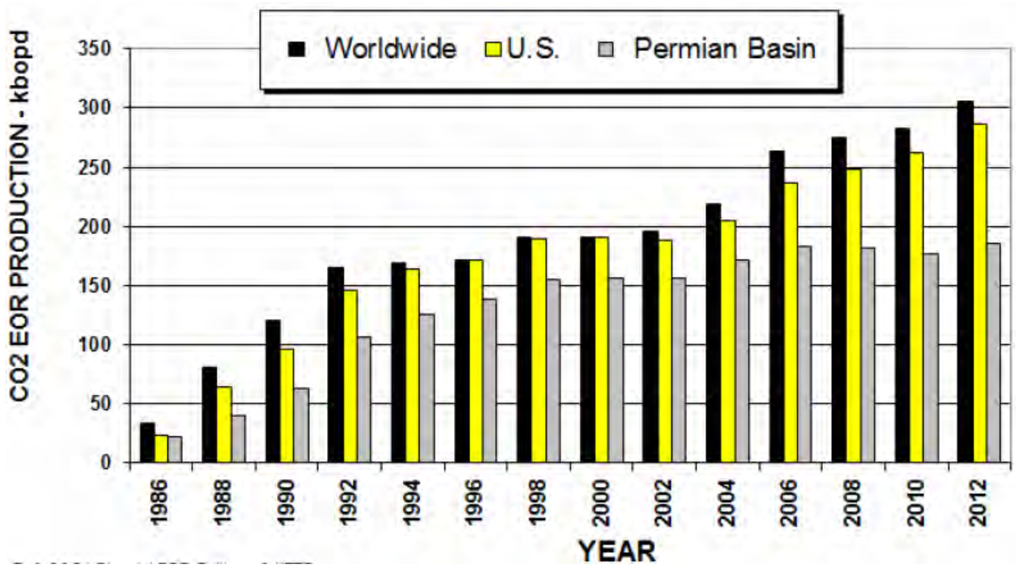

Figure 1: Global, U.S., and Permian Basin CO_2-EOR production, 1986-2012. Source: O&GJ Biennial CO_2-EOR Editions, UTPB Petroleum Industry Alliance (Murrell and Melzer, 2012).

One difference between historic CO_2 injection for EOR and current/future practice is that in the past, operators used small-volume injections of CO_2 (0.4 to 0.5 hydrocarbon pore volume [HCPV]) to maximize profitability. Higher oil prices, coupled with technology advancements in subsurface characterization and monitoring currently favor higher-volume CO_2 injections, and CO_2 slug sizes of 0.8 to 1.0 HCPV are not uncommon (Kuuskraa et al., 2011). The use of higher quantities of CO_2, combined with intelligent well placement, injection and effective monitoring has the potential to result in greater CO_2 utilization and oil recovery.

Oilfield CO_2 floods have been occurring for over 40 years and, although the incidental storage of CO_2 from the EOR projects is undocumented in aggregate, the reservoir retention volumes are projected to be in excess of 800 Mt of CO_2. For example, one large west Texas flood was recently singled out to have cumulatively purchased 115 Mt of CO_2 of which 99.7% was sequestered[1]. Another thorough carbon balance analysis of CO_2 EOR was conducted in 2009 on the SACROC EOR project[2]. It concluded the project had cumulative purchases of CO_2 of 260.0 Mt, direct/indirect emissions of 18.5 Mt and emissions from installing the surface capital equipment of 2.0 Mt. This analysis gives a total sequestered volume of 239.5 Mt or 92+% of the purchased CO_2.

The quantities of CO_2 stored by EOR are large, although in the end they are expected to be typically less than those that would be stored in saline aquifers, and the vast body of operational and safety experience gained from CO_2-EOR could be applied to carbon capture and geologic storage (CCS). For example, the technical aspects of CCS during EOR operations have been studied under the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project at commercial EOR operations in the Weyburn and Midale oilfields in Saskatchewan, Canada from 2000 to 2012. The Weyburn unit is operated by Cenovus Energy, and covers 17,280 acres, and has 170 CO_2 injection wells and 320 oil production wells (Koottungal, 2012). The Midale field is operated by Apache Corp. and covers 30,483 acres, and the first phase of implementation has 5 CO_2 injection wells and 43 oil producers (Koottungal, 2012). About 20 MT CO_2 from the

[1] http://www.energy.ca.gov/sitingcases/hydrogen_energy/documents/others/2012-06-20_OEHI_Project_Overview_workshop_presentation.pdf {Slide 15}
[2] (http://www.co2conference.net/wp-content/uploads/2013/05/Fox-KM-Presentation-SACROC.pdf

Dakota Gasification Company's coal-gasification-based synthetic gas plant in North Dakota has been stored in these oilfields since 2000 (Wildgust, 2012). CO_2 is transported to Saskatchewan by a 205 mile-long (330 km) pipeline from Beulah, North Dakota. EOR is expected to enable the recovery of an additional 130 million barrels of oil at Weyburn and Midale, and extend the life of the Weyburn oilfield by 25 years.

Geologic storage of large quantities (1 MT/y) of CO_2 (commercial-scale CCS) in deep saline aquifers has been occurring at Sleipner, Norway (1996-present), Snøhvit, Norway (2008-present), and In Salah, Algeria, (2004-2011). Together, more than 16 MT CO_2 has been stored in the subsurface as of 2010 (Eiken et al., 2010). In all three cases, CO_2 is sourced from natural gas separation plants, transported over distances ranging from 14 km to 150 km, and is injected into offshore (Snøhvit, Sleipner) and onshore subsurface sandstone saline aquifers, with widely varying geophysical and flow characteristics (MIT, 2012). The Snøhvit field is located in the Barents Sea at a depth of ~330 m, and CO_2 is stored (~0.7 MT/y) at a depth of 2400 m below the sea floor in the Tubåen Formation. The Sleipner field is located in the North Sea, at a depth of 80 m, and CO_2 is stored (~1 MT/y) in the Utsira Formation at a depth of ~700 m below the sea floor. The In Salah field is located at an altitude of ~470 m and CO_2 storage (~1 MT/y) occurs at depths of 1700 m below the surface in the Krechba Formation (Eiken et al., 2010).

A variety of monitoring, characterization, and risk management technologies have been deployed at each site to ensure CO_2 containment and to establish best practices for CCS operations. Of all three projects, the Sleipner field has injected the largest quantity of CO_2 to date. The injected CO_2 contains 0.5% to 2% of methane at all three sites (Eiken et al., 2010). CO_2 injected at Sleipner is wet, whereas at In Salah and Snøhvit, it is dried to <50 ppm water content. Other future large-scale CCS facilities with relatively long project lifespans include the Quest CCS project in Canada (~1.2 MT CO_2/y), and the Gorgon project in Australia (3.4 to 4 MT CO_2/y) (GCCSI, 2013).

1.4 POTENTIAL OF RESIDUAL OIL ZONE (ROZ) FOR CO_2-EOR

All reservoirs have a transition zone (TZ) below the oil-water contact (OWC) (Figure 2). The oil saturation below the OWC falls rapidly in the transition zone. This transition zone is generally thin and its thickness is controlled by the pore throat sizes, capillary forces and wettability behavior of the rock. A reservoir may flow some oil especially at the top of the zone but produces mostly water when perforated in the transition zone.

In some circumstances, primarily related to hydrogeological or changed tectonic (geological) conditions, the original oil zone can be invaded by water. This creates a transition zone that exists right below the current OWC and the free water level (FWL), and a residual oil zone (ROZ) or paleo oil zone that exists between the FWL and the paleo FWL (PFWL or the original FWL). This is shown diagrammatically in Figure 2. Using primary or secondary production technologies, the residual oil zone produces only water. The oil in the ROZ is immobile (i.e., at irreducible saturation) and cannot be produced by primary or secondary recovery means. In many situations, the oil saturations in the ROZ are similar to the residual oil saturation in the swept zone of a waterflood in an oil reservoir. The difference resides in the timescale of the sweep of this oil. As mentioned, the oil in the ROZ is from a paleo trap that has been partially or completely invaded by water after post-entrapment tectonic adjustments. Depending on the degree and extent of tilting or uplifting, a reservoir can have a large ROZ that may contain significant quantities of residual oil resource. This residual oil left in place after either a natural or man-made waterflood of the reservoir is oil that has not been displaced by the injected water.

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Little is known about the size TZ/ROZ resource as it has not been considered a resource in the past. But ongoing work is characterizing these zones in several areas and is showing that this resource exists both below and between oilfields. Currently, a concerted effort is being made in the United States to target this residual (or 'stranded') oil. Several operators are flooding this resource, exclusively now through the use of CO_2 injection. Currently, there are twelve commercial and field pilots in the west Texas Permian Basin region exploiting CO_2-EOR technology to target this oil.

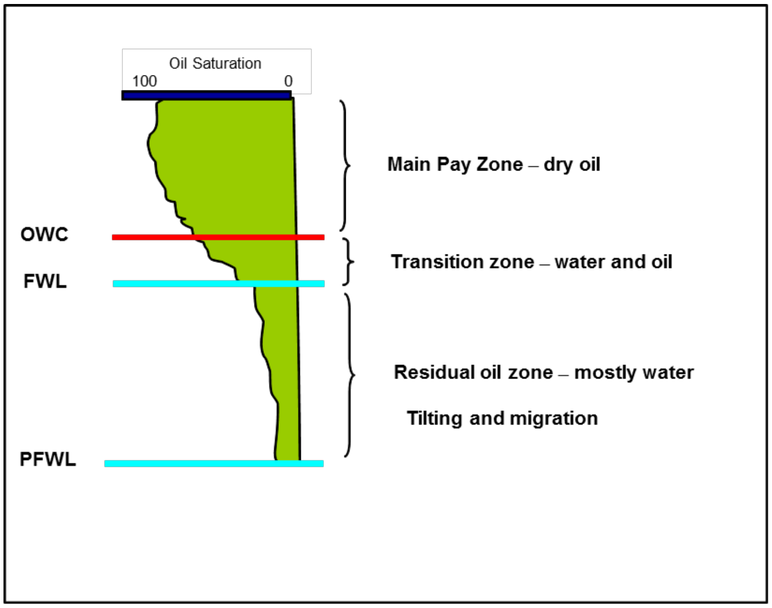

Figure 2: Definition of TZ and ROZ (from Koperna et al. 2006)

At present, CO_2 injection is the favored method to produce this oil because CO_2 properties led by its ability to greatly swell the oil (high solubility of CO_2 in oil), create large oil viscosity reductions, low to no injectivity issues, achievable operating miscibility pressures for reservoirs below depths of 3000-4000 ft (~900 to 1200 m), insensitivities to variations in reservoir water salinity and high oil recovery potential, notwithstanding the additional advantage of CO_2 capture, utilization and storage potential. A significant case history data base has been generated in the industry to evaluate the potential of CO_2-EOR in the main pay zones (MPZ). The data base includes rock and fluid property studies, estimating the minimum miscibility pressure (MMP) with CO_2, relative permeability (water/oil/CO_2) testing asphaltene studies, coreflood experiments of different injection modes, phase behavior studies, and compositional simulation studies. The industry's know-how on CO_2-EOR (in the MPZ) provides a golden opportunity to apply this technology to recover oil from the 'paleo' or residual oil zone.

1.4.1 Literature Review

The industry experience on recovery from the ROZ is limited, with only few examples reported in the literature; exclusively in the Permian Basin in west Texas. However, it is known that the hydrocarbon resource in west Texas ROZ rivals the volumes of in-place oil resource in the MPZ. It has been shown that the San Andres (carbonate) formation ROZ in west Texas fields was created from a huge paleo entrapment that was partially swept of oil when later stage geological structural changes took place. The key changes took place as the west side of the basin was uplifted, exposing the reservoir rocks to meteoric water invasion from the uplifted highlands, and the previously deep San Andres rocks were uplifted and exposed on the west side of the

Permian Basin (Koperna et al. 2006; Melzer et al. 2006). The karsted San Andres outcrop provides the source waters for the sweep. The sweep moves through the high energy (porous) facies of the formations in what have been termed “fairways” of water flushing. As currently characterized five carbonate oil field areas in the Permian Basin have been shown to possess evidence of significant paleo oil reserves in the ROZ:

1. Northern Shelf: Wasson (in particular, Denver unit and Bennett Ranch unit)
2. North Central Basin platform (San Andres/Grayburg Formation): Seminole unit
3. South Central Basin platform (San Andres/Grayburg Formation)
4. Horseshoe Atoll: Kelly-Snyder (SACROC) and Salt Creek
5. Eastern New Mexico: San Andres

The following is a summary of some CO_2-EOR pilots and projects targeting the ROZ paleo oil in Permian Basin, west Texas (Melzer. 2006, Honarpour et al. 2010; Koperna et al. 2006):

- In **Wasson Denver Unit**, the first pilot was initiated in 1991 with six pattern CO_2 flood and then expanded to 21-pattern flood. The success of the pilots led to a two additional phased development projects in 1997 and 2002, respectively.

- In 1995, Shell planned to deepen active wells into the transition and ROZs of the **Bennett Ranch unit**. However, oil prices delayed the project until 2003 when the deepened wells penetrated the ROZ and the resources were added to the MPZ.

- **Seminole San Andres Unit (SSAU)** is considered one of the largest and best documented fields with a ROZ. CO_2 injection into the ROZ in the SSAU started in 1996 with the first of two pilots. Phase 1 was developed using a 2:1 line drive, 80-acre pattern configuration with comingled injection and production into both the MPZ and ROZ. The Phase 2 pilot commenced in 2004 using nine inverted 5-spot, 40-acre patterns. In this pilot the injection was dedicated to the ROZ but MPZ and ROZ production was comingled. In 2007, full field implementation in the ROZ started with 29 each 80-acre patterns and commingled (deepened) producers, with new-drills for dedicated ROZ injectors. Currently, CO_2 injection has moved to Stage 2 full-field deployment and plans are to move field wide to the 382 producers and 190 injectors-CO_2 and water.

- In the **Kelly-Snyder (SACROC)** field, the potential of ROZ gained attention in the mid 1990’s when wells were deepened to evaluate the potential of paleo oil. One watered-out well was deepened into the ROZ and produced 20,000 barrels of oil in 18 months from ROZ CO_2 flood. This encouraged the operator to initiate a deepening program to CO_2 flood the ROZ from 1990-1999.

- **Salt Creek field** had a 120 feet (36.58 m) thick ROZ with an average oil saturation of 50% and similar properties to the MPZ. In 1996, a 16-well CO_2 pilot program was initiated to flood the ROZ with ten water-alternating-gas (WAG) injectors and six producers. The pilot was then followed by an expansion of the ROZ CO_2 flood.

- **Means San Andres Unit (MSAU)** is being currently producing in the main pay zone by CO_2-EOR in a WAG mode with 465 producers and 175 CO_2/water injectors. In more recent years, the ROZ in this unit has been carefully characterized and has begun to be exploited. The characterization effort included a full oil saturation assessment and documentation for the purpose of ROZ CO_2-EOR implementation. Some of the utilized methods to assess the oil saturation include log-inject-log (LIL), single well chemical tracer testing (SWCTT), core analysis, and open-hole logs. The oil saturation was found to be around 23% on average (ranging from 5% to more than 50%). One striking trend is that the oil saturation does not follow the conventional distribution where higher saturations are found at the top of the reservoir. In the ROZ, it was noticed that higher oil saturations can be found in the middle or even at the bottom of the ROZ (Pathak et al., 2012).

The following is a summary of the few papers that targeted the producibility of the transition zone oil, many of which were reported before it was recognized that these were often better characterized as transition zones overlying a thick ROZ. These studies found in the literature focus on the intervals just below the oil/water contacts or transition zone as shown in Figure 2. This work indicates the difficulty to fundamentally study and simulate the TZ and or ROZ in the laboratory. The avoidance of drilling into this zone during primary and secondary productions and the presence of only irreducible oil saturations poses the challenge to capture representative oil samples for ROZ studies.

Nighswander et al. (1994) used live (upper) transition zone fluids to conduct displacement tests and tune the equation of state (EoS). In this study, a slim-tube apparatus was used to measure the produced fluids displacement properties within the transition zone. The slim-tube was modified such that sampling is more refined (small pore volume samples of 0.04) for better resolution in the analysis. The tests consisted of displacing Swan Hills live oil by a multicomponent hydrocarbon mixture. This study proved that the modeling of the transition zone fluid should not follow the conventional methods as seen by the modified analysis of slim-tube tests and EoS characterization.

Masalmeh (2000) presented an experimental study to evaluate residual oil saturation and relative permeability as a function of initial oil saturation. The purpose of this study was to assess the oil mobility in the transition zone. The study concluded that the oil relative permeability increases with decreasing initial oil saturation (S_{oi}). On the other hand, the residual oil saturation is independent of $S_{oi.}$ Therefore, the study suggests that oil is more mobile in the transition zone than initially assumed.

Skauge and Surguchev (2000) compared CO_2 injection to recover paleo oil to flue and hydrocarbon gases. The study used 2D and 3D sector models to simulate down dip gas injection with vertical and horizontal wells. The results of the simulation models showed that CO_2 injection has the potential to produce paleo oil in the transition zone by vaporization and the swelling of the oil. The simulation results also showed that CO_2 is far more efficient (6-8 times higher) than flue and hydrocarbon gases even at immiscible conditions, with a potential recovery of 50% of remaining oil in place. However, these operations are characterized by high water production (60-70% water cut) before first oil is expected. This can be mitigated by injecting up dip together with the use of horizontal wells.

Yulin et al. (2000) reported on the development of the transition zone in the Daqing field in P.R. China. The field analysis indicated deeper OWC than the original OWC, resulting in a 5-25 m transition zone. The study showed that extending the test wells to target the transitional zone will encounter thick formations with high reserves. However, the oil viscosity in the transition zone is 5-30 cP (mPa·s) higher than the original oil viscosity. It was concluded that expanded development is the optimum strategy to increase the recovery in the field.

Fanchi et al. (2000) described the conventional practices to estimate transition zone recoveries and defined the procedure of their experiments to measure trapped oil relationship for water-wet media. They used two methods to describe trapped oil relationship on reserves estimates: an extended black oil simulator and an analytical model. The study showed analytically the effect of varying residual oil saturation on the primary recovery reserves of the transition zone. It suggests that the current reservoir simulators do not include a relationship between the trapped oil and relative permeabilities, which is important in calculating the reserves. It also showed the importance of including the total reservoir volume of the transition zone when calculating primary reserves available in the transition zone.

Koperna et al. (2006) helped define the distinction between the transition zone (TZ) and residual oil zone (ROZ); and, as shown earlier, discussed four pilot projects targeting residual oil zone. Two of the projects are included in Wasson oil field, one in the Seminole San Andres unit, and one in Salt Creek. All projects confirmed the viability of CO_2-EOR to produce the TZ/ROZ resource and were conducted when oil prices were considerably lower than current prices. Different development strategies were evaluated for the fields using reservoir simulation including: selectively producing the ROZ (a. top 60%, b. full interval) and simultaneously producing the ROZ and the main pay zone (MPZ). It was found that simultaneously implementing the flood in both the ROZ and MPZ is a more viable option than separately completing either the MPZ or the ROZ. The estimated recoverable TZ/ROZ reserves, in both San Andres and Canyon Reef formations in Permian Basin, are 12 billion barrels out of the 31 billion barrels TZ/ROZ OOIP.

Melzer et al. (2006) discussed the origins of residual oil zone (ROZ) examining the different types of ROZ sources and documenting some of the TZ/ROZ EOR pilots for the first time. As for the types of ROZs, the main sources covered in the study are: basin uplift and tilting, breached seals, and lateral hydrodynamic sweep. The study defines the basin uplift and tilting as a gravity-dominated OWC adjustment. This type of ROZ can translate to significant amounts of trapped oil especially if the field has large lateral extent. The breached-seals ROZ comprises a paleo oil zone that never or only partially refilled an entrapment with oil. In the later case, the ROZ lays below oil that did not escape during a temporary breach in the reservoir seal. The containment or partial refilling of the oil entrapment is a result of a reservoir reseal after geochemical and/or biological processes reformed the seal. The most common and significant ROZ in the studied basins to date is formed as a result of altered hydrodynamic conditions. These changes will occur after an uplift and infiltration of surface waters in the regional trapping formation. The Permian Basin (San Andres Formation), the Bighorn Basin (Tensleep formation) and the Panhandle and Hugoton fields are examples of such ROZs. Different ROZ development examples were also presented in this study, all at an oil price of $15-20/barrel at the time and still producing economically (*time of the paper*). In addition to the Seminole and Wasson Denver Unit pilot case histories, the paper also showed a sensitivity study on parameters that can affect the formation of the ROZ. Examples include aquifer flow rate, horizontal permeability and permeability anisotropy k_v/k_h.

1.4.2 Advantages and Challenges of Paleo Oil Recovery Using CO_2 Injection

Recovery from the residual oil zone (paleo oil) poses great benefits to operators mainly because it will contribute significantly in booking additional reserves. As shown by the west Texas examples, there are significant volumes of paleo oil available in that area and maybe around the world. So, this section will list the challenges as well as advantages of exploiting these resources using CO_2 as an injectant.

Advantages

- Research in this area will develop an understanding of an unconventional resource that will recover significant volumes of overlooked reserves. As a result, this will contribute directly to booking of additional reserves.
- The nature of residual oil zone (being in the water leg) can assist with mobility control to the injected CO_2 without the need for more expensive solutions, and can delay the need for water-alternating gas (WAG) operations.
- Injecting CO_2 in the residual oil zone offers a great opportunity to sequester CO_2. The solubility of CO_2 in water is very high and since the paleo oil is in the water leg zone, CO_2 has to go through the water. However, the solubility of CO_2 in oil is even higher, which will not compromise the recovery of the oil. Sequestering CO_2 in this case will be justified economically by the production of paleo oil.

Challenges

- Collecting an oil sample at reservoir conditions from the residual oil zone represents a great challenge since the oil will not flow by primary or secondary means. This challenge adds a risk factor in simulating reservoir conditions in the laboratory. Techniques to acquire residual oil samples involve additives that change the properties of the irreducible oil and lead to questions about their representative properties.
- The contact of CO_2 into the oil phase is key to commercial CO_2-EOR. If water shields significant amounts of CO_2 and prevents it from contacting the paleo oil, the economics of the process can be affected.
- Paleo oil is available only in few reservoirs and has been overlooked for years, which makes the available data and industry experience on the subject very scarce. Only researchers from the Permian Basin, west Texas, have had significant contribution to the subject.
- Paleo oil is a difficult resource and will require significant additional research efforts and resources to mobilize and recover it.

1.4.3 Summary

- Geological and hydrodynamic structural changes can cause huge amounts of oil to be stranded, creating large volumes of residual paleo oil, due to capillary and wetting force trapping along with gravitational forces. The larger the lateral extent of the reservoir, the greater the amount of stranded oil.
- There is limited publicly-available research on paleo oil in the industry and only few researchers have looked at its potential. Main efforts and most of the data on the subject come from the Permian Basin, west Texas. In that area, significant amounts of paleo oil have been mapped, developed and are being commercially produced (exclusively in San Andres formation).
- CO_2 injection has been suggested as the leading method to exploit this oil because of its highly favorable properties including its ability to swell the oil (high solubility in oil), oil viscosity reduction, low to no injectivity issues, achievable operating conditions above miscibility pressures, insensitivities to variations in formation water salinities, and high recovery potential.
- The residual oil zone (ROZ) has been regarded in the industry as the most optimum part of an oil reservoir to store CO_2 because of the size, high water saturation, and hydrocarbon availability (paleo oil). It has all three aspects of a successful geological

storage location while recovery of the paleo oil will provide the economical solution to offset the costs of the carbon capture and storage (CCS) project.

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2. SUBSURFACE AND OPERATIONAL CHARACTERISTICS OF CO_2-EOR OPERATIONS

In the oil industry, recovery operations are chronologically divided into three categories: primary, secondary and tertiary (Green and Willhite, 2003). The primary production is the initial oil flow out the reservoir due to natural reservoir energy. Secondary production usually follows the primary stage once the production declines. Nowadays, it almost always corresponds to waterflooding; however, it traditionally includes operations such as waterflooding, pressure maintenance and gas injection. Tertiary recovery is the third stage of production after the waterflooding and includes miscible gas, chemicals and thermal injection operations (Green and Willhite, 2003).

Sometimes, this order could change due to different technical and economic (e.g. thermal operation in heavy reservoirs without any waterflooding). This is why the concept of “enhanced oil recovery” (EOR) has become more popular than tertiary recovery (therefore primary, secondary and EOR operations). Other terminology being commonly used in the oil industry is “improved oil recovery” (IOR) which is a broader concept and includes EOR operations as well as advanced reservoir characterization, improved reservoir management and infill drilling (Green and Willhite, 2003) which has evolved today to include the adding of horizontal wells

A commonly used but hybrid definition of enhanced oil recovery today would be when an injectant (e.g., steam, miscible gas, chemicals) is used that changes the properties of the oil to make it more mobile within the reservoir. Since water and oil do not mix, water flooding would be excluded from EOR.

The residual oil after the primary and secondary production phases consists of the remaining oil either trapped due to capillary forces in very small pores of the reservoir rock and/or bypassed by the injected or displacing fluid (e.g. during waterflooding). It would also include any oil wetting the surface of the rock. These trapped or un-swept patches of oils are the main target of any subsequent enhanced oil recovery (EOR) operations.

2.1 OBJECTIVES AND PRINCIPLES OF CO_2-EOR

2.1.1 Objectives of CO_2-EOR

Numerous scientific as well as practical reasons account for the large volume of “stranded” oil, unrecoverable with primary and secondary methods. These include: oil that is bypassed due to poor waterflood sweep efficiency; oil that is physically unconnected to a wellbore (“compartmentalized”); and, most importantly, oil that is trapped by viscous, capillary and interfacial tension forces as residual oil in the pore space (Kuuskraa and Ferguson, 2008; Shen, 2010; Luo et al., 2012). Injection of CO_2 helps lower the oil viscosity and reduce trapping forces in the reservoir. Additional well drilling and pattern realignment for the CO_2-EOR project helps contact bypassed and occluded oil. These actions enable a portion of this “stranded oil” to become mobile, connected to a wellbore and thus recoverable. (Kuuskraa and Ferguson, 2008; Shen, 2010).

Based on an intensive study of CO_2-EOR technology applied in USA, the National Energy Technology Laboratory (NETL) proposed four specific “next generation” CO_2-EOR technology options. These involve:

1) Increasing the volume of CO_2 injected,
2) Optimizing well design and placement,
3) Improving the mobility ratio, and

4) Extending miscibility.

In an example light-oil field with 2,365 million barrels of original oil in-place (OOIP), the use of "next generation" CO_2-EOR technology will produce an estimated 665 million barrels of additional oil in 43 years versus only 381 million barrels in 31 years under current application of "best practices" CO_2-EOR technology. Based on reservoir-by-reservoir assessment of the 1,111 large oil reservoirs in USA amenable to CO_2-EOR, the result shows that a significant volume, 87.2 billion barrels, of oil may be recoverable with the application of "next generation" CO_2-EOR technologies. This is a significantly larger volume of oil than the 67 billion barrels of oil recoverable with current "best practices" technologies (Kuuskraa and Ferguson, 2008; Kuuskraa et al., 2009, 2011).

CO_2-EOR not only produces more oil, but also offers the potential for storing significant volumes of carbon dioxide emissions for the world. Three notable benefits would accrue from integrating CO_2 storage and enhanced oil recovery (Kuuskraa and Ferguson, 2008; Kuuskraa et al., 2009, 2011):

- First, CO_2-EOR provides a large, "value added" market for sale of CO_2 emissions captured from new coal-fueled power plants;
- Second, storing CO_2 with EOR helps bypass two of today's most serious barriers to using geological storage of CO_2 - establishing mineral (pore space) rights and assigning long-term liability for the injected CO_2;
- Third, the oil produced with injection of captured CO_2 emissions is 70% "carbon-free", after accounting for the difference between the carbon content in the incremental oil produced by EOR and the volume of CO_2 stored in the reservoir . With "next generation" CO_2-EOR, it would also increase the amount of CO_2 stored in the oil reservoirs and the oil produced by EOR could be as high as 100+% "carbon free";

Thus, the objectives of CO_2-EOR today are:

1. Producing the unrecoverable oil with primary technology for low permeability reservoirs which are unfavorable for water flooding;
2. Producing the unrecoverable oil with primary or secondary technologies for the reservoirs with water flooding;

to which one may add for the future:

3. Storing CO_2 for reducing CO_2 atmospheric emissions.

2.1.2 Principles of CO_2-EOR

According to Fanchi (2006), the recovery efficiency (E_R) of an EOR process is defined as the product of its volumetric sweep efficiency (E_V) and displacement efficiency (E_D):

$$E_R = E_V . E_D$$

The volumetric sweep efficiency is defined as the ratio of contacted oil volume by the displacing fluid to the original oil volume in place. The displacement efficiency is the ratio of the oil displaced to the amount of oil contacted by the displacing fluid. In other words, the first term is a measure of how different EOR operations could contact the reservoir, while the second one is a measure of how different EOR operations could mobilize the trapped oil. Overall, EOR techniques increase the volumetric sweep efficiency, the displacement efficiency, or both. The volumetric sweep efficiency could be increased by reducing the mobility ratio of the displacing to displaced fluid, which strongly depends on the viscosity of the two fluids. The displacement efficiency increases by increasing the ratio of viscous to capillary forces. The displacement efficiency can be increased by either increasing the viscosity of the displacing fluid or by lowering the interfacial tension between the two fluids, which cannot be achieved in the case of water. This is why water flooding is unable to mobilize the trapped oil. In contrast, chemical and miscible gas (solvent) flooding operations are successful in lowering the interfacial tension and improving the displacement efficiency, thus mobilizing trapped oil.

In contrast to water flooding, which increases macroscopic sweep efficiency, CO_2 flooding increases the microscopic displacement efficiency (Garcia, 2005). On the other hand, due to the large density difference and also adverse mobility ratio between the displacing (CO_2) and displaced fluid (oil), CO_2 flooding results in unfavorable displacement efficiency (e.g. channelling, gravity instability) and therefore, poor sweep efficiency. However, the adverse mobility ratio could be controlled by alternating the gas injection with a less mobile fluid such as water or foam in a process called Water-Alternating-Gas (WAG), illustrated in Figure 3. During a WAG process, the macroscopic and microscopic displacement efficiency of the water flooding and CO_2 flooding are combined together, leading to significantly higher incremental oil recovery compared to that from each of these processes separately (Garcia, 2005).

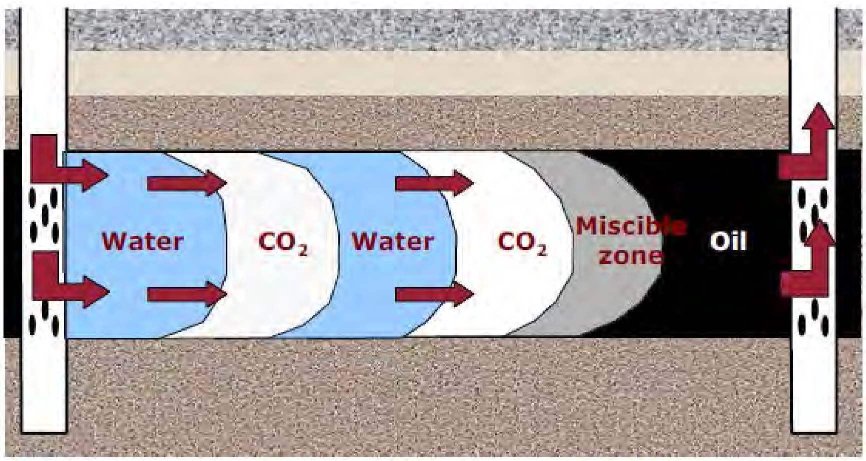

Figure 3. Water alternating gas (WAG) process for enhanced oil recovery.

There are several different factors (ranging from reservoir rock and fluid properties to operating scenarios) controlling the performance of a WAG operation such as reservoir heterogeneity, rock wettability, miscibility conditions, fluid properties, trapped gas, injection practice and also WAG parameters (slug size, WAG ratio and injection rate) (Sanchez, 1999).

An important issue in CO_2-EOR is miscibility between CO_2 and reservoir oil. In general, there are two types of miscibility between fluids: first-contact miscibility and multiple-contact miscibility. Two fluids can develop miscibility once the pressure is raised above a minimum value called minimum miscibility pressure (MMP). Once they become miscible, they form a single phase and, therefore, one could completely displace the other (Jarrell et al., 2002). The first-contact miscibility occurs if two fluids become miscible and form a single phase upon first contact in all proportions. Typical examples of this group are water-ethanol and butane-oil. Multiple-contact miscibility, on the other hand, occurs after many contacts, which are required to transfer different components of the two fluids back and forth between them to eventually become miscible, which is the case of CO_2 and crude oil (Figure 4). Multiple-contact miscibility between CO_2 and oil develops as mass transfer occurs between them (condensing/vaporizing mechanism) until the oil-enriched CO_2 and the CO_2-enriched oil become miscible and indistinguishable, with similar fluid properties (Jarrell et al., 2002).

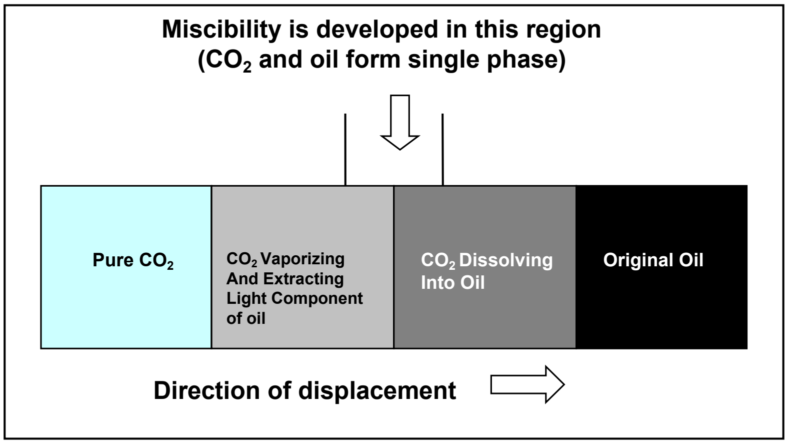

Figure 4. One-dimensional schematic showing the CO_2 miscible process (after Jarrell et al., 2002).

The advantages of using CO_2 over other gases are due to its favorable ability in the following processes (Martin and Taber, 1992a):

1) Swelling of the oil;

2) Reduction of oil viscosity;

3) Lower minimum miscibility pressure (MMP);

4) Solubility in water and reducing water density to have less gravity instability, and

5) Vaporizing a wider range of oil components resulting in easier miscibility development.

CO_2-EOR includes both miscible and immiscible flooding. Miscible or immiscible flooding depends on reservoir's pressure, temperature and on the properties of oil in the reservoir. The higher the pressure, the lower the temperature, and the lighter the oil, the more miscible the oil and CO_2 (Kuuskraa and Ferguson, 2008; Kuuskraa et al., 2009; Shen, 2010; Luo et al., 2012).

The primary objective of either miscible or immiscible CO_2-EOR is to mobilize the oil and dramatically reduce the residual oil saturation in the reservoir's pore space after water flooding. Miscible CO_2-EOR adds an important component involving a single or multiple-contact process that singly or progressively interacts the injected CO_2 and reservoir's oil during which the lighter oil fractions condense or vaporize into the injected CO_2 phase and facilitate CO_2solution into the reservoir's oil phase. This leads to two reservoir fluids that become miscible, forming a single phase, when they come in contact, with favorable properties of low viscosity, enhanced mobility and low interfacial tension (Figure 4). With miscible CO_2-EOR many projects can recover 7-23% of a reservoir's OOIP (Jarrell et al., 2002; Kuuskraa and Ferguson, 2008; Kuuskraa et al., 2009; Shen, 2010; Luo et al., 2012).

Immiscible CO_2-EOR occurs when insufficient reservoir pressure is available or the reservoir's oil composition is less favorable (heavier). When oil is heavier or the reservoir's pressure is not sufficiently high and reservoir's temperature is higher, the oil and CO_2 could not form a single phase and the fluids are immiscible. This leads to limited volumetric CO_2 contact within the reservoir (spreading of the sweep front) because the viscosity of the drive fluid is that of unmixed CO_2 instead of the miscible CO_2/oil fluid. The main mechanisms involved in immiscible CO_2 flooding are: (1) oil phase swelling, as the oil becomes saturated with CO_2; (2) viscosity and interfacial tension reduction of the swollen oil. Some extraction of lighter hydrocarbons (up to C6) into the CO_2 phase can occur as miscibility pressure is approached. The fluid drive plus

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pressure is present in all types of CO_2 flooding. This combination of mechanisms enables a volumetric portion (sweep volume) of the reservoir's remaining oil to be mobilized and produced. When implemented in a pattern flood configuration, immiscible CO_2-EOR contacts smaller volumes than miscible CO_2-EOR; field data show that with immiscible CO_2-EOR generally recovers only less than 5% of a reservoir's OOIP (Martin and Taber, 1992b; Jarrell et al., 2002; Kuuskraa and Ferguson, 2008; Kuuskraa et al., 2009; Shen, 2010; Luo et al., 2012) However, when deployed in a vertical/gravity assisted configuration, immiscible floods can be very efficient and easily exceed the recovery factors mentioned above.

2.2 SCIENCE OF CO_2 INTERACTION WITH RESERVOIR OIL

Because of its special properties, CO_2 as a supercritical fluid is extensively used in different industrial processes. Depending on pressure and temperature, CO_2 is in solid, liquid, gaseous or supercritical state. Figure 5 shows the phase diagram of CO_2 at different pressure and temperature. When temperature is 31.1 °C and pressure is 7.38 MPa (about 71.5 atm) CO_2 gas and liquid are coexist; this point is called the critical point. For higher pressures and temperatures the vaporization boundary between liquid and gaseous phases disappears and CO_2 is in supercritical state. Supercritical CO_2 has lower viscosity than liquid CO_2 and higher density than gaseous CO_2. In most cases, CO_2 is in supercritical state for miscible CO_2-EOR (Shen, 2010; Luo et al; 2012).

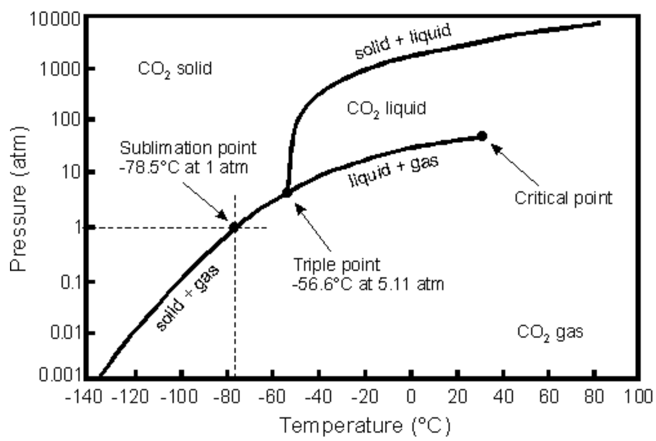

Figure 5: Pressure -Temperature phase diagram for CO_2.

Under atmospheric pressure and room temperature the solubility of CO_2 in oil is very low. As pressure increases the solubility of CO_2 in oil increases, and increases more rapidly when CO_2 is near the critical point or in supercritical state. Consequently, the oil swells and the oil viscosity decreases significantly. Due to the decrease in viscosity, the oil has more favorable flow properties in the reservoir and is more easily pumped out. The swelling of oil by dissolving of CO_2 under higher pressure is the most important factor for CO_2-EOR. In general, when temperature remains constant and as pressure increases, the volume of oil and CO_2 (gas or liquid) decreases, respectively. However, as CO_2 dissolves in oil, the volume of oil increases, and, for the same conditions, the lighter the oil is, the larger is the oil volume increase.

The study of Yang et al. (2012 a,b; 2013 a,b) shows that CO_2 disperses in oil (organic liquid) at near critical and under supercritical conditions of CO_2. Not only CO_2 molecules and oil molecules form individual molecule aggregates, respectively, but CO_2 and oil (alkanes) form CO_2-oil molecule aggregates. Because the distance (space) between CO_2 molecule aggregates, oil molecule aggregates or CO_2-oil molecule aggregates at near critical and supercritical condition of CO_2 is larger than that between CO_2 molecules or oil molecules as liquids, respectively, the volume of oil increases significantly as CO_2 disperses (dissolves) in oil. The micro-dispersion state of CO_2 and oil molecules depends mainly on the intermolecular forces that operate within the CO_2 molecules, oil molecules, and between CO_2 and oil molecules, molecular structure of oil (organic liquids), pressure and temperature.

Intermolecular Forces between CO_2 and Oil. There are three forces that affect the solubility of CO_2 in the oil and the oil volume expansion: (1) Pressure force, which squeezes CO_2 molecule into oil phase; (2) Intermolecular (attractive) force between CO_2 molecules and oil molecules, which drags the CO_2 molecule into the oil phase; and (3) Intermolecular force operating between oil molecules, which prevents CO_2 molecules to get into the oil phase and squeezes CO_2 molecules out of the oil phase. The CO_2 and hydrocarbon molecules are nonpolar. Therefore, the main intermolecular force operating within the oil molecules, the CO_2 molecules, and between the oil and CO_2 molecules is the London force (London dispersion force or dispersion force) (Kidahl, 2011; Hiemenz and Rajagopalan, 1997).

Dispersion forces depend on two features of the molecular structure. First, they increase in magnitude with the size and distortability (usually called the polarizability) of the electron clouds of the interacting particles. Size and polarizability increase as molecular weight increases. It follows that dispersion forces increase as the molar mass increases. For substances of large atomic or molecular mass, dispersion forces are strong enough that the substances are solid or liquid at room temperature. Second, the larger the surface area of molecule contact, the stronger the dispersion forces is. Molecules that are roughly spherical in shape are able to contact each other only minimally. In contrast, molecules that are planar or linear in shape can maintain a large surface area of contact, with correspondingly larger dispersion forces (Kidahl, 2011).

Effect of Pressure. When the temperature is at standard conditions, because the distance between CO_2 (gas) molecules is large at atmospheric pressure, the London force between CO_2 molecules is weak, and the London force between CO_2 and oil molecules is very weak as well. Even though the intermolecular force operating between oil (liquid) molecules and CO_2 molecules is of the same type, the strength of the London force operating between oil molecules is sufficiently strong such that it is difficult for CO_2 molecules to get into oil phase. Therefore, the solubility of CO_2 in the oils is very low and, as a result, the volume of the oil does not increase. With increasing pressure at constant temperature, the distance between CO_2 molecules is reduced dramatically and, as a result, the potential energy and the strength of the London force operating between CO_2 molecules increase more rapidly than that operating between oil molecules, such that the two forces become close in magnitude. Consequently, the solubility of CO_2 in oil increases and the volume of the oil increases as well. In fact, pressure plays a dominant role in squeezing CO_2 molecules into the oil phase. As a result of the CO_2 molecules being squeezed into the oil phase, the distance between oil molecules increases, such that the London force operating between oil molecules, which normally tends to squeeze CO_2 molecules out of the oil phase and prevent CO_2 molecules to get into the oil phase, is reduced. Meanwhile, the London force between CO_2 molecules and oil molecules, which tends to drag CO_2 molecule into oil phase, also increases. The increase in the London forces between CO_2 molecules and between the CO_2 and oil molecules, and the decrease in the London force between the oil molecules results in increasing CO_2 solubility in oil, with a corresponding increase in the volume of the CO_2-oil system. When the pressure is close to the CO_2 critical pressure (7.38 MPa) or above it, the volume increase of the CO_2-oil system is greater than the solubility of CO_2 in the oil (Yang et al., 2012 a,b).

Effect of Temperature. For constant pressure, the solubility of CO_2 in oil decreases with increasing temperature for all CO_2-oil systems, with a corresponding decrease in volume. As temperature increases, the distance between CO_2 molecules, oil molecules, and CO_2 and oil molecules increases. As a result, the intermolecular forces become weaker, in some cases dramatically (Yang et al., 2012 a,b). As temperature increases, the molecules' Brownian motion is enhanced to the point that CO_2 molecules get off the drag of oil molecules by London force, such that CO_2 molecules escape from the oil phase. Therefore, the solubility of CO_2 in the oil and the volume of oil decrease with increasing temperature.

Effect of Oil Molecular Structure. Besides the effects of pressure, temperature and intermolecular forces, the molecular structure of the oil (alkanes) has an important effect on oil volume.

The length of CO_2 molecule is about 0.33 nm (Cao and Zhang, 1986), while the length of the hexane molecule is 1.03 nm, which is about 3 times longer than that of the CO_2 molecule. Due to the linear shape of hexane, octane and decane molecules, they are able to contact each other along the entirety of their length. Therefore, for the longer molecule, the molecules have a larger surface area of contact, with correspondingly larger dispersion force. Consequently, under the same conditions of pressure and temperature, the solubility of CO_2 in the alkane and the volume of the alkane decrease as the length of the alkane molecule increases. This phenomenon indicates that the longer the alkane molecule, the London force between the alkane molecules is stronger, and it is more difficult to squeeze the CO_2 molecules into the alkane phase.

The cyclohexane molecule has a shape of a chair or boat. The cyclohexane molecules have a large surface area of contact and larger dispersion force than the hexane molecules. Therefore, for the same pressure and temperature, the solubility of CO_2 in cyclohexane and the volume of cyclohexane are less than that of hexane (Yang et al., 2012 a,b).

It should be noted that the London force is also affected by the polarizability of the molecule. For the alkane with a shorter alkyl chain, the molecular length is shorter and the polarizability is weaker, so the London force is smaller and the distance between the alkane molecules is bigger. Therefore, it is easier for CO_2 molecules to be squeezed into the alkane with a shorter alkyl chain, and the solubility of CO_2 in alkane increases as the alkyl chain length of the alkane decreases.

In summary, pressure, temperature, intermolecular forces and oil molecular structure play an important role in squeezing CO_2 molecules into the oil phase, affecting the solubility of CO_2 in oil and the oil volume expansion. It explains why CO_2 dissolves preferentially in the light oil fractions than in the heavy fractions, why CO_2 is more miscible with lighter oil, and why CO_2 miscibility with oil increases with increasing pressure, decreasing temperature and increasing oil º API (light oils have a high º API and heavy oils have a low º API).

2.3 SUITABILITY OF OIL RESERVOIRS FOR CO_2-EOR

In 2012 there were 119 CO_2 miscible and 16 immiscible active EOR projects in the world (Koottungal, 2012 in the Oil & Gas Journal biennial EOR survey), of which the great majority are in the United States (112 miscible and 8 immiscible, with the oldest one in operation since 1972). According to OGJ (2012), the US total production in 2011 in CO_2-EOR operations was 308,564 b/d in miscible floods and 43,657 b/d in immiscible ones, accounting for more oil production than by any other enhanced oil recovery method. Other countries where CO_2-EOR operations are active are Canada (three commercial and three pilot miscible EOR), Brazil (one miscible and 2 immiscible operations), Trinidad (five immiscible operations) and Turkey (one immiscible operation). It is worth noting that Apache Canada operates an acid gas enhanced oil recovery operation in the Zama oil field in northwestern Alberta, Canada, where acid gas with a composition of 70% CO_2 and 30% H_2S is used for enhanced oil recovery (Trivedi et al., 2007). A CO_2-EOR project has been operating in Hungary for a long time, but it is not mentioned in the latest review of CO_2-EOR operations in the world (it could be that it is not active at this time). A pilot project has been run in Abu Dhabi, and pilot projects are run in the Jilin and Shengli oil fields in China, and another project has recently started in Croatia.

Reservoir lithologies in these CO_2-EOR operations include both carbonate and sandstone. Table 1 presents the main characteristics of the miscible CO_2-EOR operations by reservoir lithology, and Table 2 presents the main characteristics of the immiscible CO_2-EOR operations, of which only two are in carbonate reservoirs and the remainder of 15 are in sandstone reservoirs (from Koottungal, 2012).

Table 1: Characteristics of miscible CO_2-EOR operations by reservoir lithology[3] (from Koottungal, 2012).

Reservoir Parameter	Sandstone (52 reservoirs)	Carbonate (67 reservoirs)
Depth (ft)	1150 to 11,950	3000 to 11,100
Temperature (ºF)	82 to 250	86 to 232
Porosity (%)	7 to 30	3 to 20
Permeability (mD)	2 to 2000	1 to 170
Oil Gravity (ºAPI)	35 to 45	28 to 44
Oil Viscosity (cP)	0.4 to 3	0.4 to 6
Oil Saturation at Start (%)	29 to 64	30 to 89

Table 2: Characteristics of immiscible CO_2-EOR operations (from Koottungal, 2012).

Reservoir Parameter	Range of Values
Depth (ft)	1150 to 8,500
Temperature (ºF)	82 to 198
Porosity (%)	17 to 30
Permeability (mD)	30 to 1000
Oil Gravity (ºAPI)	11 to 40
Oil Viscosity (cP)	0.6 to 592
Oil Saturation at Start (%)	30 to 86

In three cases of miscible CO_2-EOR there was no prior production from the reservoir (actually these are cases of CO_2-EOR from the residual oil zone, see below), in 20 cases CO_2 injection started immediately after primary production, in five cases CO_2 injection started after primary production and hydrocarbon gas injection, and in all other cases CO_2 injection started after primary production and water flooding. In the case of immiscible CO_2-EOR, in seven cases CO_2 injection started after primary production, in one case CO_2 injection started after primary production and gas injection, and in all other cases CO_2 injection started after primary production and water flooding (from Koottungal, 2012). The remaining oil in the reservoir at the

[3] Values are provided in imperial units, as per the original publications. For this and similar other tables, conversion factors are: m = 0.3048 ft; kPa = 0.145 psi; °C = (ºF -32) × 5/9, mPa·s = cP; oil density (kg/m^3) = 1000 × 141.5/(131.5 + ºAPI).

start of CO_2 enhanced recovery averages 47%, although in a few reservoirs it reaches values higher than 80%.

It can be seen from Tables 1 and 2 that, based on publicly-available data, there are no significant differences between the characteristics of sandstone and carbonate oil reservoirs suitable for miscible CO_2-EOR, the main difference being in oil gravity (hence viscosity). The average oil gravity for miscible CO_2-EOR operations is 36.3º API, compared with an average of 27.8º API for immiscible CO_2-EOR operations. Unfortunately, no information is available in the public domain about critical data such as initial reservoir pressure, reservoir pressure at the start of CO_2 injection, oil composition; and minimum miscibility pressure (MMP), as well as about reservoir anisotropy (ratio of vertical to horizontal permeability) and heterogeneity, which both affect sweep efficiency.

Not all oil reservoirs are suitable for miscible CO_2-EOR, thus screening criteria must be applied for the identification and selection of oil reservoirs for CO_2 flooding because most CO_2-EOR operations are based on the miscibility between oil and CO_2 and their phase behaviour. Based on the experience with CO_2-EOR in the United States, a series of authors have published between 1973 and 1997 various criteria for the identification of oil reservoirs technically suitable for CO_2-EOR, reviewed in Shaw and Bachu (2002), but CO_2-EOR is still an immature technology and these criteria are out of date by now. These criteria referred to reservoir depth, temperature, permeability, initial pressure, oil gravity and viscosity, and remaining oil fraction (same as in Tables 1 and 2 except for two publications were a minimum initial reservoir pressure of 1100 and 1500 psia is advised). To these criteria one should add that reservoir pressure at the beginning of CO_2-EOR operation should be above the minimum miscibility pressure (MMP), i.e., the pressure at which CO_2 and oil become miscible. On the other hand, the injection pressure should be less than the lesser of capillary displacement pressure in the caprock, P_{cd}, (to avoid CO_2 penetration in the caprock), minimum stress, S_{min}, (to avoid opening of existing fractures) or fracturing pressure of the caprock, P_f (to avoid fracturing the seal). Based on the previous review, oil reservoirs suitable for CO_2 flooding should meet the following criteria listed in Table 3.

It is important to note that the great majority of enhanced recovery operations, including CO_2-EOR, are based on a horizontal sweep of the reservoir. In these configurations, carbon dioxide injection can present a significant challenge because of the density and viscosity contrast between reservoir oil and CO_2 even at high injection pressures of supercritical CO_2 in low-viscosity light oils. As a result, CO_2 has the tendency to rise to the top of the reservoir (due to buoyancy) and also to flow through high permeability “channels” and reach quickly the producing well (due to the much lower viscosity than the oil). In these cases large banks of oil are not reached by the CO_2, leading to a poor oil sweep efficiency. This challenge is more pronounced in thick reservoirs with no vertical baffles to keep CO_2 from segregating at the top of the reservoir. However, in the case of oil reservoirs in carbonate pinnacle reefs, a vertical sweep is preferable and more efficient than a horizontal sweep. A gravity-stable flow is established by injecting CO_2 at the top of the reservoir, which pushes the oil bank vertically down through the reef (Trivedi et al., 2007).

Table 3: Characteristics of oil reservoirs suitable for CO_2-EOR (metric values are given in brackets).

Reservoir Parameter	Miscible CO_2-EOR
Depth (ft/m)	≥1150 (≥350)
Temperature (ºF/ºC)	82 to 250 (28 to 121)
Pressure	> MMP and < min (P_{cd}; S_{min}, P_f)
Porosity (%)	≥3, preferably >10

Permeability (mD)	≥1, preferably >10
Oil Gravity (ºAPI)	>11 and ≤40 for immiscible floods, and >27 and ≤45 for miscible floods
Oil Viscosity (cP/mPa·s)	<10 for miscible floods and <600 for immiscible floods
Remaining Oil Fraction in the Reservoir (%)	≥30 and preferably <50

Núñez-López et al. (2008) have developed a screening methodology, based on the same principles, for screening of oil reservoirs suitable for CO_2-EOR starting from reservoir size as the first screening criterion and consider only reservoirs with a cumulative production greater than 1 million standard barrels (MMstb), thus eliminating small reservoirs from consideration. However, instead of cumulative oil production, a more suitable criterion indicative of reservoir size would be the recoverable oil in place (ROIP), which is given by the product of the recovery factor (R_f) and original oil in place (OOIP).

In addition Núñez-López et al. (2008) consider only reservoirs that have already been water flooded (secondary recovery) or that have a strong water-drive mechanism because only these reservoirs would be at the stage in their production life where CO_2-EOR would be suitable (i.e., most of the mobile oil would have been produced and the remaining oil is residual oil that cannot be produced without EOR, in addition to pressure being most likely above the minimum miscibility pressure, MMP). Previous water flooding is not applied as a screening criterion for large, deep reservoirs where vaporizing gas-drive miscibility can be achieved and where CO_2-EOR can be applied directly after primary production. Finally, Núñez-López et al. (2008) apply a geological ranking based on structural regime, structural style, stratigraphic heterogeneity and depositional system, where complexity is categorized as high, intermediate and low.

2.4 OPERATIONAL CHARACTERISTICS OF CO_2-EOR OPERATIONS

Once a proper screening process identifies CO_2-EOR as the most suitable method for recovery enhancement for a given oilfield, its operational dimensioning and management strategies come into focus. Basically, the adoption of CO_2-EOR methods gives rise to three main practical concerns as described by Jarrell et al. (2002):

- The definition of volumes to be injected and how fast to inject them into the reservoir.
- The management of well artificial lifting methods and flow assurance problems that may be strengthened in the presence of CO_2.
- Facilities management.

When continuous injection is adopted, one must basically decide for the optimal rates in which CO_2 will be injected considering its availability, well injectivity and recovery ratio achieved. Although adopted in some cases, continuous injection is not commonly used. Most CO_2-EOR operations are otherwise performed through alternating gas and water (WAG). As so, operational parameters must be set in order to achieve the best from the method. Masoner et al. (2003) describe a strategy of using field data with the aim of optimizing important WAG project parameters in the Rangely Weber Sand Unit, Colorado, USA.

The first operational decision in WAG management is the setting of the so called half-cycle slug size. This parameter corresponds to the volumes of CO_2 (or water), expressed in terms of reservoir volumes, that must be injected before switching to the alternate fluid. The half-cycle slug size is directly related to the controlling of gas and water production after these fluids break through at producer wells, which impact predictability and could imply problems for artificial lifting (e.g., pumping or gas lifting) and flow assurance (scale, asphaltene or paraffin deposition).

Combined with the half-cycle slug size is the WAG ratio, the ratio between water and CO_2 volumes injected in a cycle. These two parameters define the reservoir volumes of water and CO_2 injected in a complete cycle. As a reservoir manager, one must bear in mind that WAG ratios should be adjusted during the life of the project. The optimal volumes and ratios injected at the beginning of the process may not be sufficient to recover oil with the same efficiency in later stages. Once a project area reaches a level of maturity, it is expected that the ratio of barrels of oil recovered for unit volume of CO_2 injected diminishes over time.

As the field ages, another important operational concern is the processing of gas and water produced. Facilities offer a maximum processing capacity that almost always restrict the desired CO_2 injection rates when gas or water recycling start.

The well injectivity determines how fast the volumes can be injected into the reservoir hence defining the calendar time needed for a cycle to be complete. Therefore, well injectivity monitoring and management must be performed. Depending on near wellbore effects, the reservoir three-phase relative permeability characteristics, pressure build-up, scaling, and other factors, well injectivity may emerge as a problem for achieving the injection volumes needed. Hence, the adequate number of injectors, an appropriate completion scheme and methods of initial and continued stimulation must be taken into consideration when defining a WAG project.

Setting the operational bottomhole pressures must be guided by miscibility considerations and a number of geomechanical limits. When it is not suitable to fracture the reservoir, under the risk of connecting injectors and producers directly, and then creating preferential paths inside the reservoir, reservoir parting pressure would be the most important constraint. Alternatively, caprock integrity must be respected and fault reactivation should be strongly avoided in order to prevent environmental damages.

Another well management decision is the artificial lifting method for producer wells. This decision can have an important impact over the ultimate recovery factor of the project (Yang et al., 1999). This must be optimized based on the rates and fluids produced. Issues like operational costs also must be taken into account when deciding which artificial lifting method to use. Pumps, either rod or submersible, are adequate for wells with moderate-to-high liquid productivity and low gas/liquid ratio (GLR), while gas-lifting requires low water-cut in general. In the context of WAG processes, liquid and gas production can change significantly. Hence, a policy of altering artificial lifting method of production well must be considered as necessary in order to optimize production and maximizing enhanced oil recovery.

In turn, flow assurance demands particular attention in field undergoing CO_2-EOR projects (Jarrell et al, 2002). In the presence of CO_2, higher flow rates are generally witnessed and problems like paraffin deposits, asphaltenes and scale are reported to increase. Thus, studies on the interaction between CO_2 and formation rock and fluids must be conducted previously with the objective of dimensioning of future chemical treatment and/or the programming of well workover operations.

Corrosion is also a serious problem in wells that produce both water and CO_2, as well as in injection wells in the Water Alternating Gas (WAG) process. It can be the cause of important economic drawbacks during the lifetime of a field (Kermani and Morshed, 2003). Adequate tubing metallurgy (or the use of lined pipe) must be used for well completion, and inhibition treatments are most generally adopted for producing well operations. If water is not used in injection wells, then no special metallurgy and lined pipe is need in the injection wells.

Facilities management refer to the monitoring and optimisation of operational parameters as well as managing the plant integrity. As in the case of well tubing, due to the formation of carbonic acid, corrosion monitoring and mitigation is an important part of a facility management routine. The use of proper inhibition treatment can make corrosion to drop significantly in CO_2-EOR projects.

Where water is not present as in the case of CO_2 supply pipelines, conventional carbon steel is preferred and widely used.

2.5 MATERIALS CORROSION IN CO_2-EOR OPERATIONS

As already mentioned in section 2.2.2, CO_2 is well known as a corrosive agent in the oil industry when dissolved in an electrolyte, typically water naturally present in the formation, due to flooding, or condensation. Dissolved CO_2 might cause corrosion due to the formation of carbonic acid (H_2CO_3), which can cause corrosion in producing wells, valves, pipelines, tanks and other facilities.

The corrosion speed and severity depends mainly on the water chemistry. Frequently, the dominant factor is the CO_2 partial pressure (Eckert, 2012) and the damage might be generalized or localized. Carbon steel, a very common material in the oil industry, is associated to several specific CO_2 corrosion damages, including pitting, mesa attack and flow-assisted damage.

CO_2 pitting is usually associated with low speed flows; corrosion increases with temperature and CO_2 partial pressure. Mesa damage appears at low to medium flow speeds, when corrosion products, like iron carbonates, which provide protection against corrosion, are gradually removed. Under high speed and turbulent flow conditions, CO_2 produces both pitting and mesa areas; the damage under these conditions is the result of the continuous removal of the corrosion products and the increasing presence of corrosion species (flow-assisted damage).

***CO_2* corrosion in the oil industry facilities.** Along with H_2S, CO_2 corrosion is one of the most common corrosion mechanisms of the carbon steels used in the oil and gas production and process systems (ISO 21457: 2010). Temperature, partial pressure, pH, organic acids content, and flow conditions are the most important parameters governing the corrosion process. Historically, corrosion accounts for up to 33% of the failures in the oil industry, and 28% are related to CO_2. (Kermani and Harr, 1995). CO_2 also impacts the performance of process equipment, as well as it affects the metallurgy and the corrosion rate of existing facilities. In process plants, the separation unit is made of carbon steel with an inner layer of corrosion resistant alloy (CRA) such as duplex and Ni-based alloys described in the American Petroleum Institute specifications (API, 2009), suited to resist high concentration of CO_2. However, the process accumulates corrosive species, which demand replacement of the usual carbon steel pipes for rigid CRA pipelines in accordance to API requirements (API, 1998). For most CO_2-EOR projects, this implies high cost investment to replace existing pipelines with CRA materials. (Saadawi et al; 2011)

Internal corrosion in injection systems. The most relevant corrosion mechanisms associated to injected gas, formation water, or aquifer water are similar to those described for hydrocarbon transportation systems, thus, evaluation of the corrosion speed is mandatory. There are several models available to predict CO_2 corrosion in carbon steel. (ISO 21457:2010)

Corrosion in production and process systems for crude oil and gas. To process wet hydrocarbons, it is necessary to evaluate, as a base case option to select materials including for pipelines, the response to corrosion of the carbon steel. This evaluation might include successful experiences during operation, or might be based on the corrosion annual rate calculated considering corrosion control and mitigation measures against the design life time corrosion accepted tolerance.

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Corrosion in process systems for wet/condensed gas. Processing wet/condensed gas often causes very high corrosion to carbon steel due to the low pH of condensed water. Besides, corrosion inhibition is not practical in these systems, therefore carbon steel with higher tolerance or CRA materials are sometimes adequate. In hydrocarbon systems with condensed water, CO_2 corrosion is diminished with inhibitors based on chemicals to increase the pH.

Corrosion in process systems for dry gas/crude/condensate. Processing dry gas/crude/condensate usually is possible with using carbon steel without internal corrosion control requirements, although greater wall thickness is considered, especially if periods of wet gas processing are expected at any stage of the construction, tests, or operation stages.

Acid gas injection. Some operators have found more economical to reinject the acid gases (CO_2 and H_2S) removed from the production line, than processing them. The gases are compressed and reinjected either into the producing reservoirs or into separate formations. During the compression virtually all the water is removed.

Supercritical CO_2. As mentioned in Section 2.2, supercritical CO_2 has been compressed above 7.4 MPa and its temperature is higher than 31.1^oC. Due to its special properties, between liquid and gas, lines are used to transport it (capture and storage), and in EOR. If high purity CO_2 is used in these applications, the probability of internal corrosion is very low; however if water vapor has not been removed prior to the compression, it might condense and increase the possibility of internal corrosion in the pipelines. The recommended water content after CO_2 purification, drying and compression should be 24 ppm, as reported for the Kingsnorth Carbon Capture & Storage Project in the UK[4]. A common standard of 20-30 lbs per mmcf has been adopted in the U.S.

Corrosion management. When the selected corrosion resistant alloys cannot be justified, measures should be considered to ensure corrosion control of the carbon steel materials during the expected service lifetime of the facilities. A corrosion management strategy should be developed considering all the equipment, not only the carbon steel components. The strategic management procedure documents recommended by E.ON UK plc for CCS projects must include the following: 1) CMM, Corrosion Management Manual; 2) MRP, Maintenance Reference Plan; and 3) RBI, Risk-Based Inspection[2]. Field tested plastic- and/or polymer-lined pipe is widely used in CO_2 applications in the United States and Canada.

2.6 MONITORING AND SURVEILLANCE IN CO_2-EOR OPERATIONS

An important, if not the most important, objective of monitoring and surveillance of CO_2-EOR operations has been to acquire data on how CO_2 injection impacts oil production and affects the reservoir. The focus has been on the injected and produced fluids and on the reservoir, particularly pressure, and less attention was paid to other aspects except well integrity. Monitoring results affect decisions related to flood management but are designed to have limited interference with the commercial operation. This and costs influence the design of the surveillance/monitoring program. Monitoring CO_2-EOR operations usually cease when production stops.

More specifically, the objectives of monitoring CO_2-EOR operations include:

[4] E.ON UK plc, Report No. KCP-GNS-PLD-REP-0009: Materials Selection and Integrity Protection Report for Offshore Infrastructure, Kingsnorth Carbon Capture & Storage Demonstration Project.

- Maintenance of working pressures in the reservoir above the minimum miscibility pressure and below the parting pressure. Monitoring of the fluid mass injected and mass produced are the key inputs. The terms associated with this process are most commonly referred to as pattern balancing and material balance. Observation of the the dynamic response of the reservoir to CO_2 flooding, e.g. pressure changes, is part of this objective.
- Tracking the spatial distribution of CO_2 in the reservoir and assessing the interaction with other reservoir fluids, including evaluation the reservoir sweep efficiency and identification of regions of bypassed oil by the CO_2 slug.
- Ensuring that the CO_2 does not impact the integrity of any well that penetrates the CO_2 EOR pattern;
- Ensuring that CO_2 remains within the project area reservoir, e.g., does not migrate or leak into other reservoirs or, drinking groundwater or to the surface.

Below follow brief descriptions of some commonly used monitoring methods for CO_2-EOR operations.

Production and Pressure Data. Fundamental production data, such as injected and produced volumes of gas, oil and water (sometimes even injection and production rates), and reservoir pressure, recorded on a well by well basis, allow monitoring the individual reservoir flow units response to CO_2 injection and oil production, and allow tracking of CO_2 flow at least between injection and production wells. These data then can be used in history-matching modelling (matching of injection/production and/or pressure) to infer the movement of CO_2 in the reservoir over time and can be used to calibrate other monitoring methods. After a period of time since the start of CO_2 injection one will commonly see an increase in oil production and a decrease in water production successively in wells as the distance from the CO_2 injection well increases. Usually CO_2 is injected in patterns of one injection well in the centre and several production wells surrounding it.

Geochemical Analysis of Produced Fluids. The injected CO_2 will have a different isotopic composition than the reservoir carbon and fluids, which allows tracking it by chemical analysis of the produced fluids. The method may be supplemented by use of artificial tracers to trace the CO_2 movement through the reservoir. The approach requires a baseline against which to compare the monitoring results.

Sonic Properties. The sonic velocity contrast of CO_2 rich oil or water with unaffected formation fluids is significant. For that reason, seismic techniques have become more commonplace to track areas of CO_2 contact. Sleipner, Weyburn, Postle and Vacuum fields are noted examples of 4-D seismic surveys which have been reported in the literature (refs)

Downhole Monitoring. A common method used to evaluate geological formations, including oil reservoirs, and monitor subsurface processes, is the use of well logs. These acquired by lowering instruments into the injection wells and obtaining vertical profiles of one or more properties along the well. This approach is valuable for exploration, for CO_2-EOR and other operations, as well as for general CO_2-storage operations. It is also possible to install fixed sensors in the well bore that will sample at fixed time intervals or continuously transmit data to the surface. Monitored parameters can include temperature, pressure, radioactive tracers, CO_2 saturation, resistivity and casing integrity.

2.7 REGULATORY REQUIREMENTS FOR CO_2-EOR OPERATIONS

CO_2-EOR operations are typically regulated through permitting agencies associated with hydrocarbons and/or minerals extraction. For example, in the United States and Canada basic oil and gas laws are the regulating authority, while oil and gas or mining codes could apply in EU member states. These laws are typically based on historical development of oil and gas activities and are focused on the impact that oil or gas production has, rather than CO_2 storage. The storage of CO_2 is usually viewed as incidental during a CO_2-EOR operation and, although the degree of CO_2 retention in the reservoir is always of interest, it is not typically directly measured or verified.

CO_2-EOR operations are most prevalent in North America, with some of the most significant projects being the Weyburn-Midale project located in Canada which measured and monitored the CO_2 used for EOR injection, and activities in the Permian Basin located in the United States, which accounts for over half of the oil produced by CO_2-EOR. Because of the extensive history of CO_2-EOR in the United States, the following paragraphs provide an overview of the regulatory requirements related to CO_2-EOR operations there. However, this does not imply that the regulations in other countries are any more or less developed or strict than those in the United States.

In the United States, CO_2 injection is regulated under the Safe Drinking Water Act (SDWA). The act, which was passed in 1974, seeks to protect sources of drinking water from pollutants. SDWA sets up the Underground Injection Control (UIC) program at the US Environmental Protection Agency (EPA), which specifically covers the injection of materials into the sub-surface and aims to protect those sources of drinking water which are underground. The UIC program evolved from the regulatory expertise developed at the state level, specifically at the Texas Railroad Commission, and has evolved over the years to establish six classes of wells which regulate various types of injections. Class II wells cover injections related to oil and gas activity, including CO_2-EOR. Also, if a state's existing or newly promulgated rules are at least as stringent as the rules established by EPA, the state may have primary enforcement authority, or primacy. This allows a state agency to issue permits for the program. Currently 39 states have Class II primacy.

Class II well regulations provide for both construction and operations requirements.[5] The construction requirements cover the cementing and well casing.[6] The construction requirements also call for the logging of wells and other relevant testing as needed during drilling and construction. Operating requirements limit the injection pressure such that new fractures in the confining zone are not initiated by the injection. The operator is required to monitor the nature of the injected fluids and observe the injection pressure, flow rate and cumulative volume. Additionally, mechanical integrity testing must occur every five years over the life of the well. Prior to the permitting of the site, the operator must provide the permitting authority with information about the subsurface, the injectate, the construction materials and procedure, and the planned operational review.

In addition to the injection requirements established, monitoring and quantification of injected CO_2 is covered by the Clean Air Act. EPA has been delegated the authority to track and

[5] Information about the EPA Class II program can be found at: http://water.epa.gov/type/groundwater/uic/class2/index.cfm
[6] The specific text of the regulation covering the injection of CO_2 can be found at: http://water.epa.gov/type/groundwater/uic/regulations.cfm

quantify the creation and movement of CO_2 through the US economy. EPA has promulgated regulation in several subparts that cover every sector in the US economy. CO_2 injection is covered by two subparts, RR and UU.

EPA created a tiered approach for EOR facilities. Conventional, business as usual EOR facilities can continue to operate as-is. Subpart UU covers these facilities and only requires that operators report the quantity of CO_2 delivered to the site.[7] CO_2 EOR operators that want to "opt-in" and count as geologic sequestration will have additional monitoring requirements. Subpart RR requires a report of the CO_2 received, injected, emitted from the subsurface, and emitted from surface equipment.[8] In addition to the emissions, quantification of the quantity of CO_2 in the produced gas, the quantity remaining in the oil and gas, and finally the total quantity sequestered. In addition to these quantification requirements, an operator will need to develop a plan outlining the area to be monitored, an identification of leakage pathways, a strategy for developing a baseline of soil flux, and a leak detection and quantification plan, as well as a post-closure plan that can require a monitoring time frame of up to 50 years.

Unlike in the United States, in Canada, injection of fluids in the subsurface is under provincial, not federal jurisdiction. For example, in Alberta the Alberta Energy Regulator regulates the oil and gas industry, including CO_2-EOR, acid gas disposal and CO_2 storage. Wells for injection of CO_2, acid gas (CO_2 and H_2S) and other gases are classified as Class III wells, with corresponding cementing and casing requirements, logging requirements and other tests, including an area of review of 1.6 km (one mile) in radius) and a well head pressure limited to 90% of the formation fracture pressure[9]. Additional requirements have to be met at the time of applying for the permit to inject and during the operation, including reporting of the wellhead injection rate, fluid composition, temperature and pressure, and of volumes of produced fluids (oil, gas, water, CO_2) in the case of CO_2-EOR[10].

[7] Information about Subpart UU can be found at: http://www.epa.gov/ghgreporting/reporters/subpart/uu.html
[8] Information about Subpart RR can be found at: http://www.epa.gov/ghgreporting/reporters/subpart/rr.html
[9] AER Directive 51: Injection and Disposal Wells.
[10] AER Directive 65: Resources Applications for Conventional Oil and Gas Reservoirs.

3. SUBSURFACE AND OPERATIONAL CHARACTERISTICS OF CO_2 STORAGE OPERATIONS IN OIL RESERVOIRS

Carbon dioxide capture and storage is a technologically complex process that has three major components: industrial capture of CO_2 from large stationary sources; transportation, most likely by pipeline but also by ship at some point in the future, and storage in geological media at depths where, for efficacy of storage, CO_2 is in a dense-fluid phase (supercritical) (IPCC, 2005). It should be noted that monitoring, verification and accounting (MVA) are key elements in site operation, closure and post-closure (IOGCC, 2005, 2008). The security of CO_2 storage is a common thread throughout all the stages of the storage chain, and it has to be demonstrated when applying for tenure of the storage unit and permit to operate, during operations, and after cessation of operations and site abandonment (site closure) (CSA, 2012). In addition to being safe and secure, CO_2 storage sites have to be economic, environmentally acceptable, and generally acceptable to the public.

In a CO_2 storage project, the primary objective is to store as much CO_2 as possible in the respective geological medium for extremely long periods of time (centuries to millennia; IPCC, 2005). Carbon dioxide storage in uneconomic coal beds and potentially in organic-rich shales is based on CO_2 adsorption onto the coal/shale surface, but, as understood today, storage in these media has relatively small potential and also poses issues of resource sterilization (IPCC, 2005; Field et al., 2012). In contrast, CO_2 storage in hydrocarbon reservoirs and deep saline aquifers is based on storage in available pore space by compressing the fluids present in the pores and/or displacing them. In the case of CO_2 storage in depleted hydrocarbon reservoirs, storage space has already been created by producing oil and/or gas from the reservoir. In the case of CO_2 storage in deep saline aquifers, storage space is created by compression as a result of pressure increase and by displacement of the saline water, which could be managed (engineered) to maximise the storage capacity for CO_2. A particular case of CO_2 storage in hydrocarbon reservoirs is CO_2 utilization in enhanced oil recovery (CO_2-EOR) where, just as a result of the process, 40% to 50% on average of the total volume of injected CO_2 is trapped in the reservoir (Hadlow, 1992) when the objective is to maximize oil production and minimize CO_2 loss in the reservoir given the 'scarcity" and cost of CO_2. Note that the total volume includes the recycled volumes; when only the purchased, or "new" CO_2 is considered, the storage efficiency is greater than 90-95% (see, e.g., Hill et al., 2012). The CO_2 produced with oil is separated and recirculated in the reservoir, such that the demand for new CO_2 decreases in time unless expansion of the CO_2-EOR operation is undertaken. The amount of CO_2 stored in CO_2-EOR operations could increase if the objective would become optimization of oil production and CO_2 storage, but this requires an economic value for stored CO_2. Another motivation to increase the amount of stored CO_2 in depleted oil reservoirs is to provide incentive (e.g., carbon credit) to operators. This would encourage them to capitalize on existing infrastructure before abandonment and continue injecting CO_2 for storage after oil production had stopped.

3.1 CO_2 STORAGE SITE SELECTION

Various criteria have been developed in the last decade for the screening and selection of CO_2 storage sites (e.g., Bachu, 2010). These criteria can be grouped into the following broad categories:

1) Capacity and injectivity;
2) Confinement, including avoidance or minimization of risks to other resources, equity and life, as well as of the potential return of CO_2 to the atmosphere;
3) Legal and regulatory restrictions, including access;

4) Economic, including costs, infrastructure, financing, etc.,
5) Societal attitudes.

Site screening and selection criteria in the last three categories will not be discussed here as they are a matter of policy, regulatory framework and economics. The criteria in the first two categories are technical matters and will be addressed accordingly. Although capacity and injectivity were listed as separate criteria for site selection in the past, more recent work indicates that they are not completely independent of each other, at least not during the active period of injection. Because of the link between the two, they are hence considered as a single criterion. Injectivity and/or capacity can be increased by increasing the number of injection wells, or by controlling reservoir pressure. A storage site, in this case an oil reservoir, meets the containment requirement if the injected CO_2 does not migrate or leak out of the reservoir. Also, the first criterion (injectivity and capacity) applies to the active period of CO_2 injection, which is in the order of decades, while the second one applies to a much longer period. Failure to properly assess site capacity and/or injectivity can and will be identified during the operational (injection) period, and, in the case that either of these is lacking, measures can often be taken immediately, such as increasing well injectivity, drilling additional CO_2 injection or water production wells, or moving to another site if there is insufficient capacity. However, it should be pointed out that the significant investments for CO_2 capture and transport are predicated on the storage capacity being available, and insufficient capacity or even perceived capacity risks will negatively affect the capture decision or economics of the operation. Meeting the second criterion (site security and safety) must be demonstrated prior to injection, based on site knowledge and predictions of the fate and effects of the injected CO_2. Lack of confinement, with corresponding CO_2 migration and/or leakage out of the storage reservoir, may occur much later (years to centuries) after cessation of injection, particularly if this may occur through a well that will degrade in time, in which case different remedial measures have to be taken that no longer affect the selection and operation of the site. Many other detailed site selection criteria derive from these two, related to reservoir petrophysics and heterogeneity, pressure, temperature, etc., but all these criteria can be subsumed into the broad requirements of capacity, injectivity and confinement. Some conditions, particularly in the last three categories, may change in time, but the first two usually do not change, although sometimes they can be engineered to fit.

3.1.1 Site Screening Criteria

The following are screening criteria on which basis a prospective CO_2 storage site would be disqualified.

1) Located at shallow depth. Generally a depth of minimum 800 m has been considered as desirable or even necessary for CO_2 storage to maximize storage efficacy (amount of CO_2 stored per unit of pore volume). The congruence of this and other criteria such as groundwater protection, and the general acceptance of this threshold depth, makes this generally an eliminatory criterion. However, shallow hydrocarbon reservoirs may be the exception to this criterion since they have demonstrated confinement of buoyant fluids and there is no groundwater or other resource to be protected in the reservoir itself. Their contribution to large scale storage may be small, or significant, depending on the size of existing shallow gas reservoirs.

2) Lacking at least one major, extensive, competent barrier to upward CO_2 migration. This obviously relates to the requirement of security and safety of storage, i.e., containment within the primary storage unit. A highly fractured region, with fractures reaching to the surface will also fall into this category. This criterion normally would not apply to oil reservoirs since, if they would have been fractured to the surface, the oil would have leaked out.

3) Located in an area of very high natural or induced seismicity. This relates to the security and safety of storage.

4) Located in over-pressured strata. The risks of leakage and/or losing control of the well are higher in highly over-pressured strata (approaching lithostatic pressure with a pressure gradient of 21-23 kPa/m) than in slightly overpressured (pressure gradients up to 14 kPa/m), normally-pressured and sub-hydrostatic aquifers and/or reservoirs.

5) Lacking monitoring potential. Regulatory requirements for site permitting, operation and abandonment will include monitoring of the fate and effects of the injected CO_2, hence sites where monitoring may not be possible will most likely not be approved, and, therefore, should be avoided. This may be the case where geophysical monitoring will not be able to elucidate and track the CO_2 plume because the aquifer or reservoir is below seismic resolution (too thin) or has such low porosity that the replacement of oil or brine with dense-phase CO_2 is not discernible in band-limited seismic data, or it is located below thick salt beds that blur the seismic signal. It may also be the case that wells are not available for monitoring , particularly in marine environments, or that there is no surface access for geophysical surveys to be conducted at all, or where monitoring will be difficult due to high population density or protected natural environment (e.g., Sørensen et al., 2009). It is emphasized here that lacking monitoring potential refers to the absence of any kind of monitoring ability. If one monitoring technique in particular is not available or applicable (e.g., seismic), other techniques should be available and the site would qualify for storage. Only in the total absence of **any** monitoring possibility a site would disqualify.

3.1.2 Site Selection Criteria

While the previous criteria were of an eliminatory nature, the following criteria are of a selection nature in the sense that these are favourable characteristics that would make any particular site preferable to another, all other considerations being equal. Failure to meet a particular criterion will not eliminate a site from consideration; it will only reduce its “suitability” or “desirability”.

1) Sufficient capacity and injectivity. It is important to note that the contribution of mineral trapping is negligible during the active period of CO_2 injection, particularly in the case of oil reservoirs, and should not be considered in storage capacity estimations. It is very important to assess both the “static” storage capacity based on ultimately-available pore volume and the “dynamic” storage capacity, i.e., the storage capacity that can be achieved during the active lifetime of the project by injecting CO_2 at rates and pressures that meet safety and regulatory requirements. This refers to maintaining maximum bottom hole injection pressure (BHIP) at injection wells, and/or reservoir pressure below one of, or some combination of, the following:

   a. Initial reservoir pressure,

   b. Fracture and/or fault opening or reactivation (shearing) pressure (for pre-existing fractures and faults) in the reservoir,

   c. A fraction of the fracturing threshold in the caprock (usually established by regulation),

   d. Caprock displacement pressure and rate (pressure and rate at which the injected CO_2 intrudes into the caprock system.

2) *Sufficient thickness*. Thick reservoirs are preferable to thin ones not just because of assumed higher storage capacity, but also because they allow various injection strategies. On the other hand, thin or interbedded oil reservoirs are preferable because

of better sweep efficiency. Vertical sweep is preferable for steeply dipping or reef-type oil reservoirs.

3) *Sufficient porosity.* While many recommend porosity of at least 10% for CCS projects, the North American experience with CO_2-EOR, acid gas disposal and natural gas storage suggests that, depending on the size of the project and other factors, porosity can be as low as 3%.

4) *Adequate permeability.* European studies recommend permeability to be at least 200-300 mD. However, the experience in North America indicates that, depending on the required injection rate, permeability in the order of 10-20 mD is also sufficient. Many reservoirs have been successfully flooded with permeabilities below 10 md but many wells are required.

5) Low temperature (as defined by low geothermal gradients and/or low surface temperatures). This increases storage efficacy at an equivalent depth (reservoir pressure) by ensuring higher CO_2 density, yielding higher storage capacity for the same pore volume. It also increases storage security by decreasing the density difference between CO_2 and brine or oil, hence decreasing the buoyancy force that would drive the CO_2 upwards. Since increasing depth of a reservoir target means both higher working pressures and higher temperatures, it should be noted that temperature and pressure work in opposite directions on CO_2 density so that both should be considered in concert.

6) Hydrodynamic regime. In the case of oil reservoirs supported by an underlying aquifer, water invasion may have a negative effect in the case of CO_2 storage by reducing the storage capacity if regulatory agencies limit the pressure increase in the reservoir to the initial reservoir pressure (Bachu et al., 2004), although otherwise aquifer support has a positive effect in the case of CO_2-EOR operations by helping maintain pressure. The negative effect of water invasion may be addressed by either allowing pressure in the reservoir to increase beyond the initial reservoir pressure, as is the case of CO_2 storage in deep saline aquifers, thus pushing the invading water bask, or by producing water from the water leg of the oil reservoir, as proposed for CO_2 storage engineering.

7) Low number (density) of wells penetrating the area of influence. The presence of wells increases the potential and risk of leakage. Although studies in Alberta, Canada, and The Netherlands, have shown that various well characteristics, including time of drilling and/or abandonment, affect the potential of wells to leak, generally the larger the number of wells is, the higher is the potential for leakage. The presence of wells constitutes a conundrum for the following reasons. A larger number of wells leads to a better characterization of the storage unit, increases confidence and certainty, and increases the potential for monitoring through fluid sampling, pressure monitoring and/or well-based seismic methods (e.g., microseismic surveys or 3D vertical seismic profiles). On the other hand, as stated, the potential for leakage increases with an increasing number of wells. In the case of oil reservoirs, particularly after they underwent improved oil recovery (IOR) through water flooding and infill drilling, the number of penetrating wells may be quite significant. Remediating a leaky wellbore is a well known technology, while containing flow from an unrecognized, leaky seal or fault is not.

8) Presence of a multi-layered overlying system of aquifers/reservoirs and aquitards/caprock. This increases the safety and security of storage (secondary containment in case of leakage), and is particularly important in the case of sites with a significant number of well penetrations.

9) Potential for attenuation of leaked CO_2 near and at surface (in shallow groundwater, soil and in the air for onshore operations, or in the sea and air for offshore operations). Sites with characteristics more favourable for CO_2 attenuation and dispersion near and at the ground or sea surface as a result of topographic, climatic and/or vegetation conditions should be preferred to sites where CO_2 will have a tendency to stagnate and accumulate.

It could be seen that criteria 1 to 6 refer to the efficacy of storage (capacity and injectivity) and criteria 5 to 9 refer to the safety and security of storage (criteria 5 and 6 belong in both efficacy and safety categories).

Storage of CO_2 in EOR operations represents a special case that requires additional or different selection criteria. Once an oil reservoir has been identified as suitable for CO_2-EOR, only storage security and economic criteria would apply in the decision to pursue CO_2-EOR, hence storing CO_2. All other criteria are either not applicable or are satisfied automatically.

Generally, there are both advantages and disadvantages of storing CO_2 in enhanced oil recovery operations (Hovorka, 2010):

Advantages:

a) Reservoir properties are very well known and characterized, leading to more reliable and robust prediction of the long-term fate of the CO_2;
b) Pressure and fluid flow throughout the reservoir could be controlled by production;
c) Likely better trapping of CO_2 within the reservoir as more CO_2 is dissolved in both unswept oil and water rather than remaining as a separate phase;
d) Oil reservoirs have demonstrated trapping and sealing of buoyant fluids in structural and stratigraphic traps.

Disadvantages:

e) In some reservoirs, CO_2 can migrate laterally and/or vertically and could be produced from surrounding non-project wells and may not be recycled; and
f) CO_2 may leak out of the reservoir through or along numerous drilled wells, and even if the leakage rate may be low, over a long time the amount of leaked CO_2 could be significant unless detected in time and remediated. The same issue applies also in the case of CO_2 storage in deep saline aquifers, with the main difference being the much higher density and number of wells drilled into and oil reservoir compared to a deep saline aquifer,

Currently CO_2-EOR operations are selected and permitted under a different set of regulations than CO_2 storage operations; however, for a CO_2-EOR operation to be converted into a CO_2 storage operation it will have to meet the criteria for CO_2 storage.

3.2 MONITORING AND SURVEILLANCE FOR CO_2 STORAGE

Monitoring will be a key factor to verify that CO_2 injection and storage projects perform as expected. It is also important to ensure that long-term containment is achieved. More specifically, the reasons to implement monitoring programmes include (e.g., IPCC, 2005):

- Ensuring health and safety. After injection and storage of CO_2 it must be ensured that health and the environment are not jeopardised;
- Demonstration that the geological seal has integrity and is intact;
- Verification of the stored CO_2 (mass balance). The intended CO_2 storage project must meet existing regulatory requirements, permitting and legislation, and must demonstrate storage

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for receiving carbon credits.

- Improvement of the understanding of the behavior, migration and future state of the injected CO_2 within the storage unit.
- Verification and updating of models to achieve more correct predictions.
- Development of techniques and methodologies regarding monitoring subsurface storage of CO_2 and possibly of other gases.

There are several factors that distinguish monitoring and surveillance for CO_2 storage from that for the incidental storage that occurs with CO_2-EOR operations:

- The much longer time frame for CO_2 storage; perhaps for several decades after cessation of injection;
- The significantly larger area that needs monitoring for CO_2 storage (follows at least partly from the time frame);
- The absence of production fluids that can be sampled, and of injection and production wells that can be used for monitoring; however dedicated monitoring wells that will allow monitoring will likely be left in place;
- Differing legal requirements for CO_2 storage; e.g., storage rights vs. mineral rights;
- Stronger political and public attention on CO_2 storage, e.g., waste disposal vs. resource recovery with incidental storage.

Public opposition and that of some environmental non-governmental organizations which oppose the continued use of fossil fuels can be a hurdle for large scale injection and storage of CO_2 with either CO_2 EOR or saline storage. Successful demonstration of monitoring technologies may be a key to convincing the public and other third party stakeholders that geological storage of CO_2 can be done safely and predictably in qualified sites, thus enabling broad, global implementation of the technology.

Monitoring technologies

Many of the measurement technologies for monitoring geologic storage are drawn from applications in the oil and gas industry, including reservoir surveillance for waterflood and EOR projects, natural gas storage, reinjection of produced water and oil-based drilling mud as well as disposal of acid gases and liquid and hazardous waste in deep geologic formations. Other applications from which monitoring CO_2 storage sites can learn include groundwater monitoring, and ecosystem research. Some technologies, such as reservoir modeling, mass balancing and seismic imaging, have reached a highly sophisticated level due to many decades of research, development, and application in the petroleum industry.

In addition to the above, several reports, papers and guidelines written specifically for CO_2 storage describe a range of traditional monitoring technologies and approaches that may be used for CO_2 storage sites, amongst others CO2STORE (2006), CCP (2009), Chadwick et al. (2009), NETL (2009, 2012) and Myer (2011). Particularly the NETL (2009, 2012) Best Practice Manuals are comprehensive, with benefits and challenges for a range of technologies. The IEA GreenHouse Gas R&D Programme has designed a Monitoring Selection Tool that contains a full description, including illustrations and indications of suitability, of 40 monitoring techniques[11]. Some of the above references, e.g. CO2STORE (2006), CCP (2009), NETL (2009) as well as DNV (2011), outline how to plan a monitoring programme for CCS sites. Table 4 lists some commonly applied and potential monitoring approaches, grouped into four categories:

[11] http://www.ieaghg.org/index.php?/Monitoring-Selection-Tool.html

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Table 4: Some monitoring approaches for CO_2 storage site.

Application	Examples of Instrumentation	Readiness Level* (after NETL, 2012)
Plume pathways monitoring	• 3 or 4 D seismic, including in which the source and recording instrumentation are at the surface; vertical seismic profiling, in which the source is at the surface but the recording instruments are in wells; and cross well seismic in which both the source and recording instruments are in wells • Gravity methods, surface and well based, that use the difference in density between CO_2 and water as a means of detection • Electrical and electromagnetic methods that use the difference in electrical conductivity between CO_2 and water, which is generally assumed to be saline for the purposes of CO_2 storage. • Tiltmeters • Pressure and water quality above storage formation	Generally at commercial or demonstration stage. Controlled-source electromagnetic (CSEM) surveys is at development stage
Near-surface, surface and atmospheric monitoring	• Water samples extracted from vadose zone, near-surface or shallow groundwater formations and analysed for CO_2 (pH), and/or CO_2-water-rock reaction products and/or for tracers. • Sensors placed at ground surface in the vicinity of the well to measure CO_2 concentrations in the air. • Soil gas surveys • Atmospheric CO_2 concentrations • Eddy covariance sensors • Flux accumulation chambers • Optical sensors • Sea water sampling • High resolution acoustic sampling • Multibeam echosounding	Generally at commercial or demonstration stage. New solutions, such as multi-tube remote samplers, wind-vane samplers and portable isotopic carbon analyzers, fiber optic sensors for soil-CO_2, are under development
Air- and satellite-borne monitoring	• InSAR • Hyperspectral • Gravimetry	Generally at demonstration stage.

*The following categories are used for readiness:

- Development: first step in the development of novel tools for effective CO_2 release detection and monitoring.
- Demonstration: technologies deployed at a limited number of commercial-scale operations; technologies used in the oil and gas industry with limited applications in CCS; validated prototypes used in multiple stand-alone demonstration projects.
- Technologies in the commercial stage of development, have been systematically tested and utilized in multiple commercial-scale injection sites across a wide variety of geological settings and site conditions.

Wellbore Integrity Monitoring. Wellbores that intersect the EOR/storage formation could provide pathways for CO_2 migration. Petroleum industry experience suggests that leakage from the injection well itself is one of the most significant risks for injection projects (IPCC, 2005). Some approaches for monitoring for wellbore leakage are listed in Table 4. It should be noted that some have proposed that, for many sites, there may be a need to develop advanced Data Integration and Analysis systems, e.g. combining GPS, InSAR data with seismic and geochemical data, integrating seismic techniques with other geophysical tools (e.g., electromagnetic, gravity) and to develop continuous and autonomous monitoring of CO_2 storage by pressure monitoring (NETL, 2012). Wellbore monitoring methods should be tailored to the risk profile of both the well construction methods and for the particular sites where employed.

Plume Pathways Monitoring. The second major category, plume pathways and potential leak paths, refers to subsurface geological features, of which reactivation of transmissive fractures and faults are considered to represent the greatest risks, but changes in caprock lithology should not be disregarded. Examples of approaches to mapping the movement of CO_2 in the subsurface, which can also detect leakage out of the storage reservoir through fractures and faults, are listed in Table 4.

Subsurface monitoring of CO_2 migration in the subsurface includes geophysical methods that have been developed over many years in the oil industry. In particular, geophysical time-lapse or 4D techniques, whereby repeated datasets are acquired over a period of time, have proved a powerful means of identifying and mapping subsurface changes, such as fluid movement. Such methods include seismic, gravity measurements and electrical/electromagnetic methods. Because of the evolution of seismic technology and the contrast of sonic properties of CO_2 vs. oil and water, seismic methods are generally considered able to provide higher resolution data about the presence of CO_2 in the subsurface between wells than any other technique. However, these methods cannot detect the presence of CO_2 dissolved in reservoir fluids (oil and/or water), in thin plumes, or in thin strata of low porosity. Each method has a specific detection threshold.

Gravity and electrical methods create lower-resolution images of the subsurface, and are less widely tested for CO_2 applications, but should provide additional information on movement of the CO_2 plume. Gravity methods use the difference in density between CO_2 and water as a means of detection, whereas electrical methods use the difference in electrical conductivity between CO_2 and water, which is generally assumed to be saline for the purposes of CO_2 storage. Gravity and electromagnetic methods have seen limited field applications. They have been explored in simulation studies, e.g. Gasperikova and Chen (2009), and likely have application at certain sites.

The technologies for plume pathway detection in deep geological structures can be applied both onshore and offshore, albeit with different logistic and cost implications.

Near-surface, Surface and Atmospheric Monitoring. The third group of monitoring technologies involves near-surface, surface and atmospheric monitoring. For onshore applications, a wide range of established techniques for the detection and measurement of CO_2 and other gases in spring and well waters and in the soil are available for monitoring potential migration and leakage pathways.

Surface-flux monitoring can directly detect and measure leakage. Direct measurement techniques include covariance towers, flux accumulation chambers, and instruments such as a field-portable, high-resolution infrared (IR) gas analyzer. Year-round monitoring is needed to distinguish leakage from the highly variable natural biological CO_2 fluxes caused by microbial respiration and photosynthesis at the surface.

Technologies for the direct measurement of CO_2 leakage offshore are very much in their infancy (Chadwick et al., 2009) and presently the options seem fewer. Seabed sampling systems are under development, and acoustic methods have been employed to detect possible bubbles from leaks through the sea bed (Eiken et al., 2010).

Air- and Satellite-borne Monitoring. The fourth group includes Synthetic Aperture Radar (SAR) Interferometry (InSAR), which is a technique that uses the phase differences contained in multi-temporal satellite-borne SAR datasets and in effect converts these to distances. The change in distances over time can be used to detect and monitor relative motion on the Earth's surface. There are several versions of InSAR. The technology has been used with success to monitor the pressure build-up effects (pressure propagation) at In Salah (e.g., Wright et al., 2010). There may some challenges in applying InSAR technology to regions subjected to soil freezing and thawing, muskeg areas, or in areas of dense vegetation, but these challenges can be overcome.

There are at least two approaches to detect CO_2 surface leakages from air and space using spectral methods:

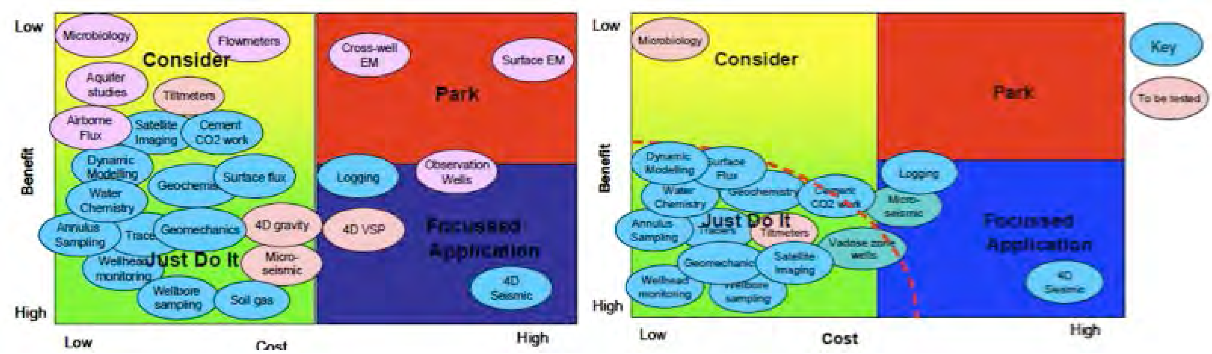
1. Indirect detection of CO_2 via its effects on vegetation
2. Directly sensing the CO_2 gas via its absorption effects in certain spectral bands

Both of these methods are in their infancy and more research and development is needed before they can be applied operationally.

InSAR and spectral methods are not applicable offshore. This triggered a feasibility study on the use of air- and satellite-borne gravimetry (Eide, 2012). The results were negative for satellite gravimetry, but it may be feasible to use air-borne gravity measurements given a low flight height and relatively large plume.

Adapting monitoring methods

Much has been learned over the many years of oil and gas reservoir management. Continuing experience there is being achieved through "learning by doing" and will increase the applicability and value of several monitoring techniques. Figure 6, from Wright et al. (2010), shows how an operator evaluated different monitoring technologies before and after initial testing. During



evaluation, some were found to be ineffective at the sampled site and others showed promise, see the left Boston Square in Figure 6. After initial testing, the cost-effectiveness of the remaining technologies was re-evaluated and the technologies moved around the Boston Square until the current view is shown on the right-hand chart. The red line indicates a conversation that should take place between a developer and regulator around monitoring technologies that may be necessary to satisfy regulatory requirements in a cost-effective manner.

Figure 6: In Salah CO_2: Storage monitoring options – before (left) and after (right) evaluation (from Wright et al., 2010)

Many of the same monitoring technologies and methods can be used for CO_2 storage and CO_2-EOR operations. In general monitoring CO_2-EOR operations will employ fewer approaches than CO_2 storage, due to less stringent requirements, shorter time-frame, smaller area and possible interference with the operations for CO_2-EOR. In both cases one will want to keep costs manageable and under control. Thus, the technologies and methods described for incidental storage during CO_2-EOR in Section 2.6 will be a sub-set of those for pure CO_2 storage projects, although monitoring approaches that require wells may be less common in pure CO_2 storage than in CO_2-EOR operations.

3.3 REGULATORY REQUIREMENTS FOR PURE CO_2 STORAGE

Many countries throughout the world, as well as international bodies, have either enacted or proposed regulatory requirements, or are developing standards or guidelines, for pure CO_2 storage. The regulatory requirements for CO_2 storage operations are similar to those for CO_2-EOR operations, but typically are more stringent, given the emphasis on long-term storage of CO_2. For example, CO_2 storage operations typically require more detailed plans the selection of storage sites, for testing and monitoring of the injection wells, for monitoring of the CO_2 plume and pressure build-up; for post injection site care and closure, and for emergency and remedial response.

These requirements can typically be described by the phase of the project: permitting, construction, operation, closure, and post closure periods[12]. They also typically include requirements for financial liability and reporting, and record keeping that may be required

[12] The text of the final regulation can be found at: http://www.gpo.gov/fdsys/pkg/FR-2010-12-10/pdf/2010-29954.pdf

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throughout multiple phases of a project. Also, the context of the development of regulations is also an important consideration. For example, in the United States, regulatory requirements for EOR operations and CO_2 storage were developed under the Underground Injection Control (UIC) program that protects underground sources of drinking water (USDWs) (EPA). Unlike wells for CO_2 injection in CO_2-EOR operations, which are classified as Class II wells, wells intended for CO_2 injection in CO_2 storage operations are classified as Class VI wells[13]. The requirements for Class VI wells are more stringent than those for Class II wells.

Permitting. In the United States, during the permitting stage, the operator must provide the regulatory authority with extensive geological, geochemical, geophysical, and hydrogeological characterization and modeling of the site to ensure it is adequately characterized and that storage wells are appropriately sited. Operators must determine, often through some form of modeling, the Area of Review (AoR), defined as the region that may be endangered by injection operations. The operator must also demonstrate control of the necessary subsurface rights within the AoR. The owner or operator of the CCS project must typically also provide several plans related to injection operations. For example, an emergency and remedial response plan may be required that describes actions the owner or operator must take to address movement of the injection or formation fluids or any adverse impacts. Also, plans related to testing and monitoring, injection well plugging, and post-injection site care and closure may also be required.

Construction. Requirements for the construction and operation of the wells for CO_2 storage, such as casings and cement, should have sufficient structural strength and be designed for the life of the storage projects. Well materials should be compatible with the materials that may be expected to come into contact. During construction, some regulations may require that the wells have surface casing through the deepest drinking water source and long string casing from the surface to the injection zone (EPA). In the United States, some of the standards that are considered applicable for well construction are those developed by the American Petroleum Institute and ASTM International.

During drilling and well construction, various data collection and monitoring is typically required to ensure the well is properly constructed. In some cases, this may be more involved than what is typically required for an EOR operation.

Operation. During injection operations, the operator needs to monitor the movement of the plume, groundwater, and pressure, as well as the integrity of the operation (e.g., wellbores). Rigorous testing and monitoring of well integrity typically includes the following: a mechanical integrity test of the injection well; recording devices to monitor injection pressure, rate, volume or mass and temperature of the CO_2 stream; and corrosion monitoring. Monitoring of the location of the injected CO_2 can utilize direct and indirect methods, and the frequency and spatial distribution for any surface monitoring must be decided by using baseline data.

Periodic re-evaluation of the AoR around the injection well to incorporate monitoring and operational data and verify that the CO_2 is moving as predicted within the subsurface may also be required during operations. The purpose is to ensure the operation is going according to plan and if not, to take the necessary corrective action. Finally, alarms and shutoff systems to check for fluid movement into unintended zones may also be required.

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[13] General information about the EPA Class VI program, including guidance documents on the implementation of various provisions of the regulation can be found at: http://water.epa.gov/type/groundwater/uic/class6/gsregulations.cfm

Post-injection Site Care. Extended post-injection monitoring and site care is required to track the location of the injected CO_2 and monitor subsurface pressures until it can be demonstrated that there is no longer any danger. After plugging of the well, post-injection site care can range from 20 years (UNFCC CDM-Durban) to 50 years (US EPA), but in some cases, these timeframes can be raised or lowered if the owner or operator can demonstrate there is no endangerment to the environment or public.

Financial Responsibility. Operators must have approved financial instruments to cover all obligations typically starting with the injection phase and covering all the way through the post injection site care period. Typically, financial obligations are necessary to cover injection well plugging, post-injection site care and closure, and emergency and remedial response and corrective actions. There are multiple instruments that can be used to cover financial responsibility, such as self-insurance by the owner or operator via a financial test or corporate guarantee, or third-party instruments such as insurance, trust fund, surety bond, or escrow account.

Reporting and Record Keeping. Reporting requirements and record keeping are critical components to ensure safe CO_2 storage operations. In most cases, regular or frequent reporting is necessary. For example, in the United States, the EPA Class VI wells require semi-annual reports; reports within 24 hours if there is an event that triggers a shut-off system, non-compliance with a permit condition, or failure to maintain mechanical integrity; and 30-day advanced notice of any planned well workovers or stimulation activities. Data typically needs to be retained for the life of the project and for 10 years following site closure.

In addition, in some cases, operators may also be required to report the quantities of CO_2 received, injected, emitted from the subsurface and from surface equipment.[14] From these values the operator must report the quantity sequestered in the formation. In addition to these quantification requirements, an operator will need to develop a plan outlining the area to be monitored, an identification of leakage pathways, a strategy for developing a baseline of soil flux, and a leak detection and quantification plan.

Regulations for Transitioning from CO_2-EOR to Pure CO_2 Storage. Currently, the only example of regulations or guidelines for transitioning from a CO_2-EOR project to a pure CO_2 storage project is in the United States. Under the regulations, EOR operators may “opt-in” to the regulations for CO_2 storage, or the appropriate regulatory authority can make this decision based on increased risk to USDWs. For those projects that do transition from CO_2-EOR to pure CO_2 storage, the permitting authority can authorize EOR wells for a pure storage operation and will use risk-based criteria to understand if conversion is appropriate and/or necessary.

Other International Examples of the Status of Regulations for CO_2 Storage. As mentioned in Section 2.7, injection of fluids in the subsurface in Canada is under provincial jurisdiction. Alberta has over 23 years of operational and regulatory experience in the injection of CO_2-containing acid gases (CO_2 and hydrogen sulfide [H_2S]) which are produced and separated from natural gas[15]. The quantities of CO_2 and H_2S injected via acid gas disposal in to the subsurface

[14] Information about Subpart RR can be found here: http://www.epa.gov/ghgreporting/reporters/subpart/rr.html

[15]IEAGHG, 2003. Acid gas injection – A study of existing operations. Phase I: Final report, Report Number PH4/18, Available at:

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are considerably lower than the quantity of CO_2 injected for EOR in the US and Canada for CO_2-EOR, but nevertheless provide a useful reference for saline aquifer CO_2 storage. Acid-gas disposal is overseen by provincial regulators in Alberta and British Colombia. The permitting process requires detailed information on surface facilities, injection well layout and design, characteristics of the injection reservoir or aquifer and injection operations. These applications are evaluated to ensure maximum hydrocarbon conservation, minimal environmental impact, and the safety of the public. A set of licensed operating parameters is established by regulators and verified at biannual intervals. Because H_2S is considerably more toxic than CO_2, regulations framed for acid gas disposal should be more stringent than those for CCS. However, current regulations for acid gas disposal require less comprehensive storage accounting and monitoring compared to those for CCS, and do not require any monitoring after cessation of injection and site abandonment. Recently, Alberta passed legislation under which the Crown (province) owns the pore space and for lease of the pore space for the purpose of CO_2 storage[16], and is reviewing its regulatory framework for CO_2 storage, which will cover the closure period after permanent cessation of injection.

The European Union (EU) Storage Directive[17] on CCS removes CO_2 storage from waste legislation, requires captured CO_2 to be stored permanently, establishes a regulatory regime for long-term liability and stewardship, and provides pipeline access and capacity expansion rules to ensure growth in CO_2[18]. The EU directive covers elements such as site selection, permitting, CO_2 stream composition, monitoring, reporting, corrective measures, closure, and post-closure obligations, transfer of responsibility, and financial security. The EU directive permits CO_2-EOR to be combined with CCS, but requires storage to occur. It likely does not accept recycle and re-use of CO_2 required for EOR operations[18].

CCS was formally included in the Clean Development Mechanism (CDM) under the Kyoto Protocol in December 2011. Currently, CCS under CDM is restricted to capture, transport and storage of CO_2 within the boundaries of a nation. CO_2 EOR/EGR was not included in CDM at that point[19].

Due to the global nature of both CCS and CO_2-EOR, there is a need for standards detailing the requirements and recommendations for the safe, long-term containment of geologically stored CO_2. International standards are also needed to verify CO_2 storage, containment, and ensure additionality for carbon offset and trading schemes such as the CDM. The Canadian Standards Association (CSA) Group and the International Performance Assessment Centre for Geologic Storage of Carbon Dioxide (IPAC-CO_2) recently developed a US-Canada bi-national standard (CSA Z741) with a primary focus on CO_2 storage in saline aquifers and depleted hydrocarbon reservoirs[20]. CSA Z741 could also be applicable to CO_2-EOR project sites. The CSA Z741

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http://www.empr.gov.bc.ca/OG/oilandgas/petroleumgeology/CarbonSequestration/Documents/IEA_Acid_Gas_Apr03.pdf

[16] Alberta Regulation 68/2011, Mines and Minerals Act, Carbon Sequestration Tenure Regulation.

[17] EU, 2009. Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32009L0031:EN:NOT

[18] Havercroft, I., Marston, P., 2012. Bridging the gap: An analysis and comparison of legal and regulatory frameworks for CO_2-EOR and CO_2-CCS. Available at: http://www.iea.org/media/workshops/2012/ccs4thregulatory/Ian_Havercroft2.pdf

[19] Carbon Capture Journal, 2012. CCS included under CDM at COP17. Available at: http://www.carboncapturejournal.com/displaynews.php?NewsID=903

[20] http://www.gwpc.org/sites/default/files/event-sessions/04Leering_Michael.pdf

consensus standard is intended to meet the needs of multiple interests, to provide accredited third-party oversight, and to complement existing regulations for geologic storage of CO_2. The scope of CSA Z741 standard covers site screening, selection, site characterization, design and development, CO_2 injection operations, monitoring, verification, risk management, site closure, and long-term stewardship. The International Standards Organization (ISO) is also developing an international standard for CCS (ISO/TC 265) based on CSA Z741.

4. DUAL CO_2-EOR AND CCS, AND TRANSITIONING CO_2-EOR TO CCS

4.1 CO_2 STORAGE INTEGRITY IN OIL RESERVOIRS

Oil and gas reservoirs are generally considered as appropriate candidates for CO_2 storage partly because they have been capable of holding in place buoyant fluids, similar to CO_2, and some even contain CO_2, hence it is assumed that they will act in a similar manner in the case of CO_2 storage. Nevertheless, the integrity of these reservoirs for CO_2 storage is not always guaranteed and it should not be taken as granted, particularly if their integrity might have been affected during their production history. The most likely pathways for fluids to migrate/leak from an oil reservoir are through faults and fractures or along wells, driven by the increased pressure due to injection and by buoyancy in the case of lighter fluids such as CO_2. The integrity of oil reservoirs in regard to CO_2 storage may be affected through capillary, geomechanical and geochemical processes.

Capillary leakage through the caprock occurs when a non-wetting phase (in this case CO_2) flows into the caprock as a result of pressure being higher than the capillary entry pressure of the caprock. The capillary entry pressure is mainly controlled by the caprock pore distribution, wettability, and interfacial tension between the displacing and displaced fluids in the caprock, in this case CO_2 and brine (as oil is not present in the caprock). The thickness of the caprock is also a very important parameter for controlling this type of leakage. Because the interfacial tension between either natural gas or oil and water is greater than the interfacial tension between CO_2 and water, the assumption that a reservoir will hold CO_2 in place if it held oil may not be necessarily true, depending on pressure. In addition, more recent laboratory studies have shown that rock wettability, particularly in the case of shales, may change in the presence of supercritical CO_2, with CO_2 becoming medium wet (see, e.g., Chiquet et al, 2007 and Chalbaud et al., 2009), with the effect of lowering further the capillary entry pressure. Thus, necessary studies must be performed to ensure that capillary leakage is not a threat for the hydraulic integrity of the caprock. However, the potential for capillary leakage through the caprock is less of an issue than the geomechanical and geochemical effects of oil production before and during CO_2-EOR.

4.1.1 Geomechanical Effects

During primary and secondary production, including infill drilling, oil reservoirs may be exposed to acid stimulation and/or hydraulic fracturing. These operations are designed to alter the initial properties of the reservoir and can create questions related to the degradation of the caprock seal integrity. They also create new fractures, can re-open existing fractures, reactivate faults, and can even propagate to abandoned and/or operating wells in the field (e.g., Grasso, 1992; Zoback and Zinke, 2002). Any of these geomechanical effects may create pathways for fluid (CO_2) leakage out of the reservoir and threaten the hydraulic integrity of the reservoir. However, depleted reservoirs (including those that have undergone CO_2-EOR) are normally at a lower pressure than the initial pressure since they have produced oil and gas, and may still be sealed. During the transition to CO_2 storage, the reservoirs will be re-pressurized, their temperature will change as a result of the lower temperature of the injected CO_2, and, consequently, the risk of leakage will increase.

The major geomechanical potential risks related to underground injection and storage of CO_2 include:

- induced seismicity;

- ground movement (subsidence during production or heaving during injection), depending on reservoir thickness, rock type, pressure, and overburden; and
- CO_2 leakage.

Several cases have been documented in which earthquakes, sometimes as large as 5.5 on the Richter scale, have been induced by production or injection of gas or water (e.g., Grasso, 1992; Ottemöller et al., 2005), but still there is no tool to predict induced seismicity. The mechanisms of ground surface movement during production have been under study for many years, but still prediction is difficult (e.g., Hettema et al., 2002). The most significant effect of ground movement is when this results in well failure and/or faults sliding (e.g., Bruno, 1992).

Initial in-situ stresses change during production and injection as a result of pressure and temperature variations. These changes may lead to different geomechanical issues in the field including wellbore instability, fault reactivation, and fracturing. Wellbore instabilities are very common in oil and gas fields. Significant pressure and temperature changes in the vicinity of a borehole may cause different problems such as borehole collapse, uncontrolled fracturing, sand production, casing failure, etc. In addition, stress changes may reactivate inactive faults in the field, if present. This not only can result in induced seismicity and ground movement, but may also change the sealing properties of the fault gauge and affect its role as a sealing barrier acting against fluid leakage. Perturbation of in-situ stresses will induce new tensile and shear fractures in the reservoir and its surrounding rocks if the stresses exceed the rock strength. Furthermore, as a result of stress changes, existing fractures may be re-opened and act as flow conduits or even propagate progressively in the caprock and open up new pathways for fluid flow out of the reservoir. Mechanical stresses induced by pressure variations are of lesser concern as long as the injection pressure is maintained below a certain threshold (fracture pressure or minimum stress), usually imposed by regulatory agencies when permitting a CO_2-EOR or CCS operation, to avoid fracturing or fracture opening. Of greater concern are thermal stresses induced by the difference in temperature between the colder water and/or CO_2 injected in the reservoir and reservoir initial conditions. For example, there are documented cases in western Canada where geological disposal of acid gas (a mixture of CO_2 and H_2S separated from produced sour natural gas) has led to reservoir cooling.

Because in the short-to-medium term the caprock is the main trapping mechanism in a reservoir, its hydraulic integrity is of paramount importance. Thus, studies are required to ensure that the reservoir integrity, including both the caprock and penetrating wells, has not been compromised during its production life and it will not be threatened by future CO_2 storage operations.

4.1.2 Geochemical Effects

The oil and gas industry has gained a lot of practical experience with geochemical issues, especially when producing slightly acidic waters during oilfield operations. For example, hydrogen sulfide is a commonly associated gas and weak sulfuric acid solutions are ubiquitous in many regions of the world. Thus, developing experience with CO_2 injection in oil reservoirs for tertiary oil recovery and geochemical simulations is not entirely new. Specific CO_2 experiences indicate that, over short time periods (up to several tens of years), the majority of the injected CO_2 remains in free state or it mixes with the reservoir oil. The mixing includes both the formation of a new, combined CO_2/oil liquid and solution into static (unswept) oil. If the injected CO_2 comes in contact with the formation water or injected water (either from secondary water flooding, or in water-alternating-gas, or WAG, processes), CO_2 will dissolve in water, which is a slower and lower-solubility process than the mixing with oil. However, over time the dissolution of CO_2 in reservoir oil and water is the second largest geochemical “sink” for CO_2 in oil reservoirs.

Carbon dioxide dissolves in water to form a weak carbonic acid according to the following reaction:

$CO_2 + H_2O \rightarrow H_2CO_3$

Carbonic acid reacts slightly and reversibly in water to form a hydronium cation, H_3O^+, and the bicarbonate ion, HCO_3^-. The formation of carbonic acid can cause corrosion in producing wells, valves, pipelines, tanks and other facilities. Another issue of concern is that CO_2 dissolution in water results in a more acidic water that can dissolve reservoir minerals, primarily carbonate minerals, according to the following reactions:

$$CO_2 + H_2O \rightarrow H_2CO_3$$

$$CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^-$$

$$MgCO_3 + H_2CO_3 \rightarrow Mg^{2+} + 2HCO_3^-$$

These reactions lead to an increase in the concentration of Ca^{2+} and Mg^{2+} in water. As pressure or temperature change, Ca^{2+} forms $CaCO_3$, and precipitate out.

$$HCO_3^- + Ca^{2+} \rightarrow CaCO_3 + CO_2 + H_2O$$

and similarly for Mg^{2+}. Because in the short- to medium-term (tens to a few hundred years) precipitation of solid phases is very limited, the main effect of CO_2 injection on the reservoir could be an increase in porosity and permeability as a result carbonate mineral dissolution, which is a positive effect. Significant precipitation of carbonate minerals is controlled by the presence of silicate and other minerals containing divalent cations which react slowly with the acidified water. However, significant decrease of pressure or temperature, and exsolution of CO_2 from water in the vicinity of production wells can cause precipitation of carbonate minerals in the pores of reservoirs, the wall of the borehole and the pipelines used to transport the produced oil and water. Precipitation of carbonate minerals could decrease oil production, well clogging or blocking the pipelines.

The acidification of reservoir water, however, may have negative effects on reservoir caprock and wells, hence on the reservoir as a whole. The acidic water can interact with the caprock, particularly clay minerals, affecting seal integrity, and/or well cements. Cements are alkaline in nature, thus, contact with acidified water can result in significant cement carbonation and degradation, depending on initial well conditions and flushing of reaction products by the injected water (see Zhang and Bachu, 2011). If existing wells that penetrate the oil reservoir have some initial mechanical defects particularly relating to cement integrity, then these defects can be enhanced in the presence of acidified water. Thus, the main concern is that the geochemical reactions at the reservoir-caprock and reservoir-well interfaces may increase fluid movement across the caprock or along wells, resulting in fluid migration out of the storage complex and loss of storage integrity. Nevertheless, the evidence so far from the existing CO_2-EOR operations indicates that these effects are either minor or have not demonstrated themselves on the time scale since these operations started.

Evaluation of reservoir integrity under CO_2-injection conditions requires geochemical modeling based on representative reservoir fluid and mineralogical samples, pressures and temperature. Geochemical modelling of CO_2 storage operations in a former CO_2-EOR reservoir presents some challenges. The first challenge is that the effects of primary, secondary (generally water flooding) and CO_2-EOR production on reservoir mineralogy and fluid compositions are generally not known. Particularly in some older operations, generally no analyses of the injected water composition (which could vary widely) exist, often very limited information of the water source exists, and there is little or no information on the amount and composition of the recycled water. The second challenge is operational. Reservoirs are not developed in a fashion where one area is completely developed and all hydrocarbons recovered and CO_2 stored before moving on to the next one. Rather, reservoirs are initially developed in an area, with perhaps multiple stages of infill drilling, and several stages of different recovery methods with individual wells being used as an injector or a producer, depending on hydrocarbon recovery. This makes it very difficult to define a good baseline and model the geochemical reactions that take place during CO_2-EOR operations and subsequent conversion to CCS.

4.1.3 Well Leakage

A fundamental component in the process of assessing the suitability of utilizing an existing oil reservoir for subsequent storage of CO_2 is that all wells penetrating the respective reservoir must be investigated for vertical hydraulic integrity or leakage potential. New wells for CO_2 injection should be drilled, cased, cemented and completed specifically to maximize vertical hydraulic integrity. Older wells converted to CO_2 injection have a higher potential for leakage than wells drilled for purpose, as shown by a study of CO_2 and acid gas injection wells in Alberta (Bachu and Watson, 2009). All other wells penetrating the reservoir should be investigated to assess their leakage potential.

Wells penetrating an oil reservoir should be assessed for both deep and shallow leakage potential. The potential for deep leakage, defined as leakage (cross-flow) from a production zone or CO_2 injection zone back into the wellbore or outside the well casing up and into an overlying permeable zone (another reservoir or a deep saline aquifer) depends on a number of factors such as hydraulic fracturing, acid stimulation, cement type, number of completions and perforations, and abandonment type in the case of abandoned wells (Watson and Bachu, 2008).

Shallow well leakage is defined as the loss of hydraulic isolation in the upper part of the well, including the shallow protected groundwater. It is observed when gas flows up inside the well annulus or outside the casing above a low cement top to the surface casing shoe. From there the gas will flow up inside the surface casing, pressuring-up the surface casing annulus thereby inducing sustained casing pressure (SCP) or gas flow out of the surface casing vent (surface casing vent flow, SCVF) at surface. Gas can also flow outside the surface casing and vent to atmosphere out of the ground at the surface (gas migration, GM). Watson and Bachu (2009) have identified the following criteria to assess the potential for shallow well leakage based on well history: spud date (when drilling of the well began), abandonment date, surface casing size, well type (cased or open-hole), total depth, well deviation and cementing (low cement tops are a major contributing factor to SCVF/GM).

Assessment of well leakage potential using these and possibly other criteria should identify wells that require special attention and maybe field testing for integrity. Wells that have confirmed cases of surface casing vent flow (SCVF), sustained casing pressure (SCP), gas migration (GM) or casing failure (CF) and wells with extended histories of multiple recompletions (re-perforating), acid and especially fracture stimulation in the proposed EOR/CCS reservoir should be investigated further and plans should be put in place for re-entering the well and conducting remedial work-over operations to remedy any leakage issues when converting from a CO_2-EOR project to a CO_2 storage project.

4.2 SUITABILITY OF OIL RESERVOIRS FOR BOTH CO_2-EOR AND CO_2 STORAGE

Fundamentally there are no special requirements for CO_2 storage in oil reservoirs through CO_2-EOR operations. As Hadlow (1992) has shown, about 40-50% of the total injected CO_2 (as contrasted to just the purchased or “new” volumes) remains in the reservoir just as a result of the process. However, many reservoirs, including ones with mobile oil in the pore space, have small CO_2 storage capacity. For example, Bachu and Shaw (2005) applied the screening criteria developed by Taber et al. (1997) and the additional miscibility criterion to approximately 10,300 oil reservoirs in western Canada and identified that less than 5000 would be suitable for CO_2-EOR. Most of these reservoirs are quite small, with an average CO_2 storage capacity of ~135 kt CO_2, which does not justify the costs of building the necessary infrastructure for storing CO_2 from a large CO_2 emitter such as a power, chemical, steel or cement plant. Thus, Bachu and Shaw (2005) introduced an additional screening criterion, namely of the reservoir having a CO_2 storage capacity of preferably 5 Mt CO_2, but at least 1 Mt. This additional criterion reduced the number of reservoirs suitable for both CO_2-EOR and CO_2 storage to 81. This capacity criterion is similar to the criterion introduced by Núñez-López et al. (2008) of the oil reservoir having a cumulative oil production of at least 1 million standard barrels (MMstb). Application of either one of these criteria would eliminate small oil reservoir from consideration.

The problem of CO_2 storage capacity in CO_2-EOR operations is compounded by the issue of water invasion in the case of oil reservoirs with strong aquifer support or by water flooding (secondary recovery) prior to CO_2 flooding (tertiary recovery). In many/most cases oil reservoirs are underlain by an aquifer. Oil can be produced from a reservoir as a result of reservoir pressure (primary drive), but in many cases the underlying aquifer has sufficiently-large permeability to provide pressure support to the oil reservoir, thus helping oil production. However, the downside of this is the fact that the same large permeability that allows pressure support to the oil reservoir allows also the flow of aquifer water into the reservoir (water invasion), thus reducing significantly the amount of CO_2 that can be stored in the reservoir. On the other hand, water invasion from the underlying aquifer helps in maintaining pressure, which is beneficial to miscibility. Using simple mass-balance modelling for oil reservoirs in the Alberta basin, Bachu and Shaw (2005) have shown that the reduction in CO_2 storage capacity in the case of oil reservoirs with strong aquifer support is in the order of 40% on average if the reservoir is allowed to reach its initial pressure but not higher. Of course, if pressure is allowed to increase beyond the initial pressure, then the reduction in CO_2 storage capacity will be less because some of the water that invaded the oil reservoir will be pushed back. However, raising reservoir pressure beyond the initial pressure may lead to geomechanical problems (see previous section) and may not be allowed by regulatory agencies. Water flooding of an oil reservoir has a similar effect on CO_2 storage capacity as water invasion from a strong underlying aquifer, if not even worse, in reducing the CO_2 storage capacity of the reservoir (e.g., the same study by Bachu and Shaw, 2005, has shown that the CO_2 storage capacity in more than 400 very large, water-flooded oil reservoirs in Alberta, Canada, is comparatively quite small and insufficient for a medium-size power plant).

Considering the widely accepted criteria for CO_2 storage (see Section 3.1), it seems that the minimum depth for CO_2-EOR and CO_2 storage should be 2500 ft (~760 m) and reservoir temperature should be greater than 90 ºF (32.2ºC), although there is no real reason not to store CO_2 in shallower reservoirs if the broad conditions of capacity, injectivity and confinement are being met.

In addition to the capacity and depth criteria discussed above, the condition of injectivity is implicitly satisfied in the case of oil reservoirs, and the only other condition that has to be met for CO_2 storage is the condition of confinement (security and safety of storage). Thus, oil reservoirs located in areas of high seismicity or in over-pressured strata, lacking monitoring potential, or having the caprock geomechanically or geochemically affected as a result of prior production (see previous Section 4.2), should generally not be used for CO_2 storage even if they are suitable for CO_2-EOR (the concept here is that the CO_2 that normally would remain in the reservoir as a result of CO_2-EOR will stay there, but that no additional CO_2 should be stored). Figure 7 below presents the process of technical selection for CO_2-EOR and CO_2 storage (Hill et al., 2013).

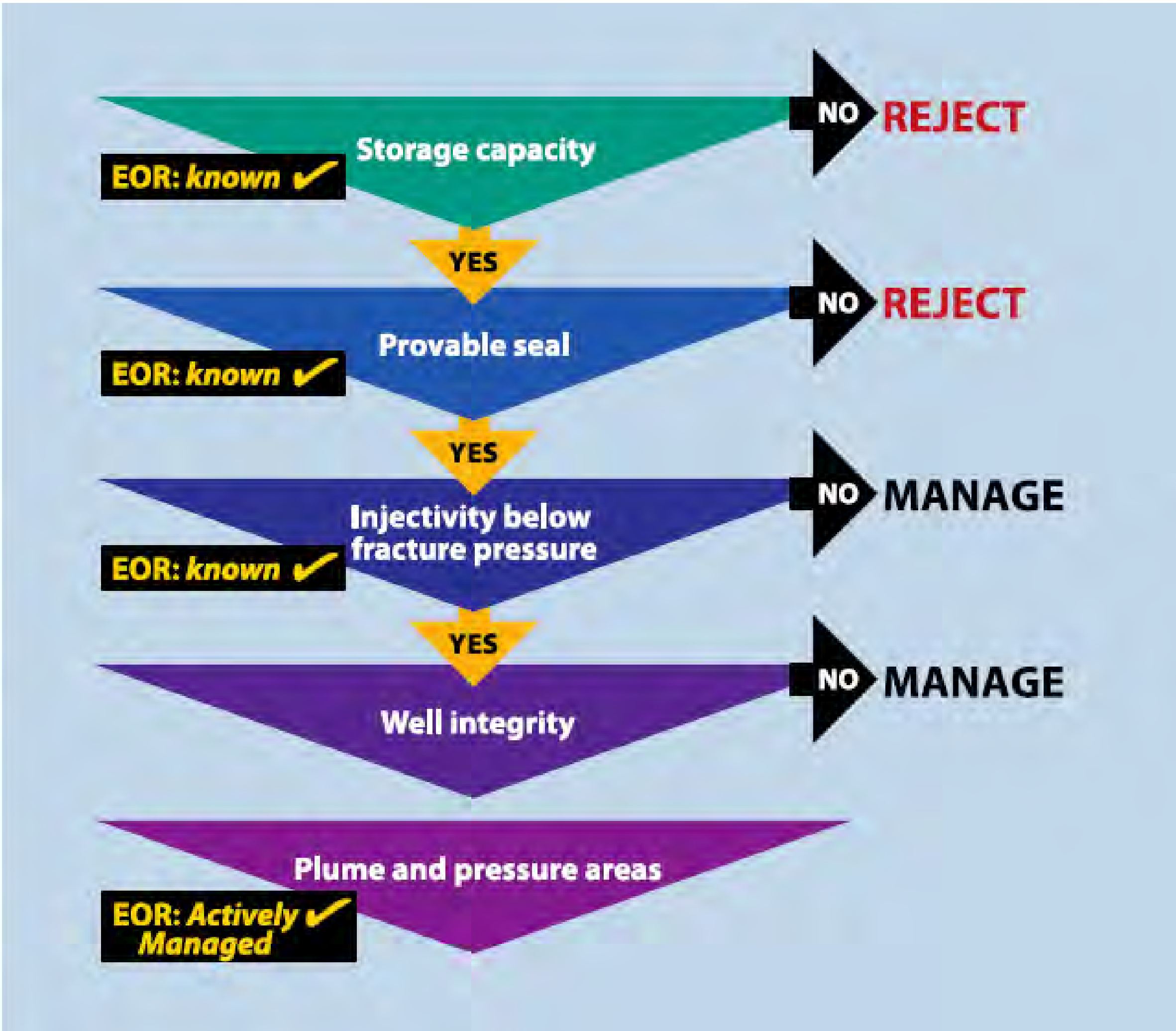

Figure 7: Technical selection of a CO_2-EOR operation for CO_2 storage and associated processes (from Hill et al., 2013).

All other possible screening and selection criteria of oil reservoirs for both CO_2-EOR and CO_2 storage would refer to surface and economic conditions, and legal and regulatory aspects.

4.3 OPERATIONAL SCENARIOS FOR CONVERSION FROM CO_2-EOR TO CO_2 STORAGE

For the purpose of this scenario, it is assumed that the oil reservoir is large, that the oil contains solution gas (methane) in a high gas/oil ratio (GOR), and that the reservoir is underlain by a saline aquifer (water leg). Other deep saline aquifers are present in the sedimentary succession above and/or below the oil reservoir.

In most conventional CO_2-EOR Projects, produced water is injected in an alternating fashion with CO_2 into the oil reservoir to sweep/push oil to production wells. Injection and production

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wells are distributed in a pattern designed to optimize sweep efficiency and oil production. At surface, the produced oil, water, solution gas and CO_2 are gathered from all the producing wells and run through a liquid-gas separator. The oil and water are run through another separator, where they are separated, and the oil is sent to sales out of the oil field, while the water is sent to pumps for injection back into the reservoir and for disposal into another deep saline aquifer if there is surplus water. The solution gas and the CO_2 are also separated in another separator, after which the solution gas (methane) is sent to a compressor and dehydrator station and then to sales, while the CO_2 is similarly compressed and dehydrated, and then recycled back into the oil reservoir, being injected together with new CO_2 brought in to the oil field. For small or low GOR schemes, separating the solution gas from CO_2 is uneconomic and both gases are re-injected into the reservoir. When CO_2 breaks through uncontrollably at producing wells, the wells are shut in and additional patterns are developed across the oil field. The conventional CO_2-EOR project terminates when all the potential flood patterns have been developed and/or when the operating costs are higher than the revenue from oil and gas sales. In some cases, rather than abandoning the injection and production wells, they may be suspended, thus allowing restarting the CO_2-EOR scheme if the price of oil goes up. Pressure blow-down of the field for additional gas recovery is commonly reported as standard procedure but uncommonly done at the end for additional gas recovery. Most commonly, the wells are plugged as no further development of the field is contemplated, and the economics of recovered CO_2 is marginal.

Conversion of a CO_2-EOR scheme to a CO_2 storage project makes sense only if there is a monetary value associated with the stored CO_2.The oil reservoir can be converted immediately into a CO_2 Storage Project. The oil and gas production and separation facilities at surface are dismantled, production wells are abandoned, and the land is reclaimed according to regulatory requirements. Only new CO_2 is being injected into the oil reservoir until the maximum reservoir pressure allowed by the regulatory agency through permitting of the CO_2 storage project is reached. The storage capacity of the oil reservoir can be increased if water from the water leg is produced and disposed of into another deep saline aquifer in what is commonly known as "storage engineering" (in which case production wells will have to be re-perforated deeper into the water leg to avoid producing skim oil or oil from the residual oil zone – ROZ). The operating costs are reduced by not producing and separating oil and gas, and the source of revenue is based only on the value of/credits for the stored CO_2. If the costs of increasing the reservoir CO_2 storage capacity by producing and disposing of water are greater than the value of the stored CO_2, then this would be not implemented, or if started, it would be terminated. Some production wells may be converted into monitoring wells rather than be abandoned.

Sometimes, even if the CO_2-EOR scheme becomes uneconomic, it may be more advantageous to continue as Hybrid CO_2-EOR/CCS Project rather than convert directly into a CO_2 storage project (Jafari and Faltinson, 2013). Again, this is based on the stored CO_2 having a monetary value. The objective is to continue production of oil from the oil leg of the reservoir or from the ROZ even if oil production by itself is uneconomic, while at the same time store CO_2, with the value of the stored CO_2 offsetting the "loss" incurred from producing oil. By continuing production, fluid continues to be removed from the reservoir, thus creating additional CO_2 storage space. Water injection into the oil reservoir is terminated, and the produced water is disposed of by injection into another deep saline aquifer. The produced CO_2 and gas are not separated anymore, but are re-injected together with new CO_2 to reduce costs. The remaining injection wells are switched to pure CO_2 injection to contact more oil and sweep it to producing wells. Operating costs are reduced by dismantling the CO_2/solution gas separation facilities, and the gas separation compression and dehydration equipment. Revenue is created by the sale of the produced oil and through the value of the stored CO_2. As the oil production continues to

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decrease, at some point the hybrid CO_2-EOR/CCS scheme becomes itself uneconomic, at which point it should be converted to a pure CO_2 storage project.

4.4 REGULATORY AND MONITORING REQUIREMENTS DURING CONVERSION FROM CO_2-EOR TO CO_2 STORAGE

For CO_2-EOR operations to transition to CO_2 Storage, they may likely have to meet some incremental CCS requirements. These include the origin of CO_2 (it should be captured from an anthropogenic source), meeting more stringent operational regulatory requirements than CO_2-EOR operations, and the integration of a robust Monitoring and Surveillance (M&S) program. This is the focus of this section and it will indicate certain parameters to be monitored and verified in order to ensure safe and permanent storage for the CO_2. For each parameter to be monitored, such as well cement and casing, CO_2 concentrations or fluid pressures, there are different technologies/tools that can be used to measure and record values, confirm integrity in the case of wells, and verify the forecasted predictions.

The M&S program for each project should cover three periods of the project lifetime: 1) pre-injection to establish baseline conditions, 2) during injection to monitor the plume and behavior of CO_2, and 3) post-injection, which is monitoring the site after CO_2 injection has permanently ceased and also includes the well abandonment and the removal of the infrastructure. It is similar to the “during injection monitoring” period, but perhaps with lower frequency. The baseline and post-injection data acquisition M&S activities are likely the key differences between CO_2-EOR operations and CO_2-EOR for CO_2 storage in terms of monitoring. From a technical point of view, the post injection period is further divided into two parts: abandonment (termination of the project) and post abandonment. The reason for this subdivision is to further illustrate the proper practices of abandoning the wells and the removal of the infrastructure, which is short in duration, as opposed to monitoring the fate of the stored CO_2 which will likely last several years. Furthermore, from a legal point of view, the post-injection period is divided into a “Closure Period”, during which the operator maintains liability for the CO_2 storage operation, and “Post-Closure Period”, when liability may be assumed by a state (government) agency (CSA, 2012). However, this sub-division is a policy matter and won’t be addressed further in this report.

Typically, the M&S program is divided into three categories: Surface, Near-surface and Subsurface monitoring. Surface monitoring is done to verify that the sequestered CO_2 will not leak to the atmosphere and to detect any leak in case it occurs, the near surface monitoring usually involves monitoring shallow ground water for the same reason as surface monitoring, while the subsurface monitoring is performed to confirm the location of CO_2, fluid movement in the reservoir, the isolation of the sequestered CO_2, wells’ downhole integrity, reservoir pressures, and the integrity of the reservoir seal.

It should be noted that monitoring techniques, technologies and tools should be project specific as each commercial-scale project has its own geological and operational features and characteristics. Prior to any project, risk assessment and site evaluation should be carried out to identify the appropriate monitoring and surveillance program for the project (pre-injection phase). However, the main goals of any M&S program can be universal (Litynski et al. 2008) and it will be implemented to provide solid technical assessment of a project to support decision making, ensure the health, safety and environment (HSE) of the project, evaluate CO_2 movement and interaction with reservoir fluids, and provide a detailed mitigation and corrective action plans should a leak or a problem occur.

Weyburn and Zama in Canada are the only CO_2-EOR operations that are recognized as a CO_2 storage sites. The Weyburn site has been subjected to very extensive monitoring, as described in, e.g., White et al. (2004). The SACROC field in Texas, the Cranfield project in Mississippi also have had extensive monitoring programmes. All mentioned monitoring programmes have a large degree of research.

4.4.1 Surface and Near-surface Monitoring

The public is mostly concerned about CO_2 leaking to surface or shallow groundwater. When CO_2 is stored in depleted oil reservoirs, the integrity of the reservoir seal is arguably much more competent than other geological storage options (e.g. saline aquifers). This is because the seal has retained reservoir buoyant fluids for very long periods of time (tens of thousands to millions of years). The primary risk of leaking CO_2 is through the wells drilled for injection and production or abandoned wells. This is why for CO_2-EOR for storage, monitoring techniques for the well integrity is receiving attention.

Surface and near surface CO_2 monitoring is established by studying the time varying natural CO_2 concentrations and properties in the atmosphere and ground soil and water. Then, it is compared to the properties of CO_2 from the capturing source and reservoir oil. This will establish a baseline measurement of different CO_2 concentrations and properties (pre-injection phase), including isotopic signature. During the injection phase; surface soil and ground water is periodically monitored for any changes in the CO_2 properties and concentrations. The monitoring needs to take into account the diurnal, seasonal and annual variations in CO_2 emissions from natural sources such as vegetation and soil, and other climatic and terrain conditions.

The challenge in this method is the fact that for some projects, the properties of CO_2 are similar from all locations, which makes it difficult to distinguish the actual source of CO_2. A mitigating approach to distinguish the sources of measured CO_2 is to add tracers in the injected CO_2 to distinguish it from other natural CO_2 emitted by vegetation and soil.

On the other hand, the main advantage of surface and near surface approaches is that most of the technologies used are established and proven, they are relatively inexpensive, and they are usually easy to employ by the use of portable devices. Efforts therefore are exerted to monitor CO_2 concentrations in the atmosphere and in shallow groundwater in a time-lapsed mode throughout the project life, starting before the injection of CO_2 and continue after project abandonment. The following tests are normally used for surface and near surface CO_2 monitoring:

Ambient CO_2 Concentration (Surface). The measurement of CO_2 concentrations in the atmosphere is one monitoring technique to detect CO_2 leakage and seepage from the storage site to the atmosphere. It involves studying the time varying CO_2 concentration in the atmosphere within the vicinity of the injection site. The initial measurement involves determining a temporal baseline where the existing CO_2 concentration is recorded. The use of CO_2 detectors, which analyzes the changes of CO_2 isotopic properties as well as concentrations, is the main technique for CO_2 surface monitoring. Detectors can be stationary positioned at different locations at the surface, or portable devices mounted on different types of mobile vehicles (cars, farm animals, etc.).

Soil and Groundwater Monitoring (Near-surface). Near surface monitoring is important to preserve the quality of soil and shallow groundwater sources, and ensure no migration of injected CO_2 to nearby surface waters. Soil and vadose zone gas monitoring is based on collecting gas samples from soil and the vadose zone to quantify CO_2 concentration profiles near the surface and to assess the origin of the gas, i.e. biologic-respiration versus other sources. The approach requires samples from a grid and a baseline. Another technique to monitor the surface soil is based on flux measurements where closed chambers can be used to measure the soil flux in and out of the soil. The air in the chamber is circulated through simple infrared analyzers to check the rate of changing CO_2 concentrations (Klusman 2003).

Monitoring groundwater quality is usually done using geochemical techniques such as the isotopic analysis of the water before, during and after CO_2 injection (during all phases of the project). The main advantage of this approach is the simplicity of conducting tests, as most of the techniques to check the quality of groundwater are considered basic. The other technical advantage (over surface monitoring) is that CO_2 retention time in groundwater is longer than it is in the atmosphere, providing a longer window of opportunity to detect leaks. Some of the techniques to monitor near surface groundwater include studying the properties of the water such as conductance, alkalinity and pH levels. Trace elements and chemical tracers have also been used to determine fluid flow paths and origins, while partitioning techniques were used to identify residual gases. Other indicators include dissolved gases and stable isotopes. These approaches need water wells and natural sample points such as springs, as well as a baseline.

Soil sampling has been used at Weyburn to detect possible CO_2 migration from the reservoir to the surface (White et al, 2004) and SACROC has used groundwater monitoring (Smyth et al, 2012)[21].

4.4.2 Subsurface Monitoring

The purpose of subsurface monitoring is mainly to track the CO_2 plume and its propagation in the reservoir, indicate reservoir pressure profile, and test reservoir and seal integrity and well cement integrity. Subsurface monitoring is the most difficult, labor intensive, and expensive of the three. The following are the main parameters and technologies that need to be considered during CO_2-EOR for storage projects.

Laboratory and Simulation Studies. Prior to any CO_2-EOR project, meticulous laboratory tests are conducted to characterize the phase behavior between CO_2 and the reservoir oil. Examples of laboratory tests include: minimum miscibility pressure (MMP), PVT (pressure-volume-temperature) phase behavior, asphaltene precipitation, relative permeability measurements, and recovery potential (Jarrell et al. 2002; Mungan 1992; Stalkup 1992). The data and results from the laboratory are then used to tune a compositional reservoir simulator and conduct performance predictions, sensitivity analysis and field optimizations. These studies are very important during the pre-injection phase to establish baseline predictions of CO_2 behavior in the reservoir and oil production. The models are updated regularly during the injection phase and laboratory studies are used to explain certain phenomena during the injection period. The updated models are then used to forecast the behavior of stored CO_2 for the post-injection phase.

Rate Monitoring. CO_2 "accounting" is a very important element in CO_2-EOR for storage operations because not all injected CO_2 remains underground; rather some of it (~40%, Hadlow,

[21] http://www.permianbasinccs.org/conferences/forum_040412.htm

1992) is produced with the oil at surface. Therefore, all wells should be monitored for injection and production rates which will provide accurate data on how much CO_2 has been injected and how much has been produced and recirculated, and eventually stored. In many jurisdictions rate monitoring and reporting of fluids injected and produced is required by oil and gas regulatory agencies. Multiphase flow meters (MPFM) are common equipment used to measure the rates and provide reliable data on production and injection profiles. Trap testing is also used to measure rates but with less accuracy as the wells are not continuously monitored for rates as in the MPFM. The main advantage of the MPFM is the continuous testing without the requirements to shut-in wells or switching to testing lines. This provides sufficient data to determine anomalies such as production or injection decline.

Reservoir Pressure Monitoring. Monitoring pressure throughout the project life span is an essential tool for inferring injection volume, reservoir compatibility with CO_2, and safe storage of CO_2. Monitoring pressure can be done using wellhead and downhole pressure gages or a permanent downhole monitoring system (PDHMS). Other important pressure measurement points include surface casing pressure and annulus pressure, to ensure no leaks are occurring in the casing, tubing and/or well packers (this is covered in the well integrity monitoring). Reservoir pressures are monitored prior to injection to determine the MMP with CO_2 and injection capacity. Monitoring continues during the injection phase to check for injection decline and/or loss of CO_2 underground.

Seal (Caprock) Integrity. Oil reservoirs are trapped under a geological seal known as 'cap-rock' which held the oil in place for tens of thousands to millions of years. The competence of this seal is extremely important to hold the hydrocarbons from migrating to other geological traps, more importantly so when a pressure-depleted oil reservoir is chosen for CO_2-EOR and storage. This seal will be the main mechanism to store the injected CO_2 for geological times. Therefore, geomechanical models are usually built to investigate the integrity of this seal and the likelihood of CO_2 leaks prior to injection. The main objectives of geomechanical studies are to provide a quantitative understanding and risk assessment for cap-rock integrity, natural fracture stability, and induced fracture/wellbore stability for the planned CO_2 injection project. The model usually contains both static and dynamic properties relating to seal geomechanics, including in-situ stresses, rock strengths and elastic properties. The baseline risk assessment data should provide the initial answer whether or not the reservoir is suitable for CO_2 storage. The model is then continuously updated with new field data as the project progresses, including reservoir simulation predictions of temperature and pressure variations in the reservoir, particularly considering that CO_2 is injected at a lower temperature and higher pressure than reservoir temperature and pressure, respectively.. During the implementation phase of the project, be it for CO_2-EOR, for CO_2 storage or for monitoring, wells are drilled through this seal (caprock) to reach the intended reservoir. The cement integrity of these wells is an important parameter to monitor during CO_2 storage as well.

Routine Logging and Coring. The routine logging and coring is a common practice in the oil and gas industry to monitor wells for production and injection, changes in fluid saturations, and fluid movement in the reservoir. It is considered nowadays the simplest geophysical measurement to obtain petrophysical information from reservoirs. An array of available logs is usually used for fluid saturation monitoring and lithology assessment, which can also be compared to data obtained from core analysis. This practice is extended to cover the basis for any CO_2-EOR project, especially if the intent is CO_2 storage. The shortcoming of this method is the depth of investigation, which is limited in most cases to a few inches (cm) near the wellbore and it will not read deeper in the reservoir. To overcome this shortcoming, interpolation between wells is usually carried out. Another option is to use geophysical techniques but that will incur relatively significant costs. Table 5 summarizes the available logs, type of completion, and purpose (Bassiouni 1994):

Table 5: Common well logs used for monitoring in CO_2-EOR operations.

Type	Completion*	Purpose
Resistivity	OH	Fluids saturation
Density	OH	Lithology/ and fluid type
Neutron	OH	Lithology/porosity
Image Log	OH	Rock properties and presence of fractures
ADT	OH	Fluid saturation
NMR	OH	Pore system/ porosity, permeability, and free and bound fluids.
MDT	OH	Formation pressure testing and sampling to identify fluid contacts (GOC & OWC)
ECS	OH	More details on lithology in term of elements and minerals
CBL/USIT	CH	Casing cement condition and communication between zones
Sonic	OH	Porosity, fractures and shear & wave stress for rock properties and geomechanics
CO sigma	OH/CH	Reservoir fluid saturation changes
MPFM	OH/CH	Downhole and surface production for horizontal wells (pressure, temperature, rates for gas/oil/water) by zones

*OH means open hole well; CH means cased well.

Logging is usually done during drilling to take advantage of the open-hole condition of the well to run certain types of logs. However, wells may be left with open-hole completions for the life of the well. When the well is cased, there are other types of logs that can be run to collect data, albeit with limited number. Well logs data are essential to determine fluid saturations throughout the project life. During the pre-injection phase, baseline saturation measurements are collected to indicate the current condition of the reservoir. These data are then compared to saturation measurements from core analyses (e.g. sponge core saturating data). Saturation data are then fed to the reservoir simulator to construct the model and forecast performance. During the injection phase, time-lapse well log measurements are collected to monitor the changes in fluid saturations and movements. When the wells are abandoned during the post injection phase, measurements are taken from the observation wells to monitor any changes in fluid saturations while CO_2 is stored.

Well Integrity. Well integrity usually covers the practice of using CO_2-competent wells and maintaining them throughout the life of the project. Well integrity monitoring should cover the three phases of the project life: pre-injection (baseline monitoring), during injection, and post-injection (abandonment and abandoned). Pre-injection monitoring establishes a baseline measurement on cement quality, casing evaluation, and zonal isolation. During the injection period, monitoring should follow the baseline measurements for meaningful comparison, with the emphasis on areas of pressure increases (front of the plume) because of the higher risk they carry. Annuli surveys are also recommended to monitor the well's pressure and temperature during this phase. During the post-injection phase when the wells are abandoned, observation wells are used for deep monitoring, while surface monitoring can provide a second measure (Hitchon 2012).

For well integrity, cementing is usually the main concern for CO_2 leaks to surface (*provided that the wells metallurgy is CO_2 compatible*) because drilling the wells through the competent seal may introduce a man-made pathway to surface. Potential sources of CO_2 leaks to surface through cement are illustrated in Figure 7. Cement Bond Log (CBL) is a common tool to monitor the integrity of cement in wells.

From Figure 8 it can be seen that the potential places where CO_2 could leak are at the contact between the cement and another surface or through the cement itself. For example, paths 'a' and 'b' show the potential of CO_2 leaking between the cement and casing. Path 'c' shows the potential of CO_2 leaking through the cement while path 'f' shows the potential of CO_2 leaking between the cement and the surrounding rock. Other possibilities around the well, not related to cement, are CO_2 leaking through the casing (path 'd') and through fractures (path 'e').

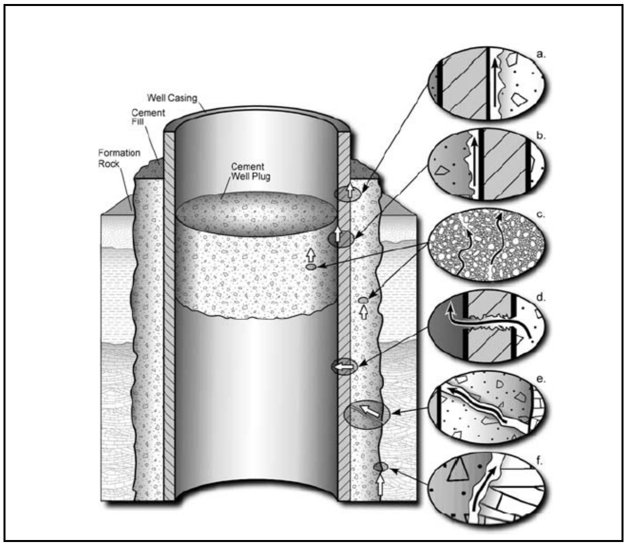

Figure 8: Potential CO_2 leakage due to cement jobs (from Gasda et al., 2004)

Fluid Movement (Single and Inter-well Chemical and Gas Tracers). The main purpose of chemical tracers is to monitor fluid saturations. In the case of single well chemical tracers, the target is to identify the fluid saturations around the well deeper in the reservoir (~20 ft, or ~7 m). Single well chemical tracers are meant to provide saturation measurement a little deeper than the radius of investigation provided by well logs (~12 in, or ~30 cm). Inter-well chemical tracers provide saturation measurement between the wells as well as fluid flow direction. Chemicals are mixed with injection fluid and pumped in the injectors. Then, fluid samples are collected from producing wells and analyzed to infer fluid saturation and preferential flow pathways in the case of multi-well projects. Gas soluble chemicals can also be mixed with CO_2 (gas tracers) and injected in the target formation and collected from producing wells to track the movement of CO_2 deep in the reservoir. The use of chemical tracers is an established technology but it gained more attention lately with the rise in monitoring techniques. This technology is usually used as a complimentary measurement to well logs to verify the results. Single well chemical tracers are usually used during the pre-injection phase to determine the current saturation in the reservoir and quantify changes in saturation caused by CO_2. On the other hand, inter-well chemical tracers are used during the injection phase to track the movement of CO_2 (plume) and changes in fluid saturations. This method is not applicable during the post-injection phase.

Geophysical Monitoring. Seismic monitoring is widely used in oil and gas exploration. In the case of CO_2 storage operations, including CO_2-EOR converting to CO_2 storage, three dimensional seismic surveys (3D) repeated at regular intervals, beginning before injection starts, will allow observation of changes in the reservoir and migration of the CO_2. The technique is known as 4D or time-lapse seismic surveying. Time-lapse seismic monitoring assesses the whole reservoir volume (and beyond if needed) and allows confident identification of the CO_2-front. However, thin plumes may be missed and the response is not linear with CO_2 concentration. There may also be limited environmental impacts from installing the geophones and from the explosions. Seismic surveys may be supplemented by other seismic approaches, e.g. cross-well seismic and vertical seismic profiles (VSP).

Micro-seismic monitoring is a passive seismic survey with origin in seismology. An array of downhole receivers detect microseismic activity triggered by shear slippage. Passive seismic can be used to monitor the formations above the reservoir for detection of CO_2 that migrates through the cap-rock, but this is dependent on systems that produce acoustic signals.

Cross-well tomography can be based on both electromagnetic induction and electrical resistivity. The electromagnetic version uses vertical and horizontal magnetic field detectors in an array of wells whereas the electrical resistivity version uses an array of electrodes. The electrical resistivity method is very challenging for waterflooding because of the mixed water salinity.

Figure 9 presents field operations and associated monitoring, verification and accounting operations in a CO_2-EOR operation with CO_2 storage (Hill et al., 2013). Table 4 gives somewhat more information on the readiness level of monitoring and surveillance technologies. More detailed descriptions about monitoring technologies and their readiness for deployment can be found in, e.g., NETL (2009, 2012).

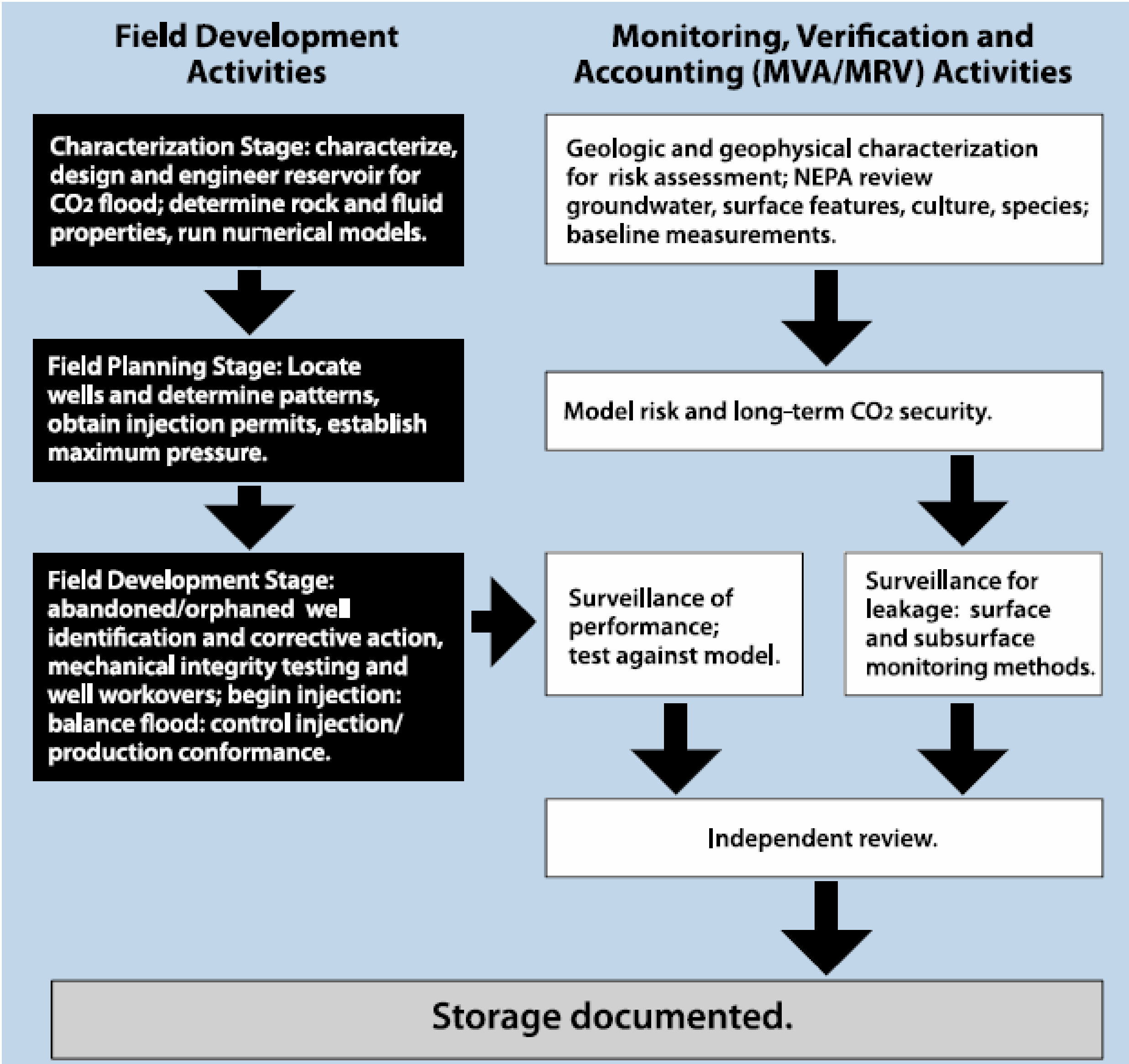

Figure 9: Suggested characterization and monitoring in a CO_2-EOR operation with CO_2 storage (from Hill et al., 2013).

5. SUMMARY AND CONCLUSIONS

The 40 years of experience and the current number of CO_2-EOR operations currently active in the world indicate that there is sufficient operational and regulatory experience for this technology to be considered as being mature. Carbon dioxide is inherently stored in CO_2-EOR operations, with a retention rate of the purchased (new) CO_2 greater than 90-95% (40-50% of the total injected CO_2) is retained in the reservoir, with the balance being produced at producing wells, separated from oil and recycled/re-injected). The CO_2 losses are due mainly to fugitive emissions in surface facilities (although operators try to minimize these due to economic and environmental reasons), and do not originate from the CO_2 injected and lost from within the reservoir. Notwithstanding the fact that almost all of the purchased CO_2 is retained (stored) in the reservoir, the objective of the operators is to maximize oil production and minimize CO_2 purchase (hence utilizing produced CO_2 to increase incremental oil production).

Application of CO_2-EOR for CO_2 storage has a number of advantages and a few disadvantages. The advantages are:

1) It enables CCS technology improvement and cost reduction;
2) It improves the business case for CCS demonstration and early movers;
3) It supports the development of CO_2 transportation networks;
4) It may provide significant CO_2 storage capacity in the short-to-medium-term, particularly if residual oil zones (ROZ) are produced
5) It builds and sustains a skilled CCS workforce; and
6) It helps gaining public and policy-makers acceptance.

The disadvantages are:

1) It is geographically limited to oil-producing regions and is capacity limited in the long term;
2) Revenue from CO_2-EOR operations alone cannot bridge the current gap from the class of power plants with high CO_2 capture costs; and
3) There are gaps in permitting between CO_2-EOR and CCS operations.

All the CO_2-EOR operations to date are onshore, and implementation of CO_2-EOR with ensuing CO_2 storage offshore will pose similar or more difficult technical challenges. Possible regions for offshore CO_2-EOR operations with or without CO_2 storage are in the North Sea, for which several studies have been carried out (e.g., Akervoll and Bergmo, 2010; Mathiassen, 2003; Pershad et al, 2012), in the Gulf of Mexico and offshore Brazil. Specific technical challenges for offshore operations are the small space and weight margins of the platforms, the costs associated with close-down in connection with modifications of the existing platforms, the lack of sufficient amounts of CO_2 and CO_2 transportation, likely by ship for significant distances, with associated compression and decompression facilities onshore and on the platform (NPD, 2005). The costs of abandonment are also likely to be higher offshore than onshore. In addition, if oil reservoirs have already high recovery factors, like in the North Sea, then application of CO_2-EOR may not be profitable enough to justify the associated costs.

The current number of CO_2-EOR operations in the world is negligible compared with the number of oil pools in the world, and the main reason why CO_2-EOR is not applied on larger scale is the unavailability of high-purity CO_2 in the amounts and at the cost needed for this technology to be deployed on a large scale. The potential for CO_2 storage and incremental oil recovery through CO_2-EOR is significant, particularly if residual oil zones (ROZ) and hybrid CO_2-EOR/CCS operations are considered. Again, the main impediment in the adoption of this technology is the unavailability of CO_2 at economic prices, and also the absence of infrastructure to capture and transport CO_2 from CO_2 sources to oil fields suitable for CO_2-EOR.

5.1 COMMONALITIES BETWEEN CO_2-EOR AND PURE CO_2 STORAGE OPERATIONS

There are a number of commonalities between CO_2-EOR and pure CO_2 storage operations, both at the operational and regulatory levels. These are:

1. In both cases CO_2 needs to be brought to the oil field (infrastructure), currently through pipelines, but in the future possibly by ship especially for offshore oil reservoirs at distances that make pipelines uneconomic.
2. Injection of CO_2 through wells that need to have casing, tubing and all other accessories made of or lined with materials resistant to the effects of CO_2, particularly if it contains impurities or water. Also, cementing of these wells usually has to be circulated to the surface or at least to surface casing, if possible (but not necessarily) using cements resistant to CO_2.
3. Wellhead operational monitoring at injection wells is basically the same: pressure, temperature, flow rate and stream composition (in CO_2-EOR operations production wells are monitored as well at the wellhead).
4. Assuming the CO_2 purity specifications are comparable, in the subsurface (reservoir) the geochemical and geomechanical effects of injecting CO_2 into an oil reservoir are similar, regardless if CO_2 is injected for CO_2-EOR or for storage.
5. In both cases regulations require hydraulic isolation of the production or storage horizon in order to protect other resources, including energy and mineral resources, and underground sources of drinking water.
6. In both cases CO_2 is economically valuable and operators try to minimize losses. To oil companies CO_2 is valuable because of the cost of CO_2, while for CO_2 storage operators CO_2 losses have to be avoided in order to obtain and retain credits.

These commonalities create a good basis for transitioning from CO_2-EOR to CO_2 storage in oil fields. However, currently there are a significant number of differences between the two types of operations.

5.2 DIFFERENCES BETWEEN PURE CO_2-EOR AND PURE CO_2 STORAGE OPERATIONS

The differences between pure CO_2-EOR and pure CO_2 storage operations can be grouped in seven broad categories:

- Operational, including CO_2 quality;
- Objectives and economics;
- Supply and demand;
- Legal and regulatory;
- Assurance of well integrity;
- Long term CO_2 monitoring requirements; and
- Industry's experience.

Operational. This refers to the quality (purity) of CO_2 and reservoir/aquifer pressure. In regard to CO_2 quality (purity), CO_2-EOR operations require high purity CO_2, with absence of impurities that negatively affect the minimum miscibility pressure and the safety of the operation (e.g., N_2, NO_x, O_2 and water, which are found in flue gases from power plants). On the other hand, some impurities, like H_2S, may be beneficial to CO_2-EOR operations in that their presence lowers the minimum miscibility pressure, as is the case in the Zama oil field in northwestern Alberta in Canada, where an acid gas comprising 70% CO_2 and 30% H_2S is used for enhanced oil recovery, but their presence may pose other challenges, particularly in the case of such a highly-toxic gas as H_2S. In pure CO_2 storage operations, various impurities may be present in quantities determined by the economics and safety of the storage operation (e.g., the cost of removing them during capture versus the cost of them being part of the stored stream, with corresponding consequences for compression, transportation and storage).

In regard to pressure, pure CO_2 storage operations in deep saline aquifers start from the initial aquifer pressure and the bottomhole maximum injection pressure (BHIP) increases up to the maximum pressure allowed by the regulatory agency in the respective jurisdiction (e.g., in Alberta , Canada, the maximum BHIP allowed is 90% of the rock fracturing threshold). Pure CO_2 storage operations in depleted oil and gas reservoirs start from the reservoir pressure at abandonment (if the reservoir has no aquifer support) or from a value between the pressure at abandonment and the initial pressure (if the reservoir has aquifer support), and may not be allowed by the regulatory agency to increase above the initial reservoir pressure because of concerns relating to caprock integrity. In the case of a CO_2-EOR operation transitioning to CO_2 storage, particularly after a waterflood, the reservoir pressure is most likely close to the initial reservoir pressure.

Objectives and Economics. The economic objective of CO_2-EOR operations is to produce additional oil from the reservoir to meet energy demand, and realize a profit for shareholders or revenue for governments in the case of national oil companies. It does, however, lead to on-going “incidental” storage of CO_2, but maximizing oil production is the main technical objective of CO_2-EOR operations. When a CO_2-EOR operation becomes uneconomic it is abandoned, unless incentives are created/provided to continue injecting CO_2, taking advantage of the infrastructure that is already in place. In contrast, pure CO_2 storage has no economic objective (if incentives are not put in place by governments), but rather it is a climate change mitigation strategy, and as such it represents a cost that has to be borne by shareholders, consumers and/or governments. From a technical point of view, the objective is to maximize CO_2 storage beyond the economic life of an oil reservoir. Notwithstanding the incidental storage occurring during pure CO_2 EOR, the different technical objectives of the two operations can translate into different operational strategies, including well patterns, injection rates and strategies, maximum reservoir pressure, and sweeping strategies.

Supply and Demand. Currently demand for CO_2 outstrips the existing supply. There are/may be situations where CO_2 supply from a single CO_2 source satisfies the needs of a CO_2-EOR operation (e.g., Weyburn-Midale in Canada), but for giant oil fields there will need for CO_2 from multiple sources, with the associated infrastructure in place. In CO_2 storage operations, particularly in deep saline aquifers, currently simple source-sink matching satisfies the storage needs (e.g., Sleipner in Norway, Gorgon in Australia and Quest in Canada).

Legal and Regulatory. Although these differences do not constitute *per se* technical challenges in the transition from CO_2-EOR to CO_2 storage, they are mentioned here because they affect or may affect the technical aspects of the operations. In most if not all jurisdictions, rights to an oil reservoir for oil production, including CO_2-EOR, can be acquired under existing tenure legislation based on mineral or petroleum and natural gas (PNG) rights, while for-purpose CO_2 storage requires specific storage rights that are under development. Furthermore, in some jurisdictions, like the United States, the mineral rights belong to the surface land owner, while in other jurisdictions they belong to the state. In other jurisdictions (e.g., Canada) the mineral rights belong to either the state (Crown) regardless of the surface land owner, or to a specific land owner who was granted in the past also the mineral rights for special reasons and under special circumstances. In addition, there is a difference between ownership of onshore and offshore reservoirs in jurisdictions where land owners or other entities own the mineral rights on land. In such cases the state (or Crown) owns the offshore mineral rights.

In CO_2-EOR operations, the operator obtains producing rights from the owner to the respective oil reservoir. The operator is also allowed to inject (and incidentally store) substances to fit that end. In CO_2 storage operations, the operator needs to operate within the Area of Review, or Area of Influence, as defined by the regulatory agency in the respective jurisdiction. In some cases the Area of Review may extend beyond the area of the oil reservoir leased by the operator into lands owned or leased by a different entity. In this case, operating (e.g., for ongoing or post EOR monitoring) on the surface or in the subsurface, on land owned or leased by another entity may pose operational and legal challenges.

In oil producing countries, regulations are in place at the national or subnational level (state or province), for oil production and field and well abandonment. The regulatory framework for CO_2 storage is being developed and evolving in some countries, and is totally absent in others, but where it is being developed it is different from the regulatory framework for CO_2-EOR. Furthermore, in federal countries with subnational jurisdictions, different regulations may be developed at the national and subnational levels, with the operator having to meet both.

Finally, liability in the case of CO_2-EOR operations is well defined, while the long-term liability for CO_2 storage operations is only being developed and is still evolving only in some jurisdictions. For example, some states in the United States (e.g., Wyoming) have stated that they will not assume the long term liability of CO_2 storage operations, while the Province of Alberta in Canada and the State of North Dakota in the United States have both passed legislation by which they will assume the long-term liability of CO_2 storage operations, although the conditions under which the transfer of liability will take place have not been defined yet. The issue of long-term liability affects operational strategies in the case of CO_2 storage.

The issue of long-term liability is a country-by-country, and/or state/province by state/province issue and it will mature as the industry evolves.

Assurance of Well Integrity. While injection, production, suspended and abandoned wells have to be tested (mechanical integrity testing) and ultimately repaired in both CO_2-EOR and CCS operations, depending on jurisdiction there might be some differences stemming from the definition of the Area of Review and from the regulatory framework in place. In CO_2-EOR operations, wells within the operator's lease must be and are being checked regularly by the operator, and, if leaks are detected and the well has to be fixed immediately or fixing it may be delayed until abandonment, depending on the severity of the leak and on the regulatory requirements in the respective jurisdiction (state/provincial or national). In CO_2 storage operations, at least based on current regulations where storage rules exist, leaky wells have to be fixed prior to the start of CO_2 injection, regardless of the severity of the leak. More importantly, the Area of Review within which wells have to be checked and possibly repaired may extend beyond the operator's lease, in which case checking the status of wells and fixing leaking wells on somebody else's lease may pose a legal and monetary challenge that has to be addressed. It is appropriate to note that some jurisdictions, such as Texas in the United States and Alberta in Canada, have wells drilled more than 100 years ago and have instituted "orphaned well funds" to assist in plugging of wells or remediating leaky wells that do not have

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an owner anymore. These funds and activities will apply on lands that might fall within an Area of Review but have no identified owner.

Monitoring. This is the area where the differences between pure CO_2-EOR and pure CO_2 storage operations may be the most obvious. Currently, CO_2-EOR operations do considerable surveillance to assure the injected CO_2 is at work within the reservoir, but for reasons of economics. Regulatory rules to monitor wellhead injection parameters, such as pressure, temperature, rate and composition, and produced fluids are generally required and reported on a periodic basis. . Depending on jurisdiction, these have to be reported to the state/provincial or national regulatory agency (e.g., in Alberta, Canada). Generally monitoring ceases when the reservoir and wells are abandoned (abandoned wells may be still monitored for leakage). In the case of pure CO_2 storage, the monitoring and reporting requirements may be more extensive, both in terms of what and in terms of frequency and duration, than in the case of CO_2-EOR or gas storage operations. More specifically:

a. Assurance monitoring (where and how much CO_2 is in the storage reservoir);
b. Requirement for more environmental monitoring that may include sensors in, or sampling from, the sedimentary succession above the reservoir, shallow potable-groundwater aquifers, soils and surface within the Area of Review;
c. Baseline monitoring prior to start of CO_2 injection.
d. Monitoring after cessation of CO_2 injection for various periods of time, depending on regulations in the respective jurisdiction, such as:
    i. until stabilization of the CO_2 plume;
    ii. for a fixed period of time (e.g., 5, 10 or 15 years); and/or
    iii. until transfer of liability to a designated governmental agency.
e. Requirement for reporting of CO_2 stored, and of any CO_2 that has migrated out of the storage unit in case of CO_2 movement off lease, or any leakage to the overlying sedimentary succession, including other reservoirs and shallow potable-groundwater (surface leaks currently are required to be reported in the case of both CO_2-EOR and CO_2 storage).

While all these activities are feasible with current technologies and with technologies under development, and while all these requirements can be met by operators where conditions exist, these activities increase significantly the costs and liabilities incurred by the operator in the case of CO_2 storage compared with the case of pure CO_2-EOR and ongoing gas storage operations.

Industry's Experience. While the oil industry has a long and well established experience with Co_2-EOR operations, there is insufficient experience with CO_2 storage operations, particularly in oil reservoirs.

5.3 CONCLUSION AND RECOMMENDATIONS

The analysis presented thus far indicates that there are no specific technological barriers or challenges *per se* in transitioning and converting a pure CO_2-EOR operation into a CO_2 storage operation. The main differences between the two types of operations stem from legal, regulatory and economic differences between the two. While the legal and regulatory framework for CO_2-EOR, where it is practiced, it is well established, the legal and regulatory framework for CO_2 storage is being refined and is still evolving. Nevertheless, it is clear that CO_2 storage operations will likely require more monitoring and reporting 1) of a wider range of parameters, 2) outside the oil reservoir itself, and 3) on a wider area, and for a longer period of time than oil production. Because of this, pure CO_2 storage will impose additional costs on the operator. In addition, the integrity of all the wells penetrating the oil reservoir and host formation in the Area of Review will have to be checked and assured. A challenge for CO_2-EOR operations which may, in the future, convert to CO_2 storage operations is the lack of baseline data for monitoring, besides wellhead and production monitoring, for which there is a wealth of data. The absence of infrastructure for the capture and transportation of CO_2 to oil fields and the high cost of CO_2 are also a challenge.

In order to facilitate the transition of a pure CO_2-EOR operation to CO_2 storage, operators and policy makers have to address a series of legal, regulatory and economic issues in the absence of which this transition can not take place. These should include:

1) Clarification of the policy and regulatory framework for CO_2 storage in oil reservoirs, including incidental and transitioned storage CO_2-EOR operations. This framework should take into account the significant differences between CO_2 storage in deep saline aquifers, which has been the focus of regulatory efforts to date, and CO_2 storage in oil and gas reservoirs, with particular attention to the special case of CO_2-EOR operations.
2) Clarification if CO_2-EOR operations transitioning to CO_2 storage operations should be tenured and permitted under mineral/oil & gas legislation or under CO_2 storage legislation.
3) Clarification of any long-term liability for CO_2 storage in CO_2-EOR operations that have transitioned to CO_2 storage, notwithstanding the CO_2 incidentally stored during the previous pure CO_2-EOR phase.
4) Clarification of the monitoring and well status requirements for oil and gas reservoirs, particularly for CO_2-EOR, including baseline conditions for CO_2 storage. Attention should be given to the fact that, unlike a deep saline aquifer, an oil or gas reservoir that has been under production is no longer at initial conditions and the baseline for CO_2 storage is most likely (surely) different. For future CO_2-EOR operations the baseline data can be obtained, but most likely they will be collected only if the operator considers transitioning to CO_2 storage.
5) Addressing the issue of jurisdictional responsibility for pure CO_2 storage in oil and gas reservoirs and if it is different from natural gas storage, both in regard to national-subnational jurisdiction in federal countries and to organizational jurisdiction (environment versus development ministries/departments).
6) Examination of the need to assist with the economics, particularly the cost of CO_2 and the infrastructure to bring anthropogenic CO_2 to oil fields.

In regard to CSLF, the Policy Group should take note of these issues and establish ways to address them within CSLF and make appropriate recommendations to the governments of its members.

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TECHNICAL GROUP

Final Phase II Report by the CSLF Task Force on CO_2 Utilization Options

Background

At the September 2011 CSLF Ministerial Meeting in Beijing, a Task Force was formed to investigate CO_2 Utilization Options. The Task Force mandate was to identify/study the most economically promising CO_2 utilization options that have the potential to yield a meaningful, net reduction of CO_2 emissions, or facilitate the development and/or deployment of other CCS technologies. A Phase I Report was completed in October 2012. This document is a Phase II Final Report from the Task Force and concludes the Task Force's activities.

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Report Prepared for the CSLF Technical Group

By the CSLF Task Force on Utilization Options of CO_2

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EXECUTIVE SUMMARY

This document follows the Phase 1 Summary Report, CO_2 Utilization Options and provides a more thorough discussion of the most attractive CO_2 utilization options based upon economic promise and CO_2 reduction potential. This report looks at the current and future economic viability, potential for co-production, and Research, Development and Demonstration (RD&D) needs of these options. The CO_2 Utilization Task Force members selected the following options for further investigation: enhanced gas recovery (CO_2-EGR), shale gas recovery, shale oil recovery, urea production, algal routes to fuels, utilization in greenhouses, aggregate and secondary construction material production, and CO_2-assisted geothermal systems. This work did not include Enhanced Oil Recovery, which is addressed by a separate CSLF Task Force.

As identified in the Phase I report, market potential for many of the utilization options is limited (i.e., small, and/or 'niche'), with some exceptions (e.g., enhanced oil recovery - not a subject of this report - or the conversion of CO_2 to fuels or chemicals). However, when taken cumulatively, the sum of these options can provide a number of technological mechanisms to utilize CO_2 in a manner that has potential to provide economic benefits for fossil fuel fired power plants or industrial processes. As such, they may well be a means of supporting the early deployment of carbon capture and storage (CCS) in certain circumstances and accelerating deployment.

One of the key observations from this report is that the potential uses of CO_2 are broad. CO_2 has the potential to be used in the extraction of other energy resources, as a working fluid, and as a chemical feedstock. These applications have different levels market potential, and technological maturity. Some applications, such as urea production, already have an existing global market, while other, less-mature options, such as fuels from algae have the potential for significant markets and require additional RD&D to address technical challenges and to validate the utilization of CO_2 as an option, by reducing the cost and improvements in efficiency.

There are a wide range of CO_2 utilization options available, which can serve as additional mechanisms for deployment and commercialization of CCS by providing an economic return for the capture and utilization of CO_2. The results offer several recommendations that can assist with the continued development and deployment of non-EOR CO_2 utilization options in this context.

1. For technologies which are commercially and technologically mature, such as urea production and utilization in greenhouses, efforts should be on demonstration projects. For urea production, the focus should be on the use of non-traditional feedstocks (such as coal) or 'polygeneration' concepts (e.g., those based on integrated gasification combined cycle (IGCC) concepts) which can help facilitate CCS deployment by diversifying the product mix and providing a mechanism for return on investment. For utilization in greenhouses, new and integrated concepts that can couple surplus and demand for CO_2 as well as energy, thus optimizing the whole energy and economic system would be valuable.

2. Efforts that are focused on hydrocarbon recovery, such as CO_2 for enhanced gas recovery (via methane displacement), or CO_2 utilization as a fracturing fluid, should focus on field tests to validate existing technologies and capabilities, and to understand the dynamics of CO_2 interactions in the reservoir. R&D efforts on CO_2 as a fracturing fluid should focus on the development of viscosity enhancers that can improve efficiency and optimize the process. Issues such as wellbore construction, monitoring and simulations should leverage those tools and technologies that currently exist in industry or are under development through existing CCS R&D efforts.

3. For algal routes to fuels and aggregate/secondary construction materials production, the primary focus should be on R&D activities that address the key techno-economic challenges previously identified for these particular utilization options. Independent tests to verify the performance of these products compared to technical requirements and standards should be conducted. Support of small, pilot-scale tests of first generation technologies and designs could help provide initial data on engineering and process challenges of these options.

4. For CO_2-assisted geothermal systems, more R&D and studies are necessary to address the subsurface impacts of utilizing CO_2 in this application. Additionally, small pilot-scale tests could provide some initial data on actual operational impacts and key engineering challenges that need to be addressed.

5. Finally, more detailed technical, economic, and environmental analyses should be conducted to better quantify the potential impacts and economic potential of these technologies and to clarify how R&D could potentially expand the market for these utilization options (e.g., in enhanced gas recovery) and improve the economic and environmental performance of the system. A holistic approach, incorporating several distinct perspectives, is important.

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1. INTRODUCTION

1.1 CSLF PURPOSE

The Carbon Sequestration Leadership Forum (CSLF) is a Ministerial-level international climate change initiative that is focused on the development of improved cost-effective technologies for the separation and capture of carbon dioxide (CO_2) for its transport and long-term safe storage. The mission of the CSLF is to facilitate the development and deployment of such technologies via collaborative efforts that address key technical, economic, and environmental obstacles. The CSLF will also promote awareness and champion legal, regulatory, financial, and institutional environments conducive to such technologies.

The CSLF comprises a Policy Group and a Technical Group. The Policy Group governs the overall framework and policies of the CSLF, and focuses mainly on policy, legal, regulatory, financial, economic and capacity building issues. The Technical Group reports to the Policy Group and focuses on technical issues related to CCUS and CCUS projects in member countries.

The Technical Group has the mandate to identify key technical, economic, environmental and other issues related to the achievement of improved technological capacity, and establish and regularly assess and inventory of the potential areas in need of research.

At the CSLF Ministerial meeting held in Beijing, P.R. China in September 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.

1.2 TASK FORCE MANDATE, SCOPE, AND OBJECTIVES OF THE REPORT

At the same meeting in Beijing in 2011, the CO_2 Utilization Options Task Force was created. The CSLF Technical Group Five-Year Action Plan (2011-2016) included Action Plan #12: CO_2 Utilization Options. At the Joint Policy/Technical Meeting, the Five-Year Action Plan was approved, and the formation of a task force to implement Action Plan 12 was proposed. This formalized the CO_2 Utilization Options Task Force. The purpose of the CO_2 Utilization Options Task Force is to identify/study the most economically promising CO_2 utilization options that have the potential to yield a meaningful, net reduction of CO_2 emissions, or facilitate the development and/or deployment of other CCS technologies.

The United States offered to chair or co-chair the new group. After the Beijing meeting, the United States drafted a planning document that contained a draft charter, which was distributed to all delegates on December 8, 2011 by the CSLF Secretariat, along with an invitation to join the task force. The first meeting of the Task Force occurred June, 2012 in Bergen, Norway.

A Phase 1 effort was completed which generated a report that summarized existing information regarding CO_2 utilization options and discussed the state of each relevant technology and application. This report also provided insight into the relative value of the utilization option, impact on CO_2 emissions and economic viability of the technology.

The objective of this Phase 2 report is to provide a more thorough discussion of the most attractive CO_2 utilization options based upon economic promise and CO_2 reduction potential. This report will look at the current and future economic viability, potential for co-production, and RD&D needs.

1.3 HISTORY OF CO_2 UTILIZATION, INCLUDING PAST AND CURRENT CCUS PROJECTS

CO_2 has been historically used in various medium-scale applications. Apart from its major use in enhanced oil recovery, CO_2 has been used industrially for a variety of applications, including synthesis of chemicals (urea, polyurethanes), refrigeration systems, solvent extraction, inert agent for food packaging, beverages, welding systems, fire extinguishers, horticulture, and many other small-scale applications (Metz et al., 2005)[1].

Urea was first produced from ammonia and cyanic acid in 1828. Urea was produced by the dehydration of ammonium carbamate in 1870[2]. The current industrial process for urea synthesis uses ammonia and CO_2 to produce ammonium carbamate which is dehydrated to form urea. Large scale production of urea from ammonia only occurred after the development of Haber-Bosch process for NH_3 synthesis in 1913. The Bosch-Meiser urea process using CO_2 and NH_3 as the precursors was developed by BASF in 1922[3] and is the primary process used by various urea plant developers (e.g., Snamprogetti, Stamicarbon, Toyo) today. Currently about 120 million metric tonnes (Mt) of CO_2 is used annually to produce urea (see Table 3). Most of this CO_2 is captured during the production of ammonia, which is mainly made from methane.

Apart from urea, CO_2 has also been used to as a feedstock for methanol synthesis, where it is fed with CO and H_2 to increase the product yield from methanol synthesis. There are several plants producing methanol from CO_2 using up to 8 Mt CO_2/y (Metz et al., 2005)[1].

[1] Metz, B. et al. eds., 2005. IPCC, 2005: IPCC special report on carbon dioxide capture and storage, Chapter 7. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, 442 pp and references therein.

[2] Mavrovic, I., Shirley, A. R., & Coleman, G. R. "Buck", 2000. Urea. In Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc. Available at http://onlinelibrary.wiley.com/doi/10.1002/0471238961.2118050113012218.a01.pub2/abstract

[3] Bosch, G., & Meiser, W., 1922. Process of Manufacturing Urea. U.S. Patent 1429483.

Liquid CO_2 is also used as an auxiliary blowing agent (ABA) in the production of flexible, low density, soft polyurethane foams used in furniture, bedding, flooring , and transportation. Polyurethanes are polymers formed by the reaction of isocyanates and polyols. CO_2 is used instead of chlorofluorocarbons and hazardous chemicals such as methylene chloride. The advantages of CO_2 over methylene chloride as an ABA are that it is less expensive, completely eliminates hazardous air pollutant emissions, and only requires 33 percent as much CO_2 as methylene chloride to produce the same amount of ABA-blown foam[4]. Proprietary technologies for the use of CO_2 in polyurethane foam production were developed in the 1990s by Cannon, Hennecke, and Beamech[5]. These involve pre-mixing the CO_2 with the polyol followed by mixing with other components under high pressure, and a controlled pressure let down during the lay down phase. Approximately 10 Mt CO_2/y is consumed in the production of polyurethanes[6]. However, most of the CO_2 is eventually re-emitted because ABAs vaporize and expand the foam, and are not consumed in the polyurethane-forming reactions.

CO_2 can be used as a solvent in various physical states, as a liquid, supercritical fluid, and a gas-expanded liquid. Supercritical CO_2 has been used as a green solvent in several applications. The decaffeination of unroasted (green) coffee beans with CO_2 was first reported in 1971[7]. Supercritical CO_2 is particularly attractive as a solvent and a reaction medium because it has relatively low critical pressure (73.8 bar) and critical temperature (31.1 °C), is non-toxic, non-flammable, relatively inert, and has a lower operating cost. The limitations of supercritical CO_2 are lower solubility and higher capital costs compared to liquid organic solvents. Supercritical CO_2 can also be used to induce crystallization, and produce fine powders using the rapid expansion of supercritical solution (RESS)[8]. Liquid CO_2 is used commercially in the dry cleaning industry, where it can be used instead of perchloroethylene (PERC), a ground water contaminant and a potential human health hazard. The use of liquid CO_2 requires the use of specialized surfactants which can dissolve all types of compounds on soiled fabrics. A combination of solid and gaseous CO_2 has been used as an environmentally friendly solution for precision cleaning to remove sub-micron particles and organic thin films from electronics surfaces. These processes were developed in the 1990s[9]. Gas-expanded liquids (GXLs) with CO_2 and an organic solvent were developed to overcome the high pressure limitations of supercritical CO_2 and co-solvents. A GXL is a mixture of pure gas and an organic solvent at pressure and temperature conditions below the critical point for the mixture. GXLs are more liquid-like compared to supercritical fluids, and operate at much

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[4] U.S. Environmental Protection Agency, 1996. Flexible polyurethane foam emission reduction technologies cost analysis, EPA-453/R-95-011. Available at: http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=2000HGDO.txt
[5] Singh, S.N., 2001. Blowing Agents for Polyurethane Foams, Report 142, Rapra Review Reports, v.12, number 10, 2001. ISSN: 0889-3144.
[6] Metz, B. et al. eds., 2005. IPCC, 2005. IPCC special report on carbon dioxide capture and storage, Chapter 7. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, 442pp.
[7] Zosel, Kurt, 1977. U.S. Patent 4247570, Process for the decaffeination of coffee.
[8] Mistry, Reena, 2008. Characterization and applications of CO_2-expanded solvents, Ph.D. Thesis, University of Leicester.
[9] Kosic, Thomas, Palser, Jeff, L., 1998. Carbon dioxide meets the challenge of precision cleaning, Solid State Technology, Available at: . http://www.electroiq.com/articles/sst/print/volume-41/issue-5/features/deposition/carbon-dioxide-meets-the-challenge-of-precision-cleaning.html

lower pressures. CO_2-GXLs offer alternative solvents to carry out industrial hydroformylations and epoxidations with easy product separation and high product selectivity[10].

The conversion of CO_2 to mineral carbonates has been investigated over the past decade (see for example, reference 11). For the most part, techno-economic studies noted that the conversion of minerals such as serpentine and olivine to magnesium and calcium carbonates and bicarbonates is technically feasible, but the costs of conversion are high[12]. Current research and development is focussed on using industrial caustic wastes such as bauxite waste (red mud) as a reactant to convert CO_2. Alcoa currently operates a red mud carbonation demonstration facility at their Kwinana Alumina refinery in Australia based on the carbonation of CO_2[13].

The conversion of CO_2 to fuels using sunlight and microalgae has also been investigated extensively as a part of U.S. DOE's Aquatic Species Program from 1978 to 1996[14]. High costs for algal fuel production were projected at that time. Current research and demonstrations projects are aimed at developing more productive, resistant algal strains, and developing novel algal processing technologies.

1.4 METRICS OVERVIEW

Comparison of the various applications for CO_2 recovery, and their relative costs and benefits helps to identify challenges and opportunities for the increased use of CO_2. An objective of this task was to develop a list of metrics to evaluate various beneficial use concepts. Performing a comparative or quantitative ranking of these options is a challenge. CO_2-use technologies in this document are at varying levels of readiness and not all of the processes can be ranked against all the criteria. That stated, the primary criteria for the relative comparison of various CO_2 applications include:

- Total amount of CO_2 permanently sequestered
- Unit value (benefit) or cost of application
- Energy consumed by the application, or net-energy saved by implementing this technology (net-CO_2 savings from the technology)

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[10] Subramaniam, B., Akien, G. R.,2012. Sustainable catalytic reaction engineering with gas-expanded liquids. Current Opinion in Chemical Engineering, v.1, no.3, p:336–341. doi:10.1016/j.coche.2012.02.005

[11] O'Connor et al., 2001. Carbon dioxide sequestration by direct mineral carbonation: process mineralogy of feed and products, SME Annual Meeting and Exhibit, Denver, CO, Feb 26-Mar 1, 2001. Available at: http://www.osti.gov/bridge/product.biblio.jsp?osti_id=897114 .

[12] O'Connor et al., 2004. Energy and economic considerations for ex-situ and aqueous mineral carbonation, Presented at the 29th International Technical Conference on Coal Utilization & Fuel Systems, April 18-22, 2004, Clearwater, Florida. Available at: http://www.osti.gov/bridge/servlets/purl/895352-R22ohy/ .

[13] Global CCS Institute, 2010. "Bauxite residue carbonation", in Accelerating the uptake of CCS: Industrial use of captured carbon dioxide. Available at: http://www.globalccsinstitute.com/publications/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide/online/28586 .

[14] Sheehan, J., Dunahay, T., Benemann, J. and Roessler, P.,1998. A Look Back at the U.S. Department of Energy's Aquatic Species Program – Biodiesel From Algae, Golden, CO, National Renewable Energy Institute, NREL/TP-580-24190, 328 pp.

- Market potential of primary CO_2 use and any by-products

The costs of CO_2 separation, compression, and delivery may be accounted in various ways, depending on the allocation of the CO_2 allowances/credits. In this Summary, the use of CO_2 is treated as a cost to the operator of the CO_2-use process and a benefit to the seller of the CO_2 offsets, possibly a CO_2 capture project developer. High-pressure, high-purity CO_2 is assumed to have a cost of $40/t (consistent with U.S. DOE/NETL analyses[15]). We do not directly account for the cost of purifying, cooling, and compressing the flue gas in applications where it is used without CO_2 separation (ex: Calera, Skyonic). The nominal benefit is estimated as the value derived from the use of CO_2 less the costs of raw material inputs to the process[16]. We note that this nominal benefit is a preliminary metric, and the actual benefits and costs may only be estimated by a full life cycle analysis, which is out of the scope of the current task.

Another metric of relevance to CO_2-use processes is the net-CO_2 mitigation, closely related to the amount of energy consumed in the process. Typical examples are the use of electrical, thermal, or chemical energy in applications which convert, compress, or use CO_2. The net-CO_2 used in the process, or mitigated per unit of process output (product) would therefore be the gross-amount of CO_2 used per unit of product, less the amount of CO_2 emitted during the process per unit of product. Because (fossil) energy use and CO_2 emissions are correlated, emissions from the CO_2-use process can also be deduced by energy consumption, energy required for capture and/or disposal, energy penalty or energy gain, and the energy use avoided.

A primary constraint on the adoption of certain technologies which use CO_2 is the dearth of pipeline-quality, low-cost CO_2 supply. In hydrocarbon resource recovery applications, the cost of CO_2 may be a major factor driving the economics. For example, data from the U.S. DOE/NETL analysis[15] indicate the cost of CO_2 to be 11 to 17% of the cost of the recovered crude oil. In other applications such as CO_2-ECBM and CO_2-EGR, the proportional cost of CO_2 may be even higher because natural gas trades at a lower unit energy cost ($/MMBTU) compared to crude oil. Such constraints would incentivize higher recycling and lower unit-utilization of CO_2. In applications where CO_2 is converted to a fuel such as gasoline or diesel using hydrogen, the cost of CO_2 is still a considerable percentage of the value of fuel, but is outweighed by the cost of hydrogen. Therefore, the cost and the availability of hydrogen derived from CO_2-free energy sources would determine the rate of adoption of technologies where hydrogen is used as a feedstock. A point to note is that market saturation may not be a significant factor affecting the development of first-of-a-kind applications such as the conversion of CO_2 to fuels, chemicals and raw materials.

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[15] DiPietro, P., et al., 2011. Improving Domestic Energy Security and Lowering CO_2 Emissions with "Next Generation" CO_2-Enhanced Oil Recovery (CO_2-EOR), DOE/NETL-2011/1504. Available at: http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=391

[16] The prices of hydrogen, and other chemical inputs are accounted for in the CO_2-to-fuels/chemicals application. The price of brine or seawater is not accounted for in Calera or Skyonic processes. It is expected that they would be considerably lower than the unit cost of CO_2 or the unit value of the product. Similarly, the alkaline earth metal silicate raw material inputs for the Calera and Novacem processes are also not assigned a price, and this may be refined in the future.

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Table 1 lists the metrics used to consider differences between the applications.

Table 1 - Metric Summary

CO_2 Mitigation	**Amount of CO_2 reduced (total : direct + indirect)**
	Amount of Captured CO_2 utilized (direct reduction)
	Amount of CO_2 consumed
	Is capture an intrinsic part of the process?
Benefits	**Cost of CO_2 reduction/ tonne (total system basis)**
	Cost of CO_2 capture and processing
	Value of by-products
Energy Consumption	**Energy penalty/ gain for total system (LCA)**
	Energy required for capture and disposal
	Energy penalty/ gain for byproduct process
	Energy use avoided (without chemical transformation of CO_2)
Market Potential	**Market size (potential tonnage removed from atmosphere)**
	CO_2 subjected to capture and storage
	CO_2 sold to commercial markets for consumption or resource recovery
	Market size of by-products
	(Nominal Benefit (Negative cost)) x Market size

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2. HYDROCARBON RESOURCE RECOVERY

2.1 CO_2 ENHANCED GAS RECOVERY

2.1.1 Introduction

The aim of CO_2-enhanced gas recovery (CO_2-EGR) is to mobilize large quantities of natural gas which cannot be recovered by conventional means of production. As a positive side effect, significant volumes of CO_2 can be stored. Under current legislation and carbon trading systems, emission credits can probably be claimed for the stored CO_2, provided additional measures, such as monitoring and verification, are taken. However, there is no experience yet with such a case and the economics are yet difficult to assess.

Gas reservoirs suitable for CO_2-EGR include both conventional gas reservoirs (siliciclastic and carbonate reservoirs) and shale-gas reservoirs, albeit that the mechanism for the natural gas recovery is different in both cases. Reservoirs containing high amounts of acid gases (CO_2, H_2S) may be particularly suitable candidates for injecting CO_2, because of the often already existing gas separation infrastructure.

Enhanced gas recovery (EGR) is not part of standard operations for gas fields, which, in general, have high recovery factors. In addition to concerns about degrading the quality of the produced gas, this has kept EGR from becoming widespread. The natural recovery factor in oil fields, by contrast, is generally low (typically only 10% during primary production), creating a much clearer potential for production enhancement methods. CO_2-EOR is a common technology, with the Texas oil fields and some early fields in Eastern Europe as prime examples.

Nevertheless, recent developments do show a market potential for EGR. One commercial project for EGR is currently in preparation in the Netherlands and a second one is being developed in the Middle East. Both projects do not use CO_2, but N_2. However these projects do demonstrate the potential for EGR in general. In this chapter more details about these two N_2-EGR projects are given, and differences with CO_2-EGR are highlighted.

For CO_2-EGR, the only known project, where an actual field test is being carried out, is the K12-B field offshore the Netherlands. Initial findings from this small CO_2-EGR pilot project, operational since 2005, are also highlighted.

This chapter does not consider shale gas, as this is treated in a separate chapter. Furthermore no special attention is given to tight reservoirs, where often hydraulic fracturing (fraccing) is required, again since fraccing is dealt with in a separate chapter. All fields considered here are supposed to have sufficient permeability to inject and produce gasses without additional measures like fraccing, even though some of these reservoirs do have quite low permeability.

2.1.2 Metrics

Feasibility of EGR

Injection of a working gas into a gas reservoir pressurizes the existing natural gas, thereby enhancing methane production[17]. EGR is economical in cases where a significant portion of the original gas in place is yet to be recovered, and where the gas reservoir has considerable vertical extent, allowing the working gas to be injected below the natural gas[17]. The economics of EGR will be strongly dependent on the size of the reservoir (1% of additionally recovered gas of a large volume will still represent a significant value).

Issues that play a role in determining whether a specific field is amenable to EGR include the following:

- *Properties of the gas field:* The geological properties of the field, such as size and geometry, determine the feasibility of EGR. The permeability of the reservoir and the required number locating injection well(s) are important parameters that drive the economics of the potential project.
- *Field characteristics:* EGR will have a lower priority for gas fields that have a strong water drive. Such fields are located in active aquifers, which provide pressure support. By contrast, for depletion driven fields, which do not have such pressure support, EGR is a potential end-of-field-life measure.
- *Re-use of wells:* The economics of an EGR project can benefit from re-using existing installations or wells. Converting existing production or appraisal wells to injectors of the working gas may reduce costs, if their location is favourable for EGR. This may of course still require a work-over of the well, for example changing the tubing to CO_2 resistant material.
- *Availability of a working gas (N_2 or CO_2)*: The location of the field relative to the locations where CO_2 or N_2 is produced is a relevant parameter. The economics of the project depend on the volumes required.
- *Composition of the original gas:* At some time during the EGR project, the working gas will reach the production well(s) and is produced along with natural gas. Depending on the specifications of the transport pipeline, a gas separation step is required. There may be an advantage for gas fields with an initially low concentration of the working gas, which may allow a higher percentage of working gas to be co-produced. On the other hand, gas separation units may already be in place to remove excess CO_2 or N_2 from the produced gas. In any case, breakthrough of CO_2 to natural gas producing wells would lead to an increase of the CO_2 content of the produced gas, increasing separation costs and eventually making reinjection economically unfeasible[18].
- *Need for monitoring:* The use of CO_2 as a working gas opens the opportunity to bring the project under the ETS [EU Emission trade system], if sufficient measures are taken to measure and monitor the injected volume. However, this

[17] Benson, S. et al., 2004. GEO-SEQ Best Practices Manual, Geologic Carbon Dioxide Sequestration: From Site Selection to Implementation, 9/30/2004: Lawrence Berkeley National Laboratory. Available at: http://escholarship.org/uc/item/27k6d70j

[18] CSLF, 2010. 2010 Carbon Sequestration Leadership Forum Technology Roadmap. Available at: http://www.cslforum.org/publications/documents/CSLF_Techology_Roadmap.pdf [Accessed November 10, 2010].

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requires additional efforts, which may not be required in the case of N_2 (depending on national regulations).

- *Re-use of injection facilities:* The production site needs to be adapted to process the working gas, such as injector wells. In the case of CO_2-EGR, these installations can be re-used after the EGR project, for storing CO_2, which will improve the economics of the EGR project. In the case of N_2-EGR, such post-EGR use of the installations for CO_2 storage requires adaptations of the system and is only possible, if additional MMV measures are taken.
- *Location of the field:* The feasibility of EGR will strongly depend on the location of the field. The economics will be generally more favourable for onshore fields because of the transport of the working gas.

Considering the above issues, it is clear that the feasibility of EGR is highly field-specific. Given the current lack of large-scale EGR projects (with the exception of the projects mentioned below), and the lack of published feasibility studies, it appears that operators have just started to consider EGR as a viable option.

The existence of the two planned N_2-EGR projects suggests that for certain fields EGR may be commercially attractive. For CO_2-EGR, the (non-)availability of CO_2 will play a key role. It is likely that when CO_2 is captured and available on a large scale and the ETS price is at a sufficiently high level, operators will take CO_2-EGR into account when considering the options for the final phase in the production of their gas fields. The Habshan N_2-EGR project in Abu Dhabi proves that the economics can allow for a dedicated air separation unit and a 50-km pipeline.

N_2-EGR compared to CO_2-EGR

N_2 as a working gas for EGR has definite advantages over CO_2:

- N_2 is inert, meaning it is not reactive with other substances or with the reservoir rock.
- N_2 is non-corrosive, not posing heavy constraints on the injection and production system.
- N_2 can be easily captured from air at any location.
- N_2 is already often added to natural gas, to adjust the caloric value of the gas for households.
- In contrast with CO_2, N_2 does not exhibit phase transitions in the pressure and temperature envelope of operations, resulting in lower complexity of the processing equipment and lower cost of compression.

However, the potential combination of CO_2-EGR combined with storage of CO_2 can potentially outweigh these advantages and make the option economically attractive. In the current market with low-CO_2 ETS prices this potential is difficult to assess.

CO_2-EGR: potential for CO_2 storage in depleted gas fields

While the role of CO_2-EOR in the development of CCS has been the subject of a large number of studies, the potential of CO_2-EGR has not been investigated in depth. The potential for CO_2 storage in conventional gas reservoirs and regional organic-rich shales in the U.S. has been estimated by IEA GHG, NETL and Kentucky Geological Survey (KGS). Recent IEA GHG studies indicate a global capacity of 160 to 390 giga tonnes (Gt) CO_2[18,19].

Other studies like a depleted gas fields study, using regional GIS-based source-sink matching was conducted for IEA GHG in 2008[19]. Capacity calculations were made with reference to the CSLF "resource pyramid" classification scheme. The IEA GHG study estimated that the available, matched, global-depleted gas field CO_2 storage capacity up to 2050 is 156 Gt CO_2.

These numbers will need to be refined in the coming period to get a better understanding of the potential for CO_2-EGR. The quantity of CO_2 required for EGR is approximately of the order of the volume of additionally produced natural gas. This quantity is smaller than the total storage potential of the depleted gas field. However, it cannot be fully decoupled from the storage project, since the economic driver of CO_2-EGR can make a total storage project economically feasible.

2.1.3 Current State of Technology

Little has been published on EGR, particularly on CO_2-EGR. Apart from the field studies described in section 2.1.5, one of the most dedicated case studies, conducted for a planned future field test was carried out in the German CLEAN project. Feasibility studies were performed for the German Altmark field, where 100 kilo tonnes (kt) of CO_2 was projected to be injected during a period of 1.5 to 2 years. Delays in the permitting process resulted in cancellation of injection and turned this study into a theoretical study[20]. These theoretical results did not show a significant enhancement in the gas recovery in case of an injected CO_2 volume ratio with respect to the gas in place of 0.06. Higher amounts of CO_2 (which were not envisaged in this pilot test) could of course change these results.

Additional modelling studies have been reported in literature.

2.1.4 Economics of the technology

As already mentioned, the existence of two market-driven N_2-EGR projects clearly indicates a potential for EGR. The main question to be addressed is whether only N_2-EGR is economically attractive, or whether a business case can also be built on CO_2-EGR.

In general, as a result of maintaining the pressure support in the reservoir, EGR can lead to the production of 10% additional gas. In the case of the de Wijk field in the Netherlands, extension of the lifetime of a field has led also to an extension of lifetime of an existing gas treatment facility, improving the project's economics. On the other hand, additional investments are necessary for CO_2-EGR. For a large part these investments

[19] IEA GHG, 2009. Storage in Depleted Gas Fields, IEA GHG Technical Report, 2009/1, Available at: http://www.ieaghg.org/index.php?/technical-reports-2009.html .

[20] Kühn, M., Münch, U. (eds.), CLEAN: CO_2 large-scale enhanced gas recovery in the Altmark natural gas field (Germany), Advanced Technologies in Earth Sciences, , Springer-Verlag Berlin Heidelberg 2013.

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are similar for N_2 and CO_2, on the assumption that CO_2 will be more readily available in the near future. An important difference is the inert and non-corrosive character of N_2 compared to CO_2. However, many gas fields already contain CO_2, for which measures have been taken. Nevertheless, additional costs cannot be excluded.

The main difference between CO_2-EGR and N_2-EGR is that after the EGR process the facilities can be used directly for CO_2 storage, which can improve the business case through CO_2 credits and/or subsidies. At this moment, no clear numbers can be provided yet due to the lack of experience with this technology. This needs to be further explored.

2.1.5 Active International Projects, planned projects

EGR is currently envisaged / performed at three locations, two of which use N_2 as the working gas, one uses CO_2.

K12-B - pilot project

At K12-B (Figure 1), an offshore site in the Dutch part of the North Sea, CO_2 is being injected at low rates (about 80 kt CO_2 injected over 8 years) in an almost depleted gasfield. The lifetime of this site has been extended by the injection of CO_2. The CO_2-EGR has been evaluated since 2005 by comparing actual tail-end gas production with forecasted gas production in case of no CO_2 injection. Because of the relatively small amount of CO_2 injected, no firm conclusions can be drawn on the EGR potential. Vandeweijer et al. note that the volume ratio between injected CO_2 and remaining gas in place is currently only in the order of 0.05[21]. Modelling studies do show a potential however, and with injection still ongoing, hopefully more definite conclusions can be drawn in the near future.

Breakthrough at K12-B of the injected CO_2 at the producing wells has been studied extensively making use of tracers. Results as described in Vandeweijer et al.[21] show results in line with expectations with a tendency towards “fast breakthrough” of the tracers. The latter is most likely caused by the type of tracers used, and currently research towards new tracers, better mimicking the CO_2 behaviour in the reservoir, is ongoing (as described in the paragraph technology advances).

De Wijk – project

Most of the gas fields in The Netherlands will be decommissioned before 2025, with many fields entering the last few years of production in the next 5 years. This has led NAM, the operator of a large number of gas fields, to consider end-of-field-life options. N_2-based EGR has been selected to prolong the production lifetime of one of the onshore gas fields, de Wijk, by ten to fifteen years. An additional 2 bcm (billion cubic meters) is expected to be produced; this is an increase in the recovery factor by about 10%. Installations (air separation unit, pipelines) and wells are currently being prepared and injection is planned to start in 2013[22].

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[21] Vandeweijer V.P., Van der Meer L.G.H., Hofstee, C., D’Hoore, D., and Mulders, F., 2009. CO_2 Storage and Enhanced Gas Recovery at K12-B, 71st EAGE Conference & Exhibition, Amsterdam.
[22] See http://www.nam.nl/nl/projects/natural-gas-de-wolden.html (in Dutch).

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Figure 1 The K12-B offshore platform in the North Sea where CO_2 is injected into a sandstone formation containing natural gas. Source: www.k12-b.nl.

Table 2: EGR projects worldwide

Project	Features	Purpose	Injection Rate
K12-B: Offshore gas field, North Sea, Netherlands (on going)	CO_2 separated from natural gas (13% CO_2) from a nearly-depleted gas reservoir and injected into the same reservoir at a depth of nearly 4,000 m	Storage, EGR	~ 40 TPD
De Wijk: Onshore gas field, The Netherlands (planned)	N_2 from air separation plants is injected down-dip in gas bearing layer, at depths between 500 and 1,500 m	EGR	Air separation units capacity: 500,000 – 700,000 m^3/day (12,000 – 30,000 m^3/h)
Habshan field Onshore oil and gas field, Abu Dhabi (planned)	N_2 from air separation units; 50 km pipeline to Habshan fields	EGR, EOR	Air separation units capacity: 670,000 m^3/h

Habshan – large-scale EGR and EOR

Currently, a project is planned in Abu Dhabi in the Habshan field, where N_2 from an air separation plant is transported over 50 km and injected for EGR. The volume of N_2 produced at the separation plants is 670,000 m^3/h; this volume is used for both EGR and EOR. For CO_2, the volume would be equivalent to almost 12 million tonnes (Mt)/y. N_2 injection is planned to start in 2014.

2.1.6 Regulatory requirements for operations

The EU storage directive is the foundation for all regulatory requirements concerning a CO_2 storage site within the EU. When appropriate measures, such as monitoring and verification of safe and secure storage are taken, CO_2-EGR can fall under the Storage Directive. In terms of the ETS system, the CO_2 flow rates in the injected and produced gas streams would need to be monitored and reported accurately. Currently, there is no experience with such a project in the EU.

There is no specific legislation in place for N_2-EGR in the de Wijk field. The permit application is treated under the existing mining regulations, considering the inertness and safety of the injected N_2.

In the case of CO_2-EGR in the K12-B field, it must be noted that the EU storage directive does not apply because it involves re-injecting CO_2 being produced by the same reservoir. It falls under existing mining regulations.

2.1.7 Technology advancement needs/gaps, RD&D needs

CO_2-EGR is still an area that has been less explored and requires several pilot projects such as K12-B, to better understand the mechanisms and the effectiveness. Some of the issues that require additional study are:

- The economic potential for CO_2-EGR needs to be further evaluated. There is currently insufficient experience in this technology to properly assess its economic potential.
- Retarding the flow of the injected CO_2, with respect to the flow of the natural gas has a direct impact on the potential breakthrough of the CO_2 at the gas production wells. Novel technologies which monitor the retardation of CO_2 flow in the subsurface relative to natural gas (e.g. tracers) should be developed.
- Another issue is the thermal impact of liquid, relatively cold CO_2, when injected in warm, low-pressure reservoirs. The possible phase changes combined with thermal stresses on the well and reservoir creates large uncertainties on safety and security of storage.
- More research is required to optimize the use of CO_2 in tight reservoirs, including for shale gas applications (discussed in a separate chapter).
- Techniques to monitor CO_2 migration and well integrity during– and after-injection should be developed.
- Finally, monitoring techniques for the (near-well) injection processes, including thermal fraccing, should be developed and tested.

2.1.8 Co-production due to breakthrough

It is obvious, that the working gas (N_2 or CO_2) at a certain moment will be co-produced with the methane gas. The main issue will be to delay this breakthrough as much as possible, while still maximising the EGR potential. In case the produced working gas

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reaches too high concentrations, it will have to be separated from the gas and either re-injected (CO_2) or vented (N_2).

2.2 Hydrocarbon Recovery by CO_2 fracturing: Shale gas recovery

2.2.1 Introduction

Shale gas requires enhanced well stimulation processes in order to achieve a commercially-viable yield of gas. In the United States shale gas is successfully exploited using fracturing technology whereby the main components used are water and a range of chemicals in small concentrations. In principle some or all the water can be replaced by carbon dioxide in its liquid or supercritical phase. Conversely, the carbon dioxide can replace methane in the shale formation thereby enhancing the release of methane and sequestering carbon dioxide in the shale formation (Enhanced Gas Recovery) in a similar way as carbon dioxide is used for EOR (Enhanced Oil Recovery).

In this section of the report the potential for using carbon dioxide for shale gas recovery and storage has been assessed according to the current state of the technology, the economics, regulatory issues, gaps identification etc.

2.2.2 Metrics

In the context of shale gas reservoirs, CO_2 can be used to replace water-based fluids during gas well drilling and completion, can enhance gas recovery (EGR), and can also be stored in gas reservoirs. CO_2-EGR was discussed in section 2.1 and therefore only the remaining two technologies were discussed in this section. The three technologies (CO_2-fraccing, EGR, storage) are not commercial and therefore all estimates in this section are based on research outcomes and assumptions. These technologies can either be used by themselves or in combination with one or two of the other technologies.

2.2.2.1 Replacement of water based fluids with carbon dioxide during the fracturing process

Currently water is used for the fracturing of shale formations in order to commercially extract methane gas. The drilling and hydraulic fracturing of a horizontal shale gas well requires approximately 3.5 million gallons (~13,250 m^3) of water[23]. It is assumed that the same volume of liquid or supercritical carbon dioxide (7,950 t CO_2[24] for an average well) is needed to achieve the required fracturing. Water for these applications is sourced from surface water bodies, ground water, and re-used produced water. Most of the producing shale gas basins in the U.S. are located in areas with moderate- to high-levels of annual precipitation. However, other competing regional water demands (e.g., agriculture), and seasonal variations in precipitation may favor the use of CO_2 instead of water for hydraulic fracturing. Similarly, the use of fraccing fluids containing CO_2 may improve public perception of fraccing elsewhere globally.

[23] www.naturalgas.org
[24] 3.5 million gallon (13.25 million litres) carbon dioxide at a density of about 0.6 kg/litre amounts to 7950 tonnes of carbon dioxide for the average well.

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Although up to 8000 t of CO_2 can be used for fracturing, it is anticipated that a large percentage of the carbon dioxide will be recycled. There is insufficient information available at this stage to make an estimate of this percentage.

2.2.2.2 Use of depleted shale formations for CO_2 storage

Depleted shale formations could also be used to store CO_2. CO_2 storage in saline reservoirs is only considered at depths exceeding 800 meters in order to ensure that the hydrostatic pressure is sufficient to keep carbon dioxide in a dense phase (supercritical phase). However in shale formations where there is carbon containing material, it is expected that the carbon dioxide will be adsorbed onto this material and the minimum depth requirement of 800 meters does not apply.

Nuttall et all[25] calculated that at a constant pressure of 400 psia (2.76 MPa), the CO_2 adsorption capacity of Devonian black shales of Kentucky varied from 14 to 136 scf/ton of shale with a median value of 40 scf/ton (1.18 Nm^3/tonne of shale[26]). In this reservoir setting, injection zones (shale) deeper than 1000 ft (300 m) and having a thickness exceeding 100 ft (30 m) were considered suitable for CO_2 storage[27]. It must be noted that these calculations were done for a specific reservoir (Devonian black shale formation in Kentucky) and therefore are used only as an example.

2.2.3 Current State of Technology

Laboratory studies have been conducted to gain understanding on the adsorption of CO_2 on organic rich shale formations[28]. The results show that CO_2 adsorbs preferentially to such shale formations compared with methane and therefore its storage in shale formations is likely to be possible and may prove to be a mechanism for EGR. However these processes have not been demonstrated in situ. More advanced studies and simulations[27] have been conducted using actual reservoir data such as advanced well log data, rotary sidewall cores, shale rock properties analyses, adsorption isotherms and production data to construct geophysical reservoir models that included the effects of parameters including porosity and permeability. The models were used to investigate CO_2 injection in the shale gas reservoir and to help design a pilot injection project. Due to the extremely low permeability of the shale formation (in the order of nanodarcys [nD]) actual injection of carbon dioxide in this type of formation remains a challenge[27].

The three technologies relevant to the use of carbon dioxide as mentioned in the previous section can be applied individually but can also be used as combination of two or all three

[25] Nuttall, B.C., Drahovzal, J.A., Eble, C.F., and Bustin, R.M., 2006. Analysis of the Devonian Black Shale in Kentucky for potential carbon dioxide sequestration and enhanced natural gas production, Final Report: Kentucky Geological Survey. Available at: http://www.uky.edu/KGS/emsweb/devsh/final_report.pdf.

[26] 1 scf = 0.026853 normal cubic meter (Nm^3) and 1 US short ton = 907 kg

[27] Nuttall, B.C., Kentucky Geological Survey, 2010. MRCSP Phase II- Reassessment of CO_2 Sequestration Capacity and Enhanced Gas Recovery Potential of Middle and Upper Devonian Black Shales in the Appalachian Basin. Available at: http://www.netl.doe.gov/technologies/carbon_seq/infrastructure/rcsp/mrcsp/topical_4_black_shale.pdf

[28] Busch, A., Alles, S., Gensterblum, Y., Prinz, D., Dewhurst, D.N., Raven, M.D., Stanjek, H., and Krooss, B.M., 2008. Carbon dioxide storage potential of shales: International Journal of Greenhouse Gas Control, v. 2, no. 3, p. 297-308.

options. Decisions on what combination to choose will be based on technical and financial criteria. A few aspects of each technology are listed below:

- The use of carbon dioxide as a fracking liquid.

The concept of fracturing with 100% CO_2 as the fracturing fluid and proppant carrying fluid was first introduced in the early 80's[29,30,31,32,33]. The method was pioneered by a Canadian service company called Fracmaster who performed fracture stimulations on thousands of wells in Canada via CO_2 sand fracturing (100% CO_2 and proppant) with great success. The fracturing mechanics with CO_2 and proppant would not be any different than the conventional water based hydraulic fluid. However, there are a few differences both in the hardware and fluid design; the primary one is the use of high pressure closed-system blending vessel to mix the proppant in the CO_2 fluid. As far as fluid design goes, the proppant concentration and size must be lower than the conventional water based fracturing due to the low carrying capacity of CO_2. The low-carrying capacity of "energized" fluids (e.g, CO_2) is offset by gains in productivityby eliminating water blockage, enhanced proppant clean-up, and shortened flow back times. There is also evidence of higher ultimate recovery of hydrocarbon from CO_2 fracced wells[34,35].

- The use of carbon dioxide for enhanced gas recovery:

  During the exploitation of the well it is expected that "breakthrough" of CO_2 will occur at some time and a mixture of methane (CH_4) and CO_2, with a gradually increasing percentage of CO_2, will be produced. It is expected that a gas separation unit, similar to the unit that used for removing acid gases from natural gas (e.g. Sleipner off shore of Norway) would be required. The recycled carbon dioxide would be reused. During the enhanced gas recovery process, a considerable amount of carbon dioxide would be sequestered in the shale formation.

- The use of depleted shale formations for the storage of CO_2:

  Once the shale formation has been depleted of gas the formation may be used for the storage of CO_2. The capacity for storage is site-specific and detailed geophysical site models are required to estimate the storage potential. To claim carbon credits for the

[29] Greenhorn, R., and Li, E., 1985, Investigation of high-phase volume liquid-CO_2 fracturing fluids, Paper no. 85-36-34, presented at the 36th Annual Technical meeting of the Petroleum society of CIM, June 2.
[30] Lancaster, G., Barrientos, C., Li, E., and Greenhorn, R., 1987. High-phase- volume liquid-CO_2 fracturing fluids, Paper no. 87-38-71, presented at the 38th Annual Technical meeting of the Petroleum society of CIM, Calgary, June-7-10, 1987.
[31] Lillies, A.T, and Steven R. King, 1982. Sand fracturing with liquid-carbon dioxide, SPE 11341, presented at the 1982 Production Technology Symposium, Hobbs, New Mexico, November 8-9, 1982.
[32] Holtmayer, M.D., Harris, P.C. and Hunt, C.V., 1985. Fracturing method for stimulation of wells utilizing carbon dioxide based fluids, U.S. Patent 4,519,455.
[33] Luk, S., Apshkrum, M., 1996. Economic optimization of liquid-CO_2 fracturing. SPE 35601, Proceedings of the 1996 Gas Technology Symposium, Calgary, Canada.
[34] Yost, A.B., Mazza, R.L., Gehr, J.B., 1993. CO_2/sand fracturing in Devonian shales. SPE-26925, 1993 Eastern Regional Conference& Exhibition, Pittsburgh, PA, U.S.A., 2-4 November.
[35] Ribeiro L. H., Sharma, M.M., 2013. Fluid selection for energized fracture treatments, SPE 163867, Hydraulic Fracturing Technology Conference, The Woodlands, Texas, USA, 4-6 February.

storage of carbon dioxide the appropriate protocols, which include accurate monitoring of the injected CO_2, monitoring the horizontal and vertical migration of the stored CO_2, monitoring for possible leakage, verification by an independent party, need to be followed [36].

2.2.4 Economics of the technology

Currently gas prices, particularly in the USA, are extremely low (around \$3/thousand ft^3 [Mcf])[37], and the price for carbon dioxide under CDM and CERs is also very low[38]. Furthermore the cost for drilling rigs and other equipment used for gas exploitation from shale formations is high due to the large demand. Together these factors make current economics for carbon dioxide supported shale gas recovery unattractive.

In the longer term developments may become more favourable particularly if the use of CO_2 can prolong the production of gas from a specific well thereby increasing the productive life of a specific gas well via pressure support. This would mean that fewer boreholes are required to produce a specific amount of gas thereby reducing cost for drilling. More research is required to understand the dynamics and cost implications of such scenarios.

2.2.5 Active International Projects, planned projects

Currently CO_2 is not used commercially for EGR, fracturing or storage in depleted shale gas formations and the technologies are researched in laboratories. Pilot projects have not been planned until now.

2.2.6 Regulatory requirements for operations

The use of carbon dioxide for supported shale gas recovery and storage requires regulation covering:

- CO_2 handling, transport and injection: These processes are also required for the use of CO_2 for EOR and it is likely that the same legislation does apply.

- CO_2 sequestration in the appropriate shale formations: There are significant similarities between the sequestration of CO_2 in shale formations and the storage of CO_2 in e.g. deep saline formations or exhausted gas and oil fields and it is likely that the same legislations would largely apply. There are some technical differences e.g. the depth of the geological formations and therefore some legislation may be different.

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[36] 2006 IPCC GHG Inventory Guidelines – Provides guidelines for accounting for CCS. These are not yet approved but developed countries are obliged to use them.
[37] EIA US Energy Information Administration
[38] Clark, P., 2012, October 2. UN-led carbon market close to collapse, Financial Times.

- Shale gas extraction enhanced by CO_2: Extraction of shale gas enhanced by carbon dioxide is very similar to current shale gas extraction and it is likely that the same legislation will apply.

Overall it appears that existing legislation in some countries will largely address the use of CO_2 as support for shale gas recovery. However it is recommended that a review of this legislation is carried out in order to ensure that all aspects are covered. In other countries where currently no natural gas exploitation and carbon storage is pursued, new legislation will be required.

2.2.7 Technology advancement needs/gaps, RD&D needs

From section 2.2.3 although carbon has a strong affinity for organic rich shale formations and that it can replace methane in such formations, actual injection of CO_2 in such formations is challenging due to the low permeability of the shale formations. Therefore permeability enhancement is a requirement for the commercialisation of enhanced gas recovery from shale formations. Such permeability enhancement has already been demonstrated on a large scale by the commercial extraction of gas from shale formations and research into a combination of known fracturing technologies with the injection of CO_2 (e.g., Ishida et al.[39]). Compared to water injection, CO_2-fracturing occurred in a larger area, and the pattern was more three dimensional. Furthermore the breakdown pressure for supercritical- and liquid-CO_2 was expected to be considerably lower than for water. The low viscosity of liquid- and supercritical-carbon dioxide (compared with water) are thought to cause these differences.

Further development of downhole monitoring techniques such as controlled source electromagnetic surveys, cable-less sensors for downhole corrosion measurement and temperature measurements will improve the understanding of carbon dioxide injection in shale formations.

2.2.8 Potential for co-production

If the laboratory results obtained by Ishida et al[39] can be confirmed by other laboratories and at a larger scale, then the commercially viability of using carbon dioxide for enhanced gas recovery could become attractive. As carbon dioxide is already widely used for enhanced oil recovery, it is likely that this technology also may become attractive for co-production of oil and gas.

[39] Ishida, T., Aoyagi, K., Niwa, T., Chen, Y., Murata, S., Chen, Q., & Nakayama, Y., 2012. Acoustic emission monitoring of hydraulic fracturing laboratory experiment with supercritical and liquid CO_2. Geophysical Research Letters, v.39, no.16. doi:10.1029/2012GL052788.

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2.3 Hydrocarbon Recovery by CO_2 fracturing: Shale Oil Recovery

2.3.1 Introduction

Producing and recovery of hydrocarbons from tight or shale intervals requires significant investment in terms of stimulation infrastructure. The oil and gas industry's current method of choice is hydraulic fracturing (or "fraccing").

Hydraulic fracturing uses large volumes of treated water, pumped at high pressure in to a shale interval to create or enhance a fracture network, and allow higher rates of production to be achieved from a targeted interval. The typical fracture treatment will require 1.5 to 5 million gallons per stage (11,300 to 18,900 m^3). In the US, the number of individual fracture stages in a single well can run as high as 30, spread across a horizontally oriented wellbore which can exceed 10000 ft (~3000 m) in length.

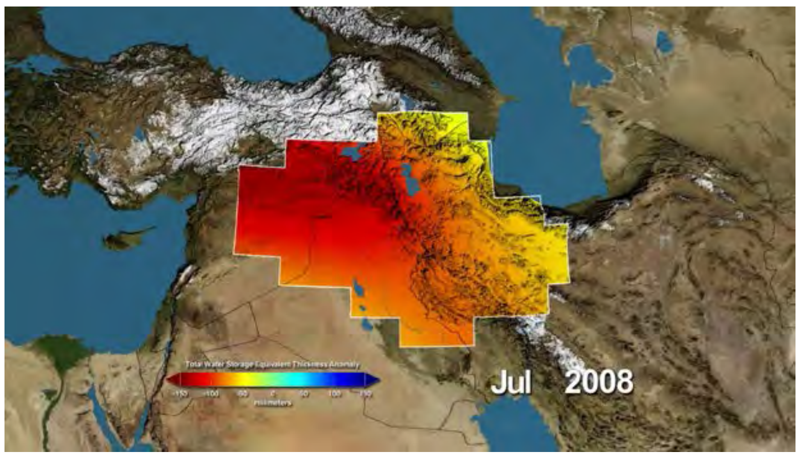

Figure 2: Variations in total water storage from normal, as measured by NASA's Gravity Recovery and Climate Experiment (GRACE) satellites, from January 2003 through December 2009. Reds represent drier conditions, while blues represent wetter

Currently, chemical constraints require that this be provided as fresh water, typically less than 2000 parts per million (ppm) total dissolved solids (TDS). Once this water has been introduced into the formation, up to 50% of it is produced from the formation contaminated with salt from the formation water. This returned fluid must be cleaned up to remove treatment chemicals, and excess salt before it can be returned to the environment. This is a costly operation, which commonly will include filtration, and reverse osmosis (RO) treatment.

Additionally, the available resources of fresh water in many regions around the world (e.g., ground water in the Middle East, see Figure 2), are declining. CO_2 in fluid (liquid/supercritical) and gas (foams) can be utilized to perform all of these functions, and eliminate water usage and save valuable resources. In addition because CO_2 stimulations are more effective than hydraulic fraccing, fewer wells and fewer fracture stages per well

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are needed to meet a specific production goal. In addition, wells can be suitably configured to be flowed back to allow re-capture of the CO_2.

2.3.2 Metrics

As mentioned in section 2.3.4, approximately 480 to 2200 short tons of CO_2 could be used per well. The exact overall quantity of CO_2 used would depend on its availability and overcoming logistics, mechanical completion, and chemical challenges.

2.3.3 Current State of Technology

Typically CO_2 fracturing programs are applied to reservoirs between 3000 to 10000 ft (~1000 to 3000 m) deep, at temperatures less than 250 °F (121 °C). They are also commonly targeted at depleted reservoirs where treatment pressures and fracture gradients are lower. These parameters are consistent with a large proportion (~90%) of current shale oil/gas plays in the world.

The concept of fracturing with 100% CO_2 as the fracturing fluid and proppant carrying fluid was first introduced in the early 80's[29,30,31,32,33,34]. The method was pioneered by a Canadian service company called Fracmaster who performed fracture stimulations on thousands of wells in Canada via CO_2 sand fracturing (100% CO_2 and proppant) with great success. The fracturing mechanics with CO_2 and proppant would not be any different than the conventional water based hydraulic fluid. However, there are few differences that exist both in the hardware and fluid design; the primary one is the use of high pressure closed-system blending vessel to mix the proppant in the CO_2 fluid. As far as fluid design goes, the proppant concentration and size must be lower than the conventional water based fracturing due to the low-carrying capacity of CO_2.

Fracturing with liquid CO_2 and proppant was found to provide stimulation benefits including decreased fluid cleanup time. However, leakoff appears to be a problem due to the low viscosity of CO_2 fluid. Therefore the fracturing pump rate must be high enough to compensate for fluid loss. Despite the higher treatment costs compared to the conventional water based fracturing treatments; the immediate benefit found in well productivity offsets this cost difference. These treatments also appear to be effective in cleaning up hydrocarbon residue damage due to the solvent characteristics of miscible CO_2 systems.

Work by Lillies and King[31], and Yost et al[34,40] showed significant improvements in total hydrocarbon production, and producing life.

2.3.4 Economics of the technology

Economics will revolve around development of a suitable infrastructure for wide application. A typical well application would require 120-220 tons of liquid CO_2/per

[40] Yost, A.B., R.L. Mazza, and R.E. Remington II, 1994. Analysis of production response to CO_2/sand fracturing: A case study. SPE 29191, presented at the 1994 Eastern Regional Conference & Exhibition, Charleston, WV, U.S.A., 8-10 November.

stage, with wells having 4-10 stages. A typical refrigerated tanker would carry 55 tons of CO_2 to the site. The CO_2 can be sourced from existing capture target sources (hydrocarbon gas streams, power plants, etc.), and since the returning gas flow can be routed back to a gas processing plant, all of the injected gas can be effectively re-captured. It is expected that the better environmental benefits of using CO_2 instead of water would drive the increased adoption of CO_2 fracturing.

2.3.5 Active International Projects, planned projects

Several US based and European companies currently have the capability of applying this technology, but there is still insufficient incentive to eliminate the use of water. The use of CO_2 is seeing increased application, not for fracturing, but in the under-balanced drilling side. Lack of appropriate fracturing equipment (pressurized mixers), and difficult logistical transport issues for liquid CO_2 make water a cheaper alternative. The lack of controls on use of water, will continue to play against the economics of going to water-less technologies, even though there are clear indications of dwindling water supplies for human consumption, especially in drier portions of the Middle East, Africa, and the U.S.A.

2.3.6 Regulatory requirements for operations

Cryogenics are a challenge in the oil field as supercritical CO_2 is transported as a dense liquid, at -22 °F (-30 °C), and 300 psig. For bulk liquid shipments, carbon dioxide as a refrigerated liquid is designated as Class 2.2 (non-flammable gas). CO_2 is non-toxic, but by diluting the oxygen concentration in air below the level necessary to support life; it can act as an asphyxiant. It is a refrigerated, supercool liquid, with very high volatility. A ton of liquid CO_2 converts to 17,198 SCF of gas. The material flashes to a heavy gas (density 1.5 times that of air), so there is a danger of suffocation if the gas is trapped in low-lying environments, under quiescent conditions.

2.3.7 Technology advancement needs/gaps, RD&D needs

The challenges for use of foamed-CO_2/liquid-CO_2 fracturing fluids fall into several categories. These include logistics, chemical issues, and completion design challenges.

1. **Logistics:** Generally, logistics become a major cost factor in all well activities. Fluids have to be trucked to remote environments, and liquid CO_2 or liquid LPG or will be no different. There is a shortage of CO_2 capture facilities available around the world, and the only source of large quantities of LPG will likely be from refinery facilities. CO_2 will need to be brought to site in refrigerated tankers – 0.4 °F (-18 °C). The same is true for service provider support –until there is a significant commitment from pump providers, to bring sealed, pressurized equipment to site, there will be little possibility of moving this technology forward.
2. **Chemical Challenges**: There a few issues related to CO_2 chemistry which needs to be addressed by the chemical industry. A critical one is the lack of a suitable liquid-CO_2 thickening agent. Enick and coworkers reviewed on the development of

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thickening agents with CO_2[41]. The issues related to the lack of viscosity agents are: 1) increased pump rates needed to fracture formations, and 2) reduced capacity to carry appropriate loads of proppant (marginally about 6 pounds per gallon [ppg]) into the fracture. This becomes less of an issue for unconventional targets where lower viscosity (such as slick-water systems), and lower-proppant density are the norm. As water percentage increases, the value for the fluid design as a "limited water" or "waterless" stimulation declines.

The low density of the supercritical CO_2 requires higher pressured containment and pumping systems will be needed for deeper, higher pressure stimulation. High pressure usually implies deeper wells, and therefore, higher temperatures. Significant research needs to be conducted in developing high-temperature viscosifiers, and density enhancers to handle deep hot wells.

3. **Completion/Mechanical Challenges**: Completions will need to be specially designed to handle the more rigorous conditions that they will be subjected to. Any elastomers and seals in pumping/completion systems need to be of CO_2-rated materials. Hydrogenated nitrile butadiene rubber (HNBR) and some perfluroelastomers (FFKM) are suitable. Dry CO_2 is non-corrosive. Pure-phase liquid-CO_2 that is completely dehydrated before injection will not cause internal corrosion of the tubing. However, corrosion can be a factor when using foams, because water is present. The primary factors that affect corrosion rates are the partial pressure of CO_2, operating pressure and temperature, flow rate of CO_2, water content and contaminants such as hydrogen sulphide and oxygen. Pure CO_2 exerts a very large partial pressure which causes reduced pH and increased carbonic acid formation. If formation water returns with the CO_2, after stimulation, or if CO_2 foams are used, then a degree of corrosion resistance will be needed. A final design consideration is the low temperatures of CO_2 liquids, as delivered to the well head (ca. -22 °F [-30 °C]). Low temperatures can result in shrinkage of tubes (especially if un-cemented) past safety limits. However, Mueller et.al[42] used cold-CO_2 injection as an enhanced fracture technique to induce thermal fractures into the well.

2.3.8 Potential for co-production

The potential for co-production in the use of CO_2 fracturing for shale oil recovery is similar to that of CO_2 fraccing for EGR.

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[41] Enick, R.M., Olsen, D.K., 2012. Mobility and conformance control for carbon dioxide-enhanced oil recovery (CO_2-EOR) via thickeners, foams, and gels – A detailed literature review of 40 years of research. DOE/NETL-2012/1540. Available at: http://www.netl.doe.gov/technologies/oil-gas/publications/EPreports/CO2-mobility-control-report-2011.pdf

[42] Mueller, M., Amra, M., Haefner, F.K., and Mofazzal Hossain, M.D., 2012. Stimulation of tight gas reservoir using coupled hydraulic and CO_2 Coldfrac Technology. SPE 160365, presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition held in Perth, Australia, 22-24 October 2012

3. REUSE (NON-CONSUMPTIVE) APPLICATIONS

3.1 UREA

3.1.1 Introduction

Fertilizers boost the productivity of the soil, leading to higher crop yields. Urea (H_2N-(C=O)-NH_2), ammonia (NH_3), urea ammonium nitrate (UAN), monoammonium phosphate (MAP), diammonium phosphate (DAP), and NPK (nitrogen, phosphate, potash fertilizer) are the key nitrogen fertilizers used to supply nitrogen which can be readily used by plants (typically as ammonium NH_4^+, or nitrate NO_3^-). Among these, urea is a major fertilizer, and is traded globally. A major fraction (~88%) of global urea consumption is used as fertilizer (see Table 3), and its demand is driven by population growth, rising incomes, and more crop-intensive diets. Urea is also used to make plastics, adhesives, and explosives. Urea-based selective catalytic reduction (SCR) is also used to control nitrogen oxide (NO_x) emissions from power plants and diesel vehicles[43].

3.1.2 Metrics

The global supply of urea in 2012 was 165.9 million metric tonnes (Mt)[44]. Urea markets are currently tight, with production (supply) nearly equaling the demand for urea, estimated to be 162.3 Mt in 2012 (Table 3).

Table 3: World Urea Supply/Demand Forecast and Projected CO_2 Consumption

World Urea Supply/Demand Balance						
		2012	**2013**	**2014**	**2015**	**2016**
Supply (Mt)	**Capacity**	192.4	202.8	207.4	224.3	226.1
	Total Supply[45]	165.9	173.7	180.3	189.7	195
Demand (Mt)	**Fertilizer Demand**	143.3	146.2	149.4	152.7	154.4
	Non-fertilizer Demand	19	19.7	20.7	21.1	21.7
	Total Demand	162.3	165.9	170	173.8	176.1
CO_2 Demand (based on urea demand)	**CO_2 (Mt/y)**	120.1	122.8	125.8	128.6	130.3

The International Fertilizer Industry Association (IFA) estimates the world supply and demand for urea would be 195 Mt and 176 Mt respectively in 2016. World supply and

[43] Solutions of urea in purified water used to control NO_x from vehicles using SCR are referred to as diesel exhaust fluid (DEF) in the U.S., and as AdBlue in Europe.

[44] Heffer, P., Prud'homme, M., 2012. Fertilizer Outlook 2012-2016, presented at the 80th IFA Annual Conference, Doha (Qatar), 21-23 May 2012. Available at: http://www20.gencat.cat/docs/DAR/DE_Departament/DE02_Estadistiques_observatoris/24_Estudis_i_documents/01_Novetats_documentals/Fitxers_estatics/2012_NDW_fitxers/NDW_120720_2012_doha_ifa_summary.pdf

[45] IFA refers to supply as the maximum achievable production (capacity x highest achievable operating rate)

demand are estimated to grow at 4.4% and 2.4% per annum respectively compared to 2011. In the previous decade, urea supply grew at 3.8% per annum between 2001 and 2010.

Most of the CO_2 used to produce urea is separated from flue gas from natural gas or hydrocarbon reforming or coal gasification required to produce hydrogen for ammonia synthesis. Approximately 0.57 t NH_3 and 0.74 t CO_2 are directly consumed per t of urea. Indirect CO_2 emissions and reductions from urea production include the emissions from ammonia synthesis from natural gas or coal, and the additional amount of CO_2 fixed as biomass due to fertilizer use. Life-cycle studies by the Canadian Fertilizer Institute indicate that the average CO_2 emission for urea production from natural gas to be 1.39 t CO_2/t urea, which covers natural gas input and urea output[46].

3.1.3 Current State of Technology

The synthesis of urea from ammonia and carbon dioxide (CO_2) is a mature process compared to other non-consumptive uses of CO_2. Ammonia and CO_2 are reacted in proportions between 2.9 to 3.5 to form ammonium carbamate at high pressure (140-150 bar) and temperature (180-185 °C), converting 60-65% of the feed CO_2. Ammonium carbamate is further dehydrated to form carbamide (urea).

- $2\ NH_3 + CO_2 \rightarrow NH_4COONH_2 \rightarrow H_2N\text{-}(C{=}O)\text{-}NH_2 + H_2O$

Different technologies of urea manufacture differ in the process used to separate urea from the reactants, and how ammonia and CO_2 are recycled back to the reactor. Refinements in urea production technology are focused on improving the conversion of CO_2, optimizing heat recovery and reducing utility consumption. Note that ammonia itself is produced by the Haber process from hydrogen (produced by steam reforming of natural gas, or by water gas shift reactions of syngas derived from coal/petcoke gasification) and nitrogen (from cryogenic air separation). .

Most modern fertilizer plants use natural gas or other gases like propane or ethylene to produce the hydrogen needed for ammonia. The production of hydrogen from methane produces CO_2, more than what is needed to produce urea. Chinese fertilizer plants primarily use hydrogen from gasifying anthracite coal to produce ammonia and urea. The most efficient plants consume approximately 0.6 kg of natural gas to make one kilogram of nitrogen as ammonia, and 0.75 kg to make urea[47].

3.1.4 Economics of the technology

The economics of urea production are cyclical, and are affected primarily by the price of feedstock (natural gas, fuel oil or coal) and agricultural demand for grain. Historically, producers in the Middle East and North Africa region have benefited from low-cost gas

[46] http://oee.nrcan.gc.ca/industrial/technical-info/benchmarking/ammonia/15230

[47] Yara Fertilizer Industry Handbook, February 2012. Available at: http://www.yara.com/doc/37694_2012%20Fertilizer%20Industry%20Handbook%20wFP.pdf

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and stable gas contracts[48]. Typical urea cash production costs[49] (4th quarter, 2011) varied from ~100 $/t (Middle East and North Africa) to $380/t (Europe)[48]. The recent increase in shale gas production has improved the economics of urea production in North America, and typical production costs were $210/t (4th quarter, 2011)[48].

An example of the cash costs for a hypothetical US plant located in Louisiana (~1300 T/d) was provided by Blue Johnson & Associates[47]. Natural gas price of $8/MMBTU and gas consumption of 36 MMBTU/t NH_3 led to ammonia cash cost of $314/t. Using ammonia utilization of 0.58 t NH_3/t urea, process natural gas usage (5.8 MMBTU gas/t urea) cost, and other production costs of $22/t urea, the total free-on-board (fob) cash urea production cost was estimated to be $245/t.

The costs of constructing a greenfield urea plant are substantial, ~1.2 billion $ for 1 Mt/y urea plant[48]. The Black Sea and the Arab Gulf regions are major global urea export hubs for urea. There are considerable regional differences in the production, consumption, and export of urea in each of the world's key markets (USA, west/central Europe, China, India, and Brazil). Benchmark urea spot prices vary with time and region. For example, average urea price in August 2012 ranged from $385/t (Black Sea), $484/t (New Orleans) to $620/t (Pacific Northwest)[50].

The nominal-net benefit using urea product cost of $430/t and NH_3 cost of $470/t, and CO_2 price of $40/t is $183/t CO_2[51]. The direct CO_2 consumption at the urea supply levels projected for 2016 would be 143 Mt/y.

3.1.5 Active International Projects, planned projects

Approximately 460 urea plants are currently operating around the world[52]. By 2016, the IFA estimates that approximately 50 Mt of urea capacity would be added by almost 60 new plants and 4 Mt would be additionally produced by expansion and revamp of existing plants[53]. Government export tariffs, policies and the availability of natural gas may affect urea production in China and India. A majority of the increase in global urea capacity would be in exporting countries such as Algeria, China, Indonesia, Qatar, Saudi Arabia and Venezuela. Capacity changes are also expected in some of the consuming countries, such as, Brazil and Vietnam.

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48 Valentini, A., 2012. The outlook for the world urea market. Presented at Diesel Emissions Conference & AdBlue Forum Asia 2012, 27-29 March 2012, Beijing, China. Available at: http://www.integer-research.com/2012/environment-emissions/news/world-urea-market-outlook-supply-demand/
49 Production cash costs exclude depreciation, overhead and debt service.
50 http://agrium.com/includes/August_2012_Roadshow.pdf
51 44 t CO_2 requires 34 t NH_3 and produces 60 t urea and 18 t water. Ammonia and urea U.S. CFR prices: 470 $/t and 430 $/t from ICIS. CO_2 price: 40 $/t. 1 t CO_2 = 34/44 t NH_3 = 60/44 t urea. Raw material costs: 40 + 34/44x470 = 403 $/t CO_2. Urea cost: 430x60/44 = 586 $/t CO_2. Nominal-net benefit = 586-403 = 183 $/t CO_2 (negative cost).
52 http://www.ureaknowhow.com/urea_j/en/library/578-2011-10-wang-brouwer-ureaknowhowcom-worldwide-urea-plants-overview.html
53 Food and Agriculture Organization of the United Nations (FAO), 2012. Current world fertilizer trends and outlook to 2016. Available at: ftp://ftp.fao.org/ag/agp/docs/cwfto16.pdf

Several new North American urea projects are being announced to harness current low-natural gas prices[54]. The lead times for constructing a greenfield urea plant vary from 3 years[48] to 6 years[47]. New urea projects announced now may not result in added capacity by 2016.

The Perdaman Collie project in Australia aimed to convert sub-bituminous coal to urea (~2 Mt/y) using coal gasification. It has been delayed over coal supply issues. Furthermore, two proposed coal-gasification-based poly-generation projects in the USA, SCS Energy's 390 MW Hydrogen Energy California Project (HECA), and Summit Power Group's 400 MW Texas Clean Energy Project (TCEP) plan to produce electricity, urea, and CO_2 for enhanced oil recovery (EOR)[55]. The TCEP plant would produce 0.7 Mt/y urea[56] and the HECA project would generate ~1 Mt/y of urea, urea ammonium nitrate (UAN), and ammonia[57].

3.1.6 Regulatory requirements for operations

The regulatory requirements for urea facilities obviously vary by region and the type of plant complex producing urea. Air and water quality permitting requirements for standalone greenfield natural gas-based urea production may be significantly distinct from those for coal-based urea production, or poly-generation-based urea production.

3.1.7 Technology advancement needs/gaps, RD&D needs

Improvements in urea production technology are focused on reducing utility consumption, and improving plant reliability. Large, single-train plants of up to 3500 T/d are being designed. Generally speaking, the amount of CO_2 emitted from natural gas reforming is larger than the CO_2 used to produce urea made by ammonia (produced by hydrogen from the reforming process). This CO_2 intensity is exacerbated in the case of coal-gasification based urea plants without agreements for using CO_2 for EOR or geologic storage.

Coal-based urea plants may offer simpler pre-combustion CO_2 capture. CO_2 for natural gas-based urea plants is captured from the methane reformer flue gas or reformed sygas using chemical or hybrid (physical-chemical) solvents, involving higher parasitic loads and capital requirements than the higher-pressure-capture of CO_2 from coal gasifiers. However the cost of coal-based urea is typically at the higher end of current global urea

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54 See for example: http://www.icis.com/Borealis/Article.asp?p=1&q=BFB3C6D1D8BDE2B6CCAD8DB96EB0D9CAAFDCC1D48DAEE7B281AED7B8E0B4D5D6B0EC&id=B28398A69B82AC, http://www.icis.com/Articles/2012/12/21/9627034/us-mosaic-may-build-700m-ammonia-plant-in-louisiana.html

55 Hellerman, T., 2012. Poly-gen CCS plant developers hope to skirt cost issues facing other IGCC projects. GHG Monitor, Available at: http://ghgnews.com/index.cfm/poly-gen-ccs-plant-developers-hope-to-skirt-cost-issues-facing-other-igcc-projects/?mobileFormat=true

56 http://www.texascleanenergyproject.com/category/press-releases/

57 http://hydrogenenergycalifornia.com/wp-content/uploads/file_attachments/030820121050070/Fertilizer.pdf

prices due to the increase in the price of anthracite coal[47]. Improvements in reducing the capital cost of coal gasifiers, gas conditioning, and energy and capital cost needed for pre-combustion CO_2 capture could be beneficial to lower the cost of coal-based urea production.

3.1.8 Potential for co-production

Two poly-generation projects based on coal/petcoke gasification HECA, and TCEP plan to integrate urea production with power generation. The addition of urea production (including ammonia production) to the IGCC plant would increase the overall capital cost, compared to both IGCC and a natural gas-based urea plant. For example, the TCEP project is expected to cost \$2.5 billion for a 195 MW_{net} power plant producing 0.7 Mt urea/y and 2.5 Mt CO_2/y for EOR, which is significantly higher than the capital cost for a greenfield gas-based urea plant (~\$1 billion for 1 Mt urea/y[48]). It is noteworthy that both of the poly-generation IGCC projects in the U.S.A. provide high-pressure stream of CO_2 for EOR in addition to the urea and power, indicating that finding a different use or storage site for the CO_2 stream needs to be a part of poly-generation IGCC plants producing urea in a carbon-constrained world.

In summary, the challenges for poly-generation-based urea production from coal are the higher overall capital costs, and the need to store or offset CO_2 emissions. The advantages of coal-based poly-generation for urea production is the additional flexibility to produce chemicals at off-peak load times, lower carbon intensity of the urea product, and the higher revenues from the sale of urea. For example, urea sales are estimated to make up approximately 54% of the revenues for the TCEP[58]. Further, cost of delivering urea over a large distance inland from a seaport would increase the overall delivered cost of urea, and a well-located poly-generation IGCC plant may result in lower urea supplied costs[59].

[58] http://www.iogcc.state.ok.us/Websites/iogcc/images/2012Vancouver/TX_clean_energy_project.pdf
[59] For example, urea price in August 2012 for delivery to New Orleans was \$484/t and \$620/t for delivery to the Pacific Northwest. See 50.

3.2 ALGAL FUELS

3.2.1 Introduction

CO_2 is a direct product of fossil fuel combustion and needs energy input to be converted to a fuel. A number of potential process routes for such conversion are being considered, including: the production of synthetic liquid fuels such as methanol, formic acid and synthetic hydrocarbons via reforming/hydrogenation/electro-chemical reduction reactions using off-peak renewable energy or hydrogen (*i.e.* effectively storing excess energy in a more useable form); the production of 'intermediates' such as synthesis gas ('syngas') which can be separated or used directly in the synthesis of hydrocarbon fuels (*e.g.* via metal catalysed Fischer-Tropsch synthesis); artificial photosynthesis ('bio-mimetic') systems/processes that produce high-energy molecules such as carbohydrates under very mild conditions (*e.g.* photo-catalytic or electro-catalytic processes); and the production of biomass such as algae *via* photosynthesis.

Microalgae are microscopic, single-celled organisms growing in fresh/salt water that use sunlight as their energy source and CO_2 and inorganic nutrients (mainly nitrogen compounds and phosphates) for their growth: the CO_2 needed for growth can be derived from concentrated sources such as power/process plant flue gas. There is considerable interest in the use of CO_2 to grow microalgae, as the resulting biomass is a versatile raw material that can potentially be used for electricity generation and as a source for a range of fuel and non-fuel products, including bio-oils and proteins, high-value chemicals and ingredients, fertilizers, feed and food.

A key attribute of microalgae is higher growth rate and productivity than for most terrestrial plants due to the more efficient use of light and nutrients. Cultivation takes place in open-ponds or semi-closed photobioreactors that can be located on marginal, non-arable land. Many species of microalgae thrive in brackish/salt water or effluents, and in these applications do not compete with conventional agriculture. However, in such applications some form of salt management (*e.g.* brine removal) is needed due to evaporation.

There is a significant energy penalty associated with the requirement for continuous mixing of the algal cultivation system and dewatering.

For several years, there has been an interest in the concept of using microalgae to produce biofuels[60]. Substantial investments in RD&D have taken place in this sector by governments and private investors – most notably in the USA (*e.g.* Chevron-NREL, DARPA-UOP) and the. These investments are justified by the high potential that algae offer for production of vegetable oils compared to alternative oil crops such as corn, soybean, canola, jatropha, coconut and oil palm[61]. To date, however, no successful large-scale production of algal biofuels has been achieved.

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[60] Sheehan, J., Dunahay, T., Benemann, J., and Roessler, P., 1998. A look back at the U.S. Department of Energy's Aquatic Species Program – Biodiesel from algae, p.296. U.S. department of Energy's Office of Fuels Development.
[61] Chisti, Y., 2007. Biodiesel from microalgae. Biotechnology Advances, v. 25, p.294-306.

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Although CO_2 utilization through algae has advantages and potential, there are several major challenges to be addressed. Even at higher productivities, microalgal systems have a substantial land requirement, which may not be available in the direct vicinity of power plants and other large point-source CO_2 emitters. Furthermore, the costs of producing algal fuel are still high. Significant R&D and technological development and cost reduction related to algae cultivation and harvesting are required to enable large-scale production systems.

3.2.2 Metrics

The global market for microalgae is currently approximately 10kt biomass (dry basis)/y, supplying various high-value food supplements, food ingredients, aquaculture feeds and cosmetics feedstock, with an estimated value of US$5 to 6.5 billion/y[62]. Potential products from microalgae include bio-oil (up to 40%), proteins (30-50%), polysaccharides for the production of chemicals, bio-active products, food and feed ingredients (including omega-fatty acids), fertilizers and fuels. The feasibility of these applications depends on achievable production costs as well as the actual entry of algal products in the market.

Current prices of algae on industrial markets range from US$5,000 to 11,000/t and €3,750-7,500/t for algae produced in China[63]. The production cost of microalgae from photobioreactors has been reported at *ca*. €10,000/t, with a projected reduction to €3,800-6,000/t due to scale factors[62]. Another study has estimated microalgae production costs for three different systems at commercial scale (open ponds, horizontal tubular photobioreactors and flat-panel photobioreactors), including dewatering, as €4,950/t, €4,150/t and €5,960/t, respectively[64]. A price of €680/t could be reached through optimisation of the most important cost drivers[64]. At this cost level, algae may become a viable feedstock for biofuel and bulk chemicals.

Evidently, lowering of the production costs and increasing the value and revenues of co-products are central elements in any optimisation effort. There are a number of algal products with a high market value (*e.g.* omega-fatty acids), but their market volume is incompatible with the market for biofuels and CO_2 fixation. More market-compatible products could include fertilizers, inputs for the chemical industry and alternative paper fibre sources[65].

The current energy balance of algae production is less favourable than of terrestrial crops due to the high energy requirements for mixing of the culture and for harvesting and drying of the resulting biomass. One study calculated a primary energy input of

[62]Muylaert, K., and Sanders, J., 2010. Inventarisatie Aquatische Biomassa: Vergelijking tussen algen en landbauwgewassen. K.U. Leuven Campus Kortrijk, 17pp. Studie uitgevoerd in opdracht van Agentschap NL.
[63]Bowles, D., (ed.), 2007. Micro- and macro-algae: Utility for industrial applications – Outputs from the EPOBIO project. September 2007. CPL Press Science Publishers.
[64] Norsker, N-H., Barbosa, M.J., Vermue, M.H., and Wijffels, R.H., 2010, Microalgal production – A close look at the economics, Biotechnology Advances, v.29, p.24-27.
[65] Lersel, S. van, and Flammini, A., 2010. Algae-based biofuels: applications and co-products. Review Paper. FAO Aquatic Biofuels Working Group, 117 pages. FAO Environmental and Natural Resources Services Series, No. 44 – FAO, Rome 2010.

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producing fractionated and dried algal biomass (with an inherent energy value of 21.8GJ/t dry weight) of 9GJ/t biomass (equivalent to 5GJ/t CO_2 fixed) for raceway ponds versus *ca*. 63GJ/t biomass (35GJ/t CO_2 fixed) for a flat panel reactor[62]. This is more than 10-fold higher than for agricultural crops. The energy balance for raceways is positive but still the energy input is 3-4-fold higher than for most agricultural crops.

A critical issue is the biomass yield that can be obtained by cultivation of microalgae, since this largely determines the costs of the biomass. In recent years, productivities exceeding 200t/ha/yr have been claimed. The upper limit of productivity is determined by the maximum efficiency of photosynthesis, which is the same for algae and green plants[66]. For Northern European countries, this would imply a theoretical maximum biomass productivity of 208t (dry weight)/ha/yr. In practice, however, the maximum efficiency is never achieved, so such optimistic projections will have to be nuanced.

The main reason for lower efficiencies and therefore lower than maximum yields, are losses caused mainly by biological limitations. The consensus view is that large-scale algal biomass productivities of up to 80t/ha/yr (*i.e.* in the range of high yields attained with crops such as sugar cane in the tropics) can be realised[62,66], with the same figure estimated for a flat-panel photobioreactor[62,64,66].

The CO_2 fixation capacity of an algal system is proportional to the occupied area and the biomass productivity per hectare. For a typical carbon content of 50wt% in the algal biomass, the fixation capacity is *ca*. 0.5t carbon (from 1.8t CO_2 taken up by the algae) for potential conversion to valuable products[67]. The fixation of a third of the CO_2 emitted by a 600MW_e coal-fired power plant (*i.e.* 4kt CO_2/day for 365 days/yr, or 1.46 GT CO_2/yr), would require an algae cultivation surface of about 10kha (*ca*. 100km^2), assuming a productivity of 80t biomass (dry)/ha/yr. The amount of algal biomass produced would be of the order of 800kt.

Algal CO_2 fixation, particularly in warmer and sunnier regions, is seen as having near-term potential in combination with waste water treatment and fertilizer recycle/production[68]. In the mid-term (15-20 years), it is expected that processes might be developed by integrating biofuels production with higher value/large market co-products such as biopolymers and animal feed. In the longer term, single purpose algae biofuels production may become feasible. Given the diversity of different algal systems and the number of products, more in-depth analyses should be performed to quantify the CO2 balance for the different systems.

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[66] Tredici, M. R., 2010. Photobiology of microalgae mass cultures: understanding the tools for the nexr green revolution, Future Science, v.1, p.143-162 http://www.future-science.com/doi/abs/10.4155/bfs.09.10.
[67] Styring, P., and Jansen, D.de Conninck, H., Reith, H and Armstrong, K., 2011. Carbon capture and utilisation in the green economy. Centre for Low Carbon Futures 2011 and CO2Chem Publishing 2012. Report 501, July 2011. ISBN: 978-0-9572588-1-5. Available at: http://co2chem.co.uk/wp-content/uploads/2012/06/CCU%20in%20the%20green%20economy%20report.pdf .
[68]Harmelen, T. van, and Oonk, H., 2006. Microalgae biofixation processes: applications and potential contributions to greenhouse gas mitigation options. TNO Built Environment Geosciences.

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3.2.3 Current State of Technology

The steps involved in algal fuel production may be broadly grouped as: cultivation, algae harvesting and/or extraction, and processing to produce fuels. Cultivation of microalgae takes place in either open-pond systems or in (semi-) closed photobioreactors to which water, nutrients and CO_2 are supplied.

High-rate Algal Ponds ('HRAP' or 'raceway ponds'), with paddle-wheels for mixing the culture, are the most common method currently used for commercial algae production[67]. These can be built at relatively low costs (*ca*. US$10/m^2) and are easily scaled-up. However, such large-scale open systems do not lend themselves to process control, thereby limiting algae productivity. Furthermore, the relative ease of contamination limits the number of species that can be successfully cultivated in open systems and care is needed in the CO_2 supply/dosing systems to minimise the CO_2 emitted to atmosphere.

Photobioreactors provide a more controlled environment, permitting the cultivation of a broader range of algal species and higher productivities than ponds[69]. However, at the current stage of development, photobioreactors have a *ca*. 10-fold higher investment cost (>US$100/m^2) compared to open systems and scale-up is hampered by engineering issues relating to gas/liquid mass transfer, prevention of wall-growth and energy efficient mixing/cooling of the culture[67]. Some recent developments are addressing these issues and are discussed here:

- HR BioPetroleum[70] has developed a hybrid system comprising photobioreactors and a large open pond area: Results at pilot scale show that selective cultivation is possible at a high yield and reduced costs. Algal oil production cost in a full-scale system was estimated to be US$84/bbl[71].

- Vertical, flat-panel reactors made from thin polyethylene film have been designed to substantially reduce investment costs. It is likely that many systems will be developed based on such design principles, with expected improvements in material lifetime (and thus costs) and energy requirement for cooling and mixing[72,66].

Research has shown that flue gas from coal- and gas-fired power plants are suitable CO_2 sources for algal growth[73,74]. Also, the removal of NO_x and its use as a nutrient (after

[69] Pulz, O., 2001. Photobioreactors: production systems for phototrophic microorganisms, Applied Microbiology and Biotechnology, v.57, p.287-293.
[70] HR BioPetroleum. Available from: http://www.hrbp.com/index.html.
[71] Huntley, M.E., and Redalje, D.G., 2006. "CO_2 mitigation and renewable oil production from photosynthetic microbes: A new appraisal", in Mitigation and Adaptation Strategies for Global Change, Springer. http://www.drfriendly.tv/PDFs/Huntley%2BRedalje200611.pdf.
[72] Wijffels, R.H., Barbosa, M.J., 2010. An Outlook on Microalgal Biofuels. Science, v.329, no.5993, p.796-799.
[73] Benemann, J., 1997. CO_2 mitigation with microalgae systems, Energy Conversion and Management, v.38, p.475-479.
[74] Benemann, J.R., 2003. Biofixation of CO_2 and greenhouse gas abatement using microalgae: technology roadmap. U.S. Department of Energy, National Energy Technology Laboratory, and the International Energy Agency Greenhouse Gas Abatement Programme.

conversion to nitrate) for algal growth, is feasible[75]. Possibilities also exist to utilise residual heat from flue gases for maintaining the optimum culture temperature to raise productivity.

Because the produced algal suspension is very dilute (*ca*. 99% water[76]), the costs for concentration and dewatering of the biomass may amount to 20-30% of overall production costs[77]. Employed technologies include centrifuging, flotation or membrane filtration – relatively costly and energy intensive. The development of reliable, low-cost harvesting technology with low energy consumption is one of the main challenges in the field.

3.2.4 Economics of the technology

The cost of algal biomass could be reduced to €4,000/t through economies-of-scale[72]. By making use of residues including waste water and CO_2 from flue gases, and technological improvements, the price could reduce 10-fold to €400/t[71]. For feasible production of biofuels, the whole algal biomass would have to be utilised, consisting roughly of 50% oil (valued at €400/t), 40% proteins (€1,200/t) and 10% sugars (€1,000/t). This ‘biorefinery’ approach causes the biomass value to rise to €1,650/t – sufficient for commercial biofuels production.

3.2.5 Active International Projects, planned projects

Various companies – mostly in the USA – are actively engaged in the development of fuels from algae. These include Solix Biofuels[78], Origin Oil[79], Sapphire Energy[80] and HR BioPetroleum[70]. Most companies are focused on the production of ‘drop-in’ fuels from oil-rich algae (*e.g.* for aviation).

In Australia, companies such as Aurora Algae and Algae Tec are active in the field of algal fuels production and other co-products[81]. Additionally, the New Energy and Industrial Technology Development Organization (NEDO) in Japan has been supporting nine R&D projects on algae-derived fuel.[82]

[75] Nagase, H., Yoshihara, K.I., Eguchi, K., Yokota, Y., Matsui, R., Hirata, K., and Miyamoto, K., 1997. Characteristics of biological NO_x removal from flue gas in a Dunaliella tertioecta culture system. Journal of Fermentation and Bioengineering, v.83, p.461-465.

[76] Gilbert, C.D., Lewis, J.J., and Jeffrey, I., 2013. AlgaeCAT: Algae carbon capture technology: Industrial CO_2 as a precursor to sustainable biomass – Summary findings, conclusions and recommendations, Draft report to TSB, 4 April 2013.

[77] Fernandez, A., Medina, A.R., and Chisti, Y., 2003. Recovery of microalgal biomass and metabolites: Process options and economics, Biotechnology Advances v.20, p.491-515.

[78] Solix Biofuels. Available from: http://www.solixbiofuels.com/.

[79] Origin Oil. Available from: http://www.originoil.com/.

[80] Sapphire Energy. Available from: http://www.sapphireenergy.com/.

[81] Lane, J., 2011. Algstralia: the Land of Gold from Green, Biofuels Digest, http://biofuelsdigest.com/bdigest/2011/03/02/algstralia-the-land-of-gold-from-green/.

[82] NEDO brochure, http://www.nedo.go.jp/content/100512497.pdf.

3.2.6 Regulatory requirements for operations

The operation of an algae farm would require the inputs of nutrients, CO_2, and fresh or brackish waters. The local regulations governing the use of these resources, and any emissions to water and air would be applicable to algal fuel production.

3.2.7 Technology advancement needs/gaps, RD&D needs

Algae have a number of attributes that enable sustainable production concepts, including high biomass productivity, the possibility of utilising marginal, non-arable land, salt water, waste streams as nutrient supply and flue gases as CO_2 sources to produce fuels and a range of non-fuel products. Furthermore, algae can attain much higher oil and protein yields than traditional crops.

The main challenges that need to be addressed in order for algae to make a meaningful contribution to CO_2 biofixation are to achieve large-scale algal production at competitive costs. Currently, technologies are not available for commercial implementation at large scale and significant R&D and investments are required for the technology to become economically viable.

Also, there is a need to develop techno-economic analysis and life cycle assessment for microalgal fuel production in the context of CO_2 emission reductions from power generation and refinery sources. In addition to fuels production, microalgae are particularly suitable for use as animal feed, which may have higher value than fuels in certain regions where the animal feed is imported. Microalgae production uses waste CO_2 emitted from refineries, power plants or similar sources, and many species can use seawater. However, factors relevant to cultivation of specific strains of microalgae in large ponds at high productivity need to be assessed. Harvested algal biomass can be used for the biofuel production or as animal feed. Further near-term applications include combining CO_2 biofixation with waste water treatment and fertilizer production. Critical objectives for fuel, animal feed and/or chemical production using microalgae, include: reducing production costs and energy requirements while maximising lipid productivity, and increasing the biomass value by making use of all algal biomass components through a biorefinery.

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It is necessary to identify potential short-term (< five years) R&D issues for utilizing algal biomass through the combination of several end uses, such as fuels, chemicals, waste water treatment, animal feed to advance this technology to a demonstration project, leading to large-scale commercial CO_2 fixation by microalgae within the decade.

3.2.8 Potential for co-production

A current trend in the industry is the co-production of biofuels and suitable co-products (*e.g.* proteins, 'green' chemicals, biopolymers) to improve economics[83].Additional studies are needed

[83] Thurmond, W., 2011. Top 11 algae investment and market trends for 2011. Excerpt from Algae 2020 study Vol. 2, updated February 2011. http://www.emerging-markets.com/ and http://www.emerging-markets.com/algae/Top_11%20Algae_Investment_Trends_%20from_%20Algae_%202020_%20Study.pdf.

to examine potential efficiencies and economics of co-production. Integrated assessments of technological and market factors are needed to identify promising opportunities and influence the direction of research.

3.3 CO_2 UTILIZATION IN GREENHOUSES

3.3.1 Introduction

Plants absorb CO_2 and H_2O in greenhouses to form organic matter (leaves, stems, fruits, vegetables, flowers). Higher CO_2 concentrations stimulate plant growth to a certain extent. For example, the rate of plant growth (photosynthesis) increases by approximately 50 percent for most crops when the CO_2 concentration in a greenhouse is increased from the natural level of 340 ppm to 1000 ppm for any light intensity[84]. CO_2 can be added to stimulate plant growth in a greenhouse by preventing the CO_2 concentrations from gradually becoming lower in the confined environment of a greenhouse. Although this is not a geographically-limited option, pertinent examples would be drawn from the Netherlands because it is a common practice.

The majority of horticulturists in the Netherlands produce the CO_2 they need on-site by burning natural gas in their on-site combined heat and power plants. However, currently about 5% of the sector's CO_2 use for greenhouses comes from industrial waste-CO_2, stemming from some of the largest point sources of pure CO_2 in the Netherlands: the Shell refinery and Abengoa bioethanol in the Rotterdam area, and the Yara fertilizer plant in the South-Western part of the country. A minority of users buy CO_2 from companies selling industrial gases.

Figure 3 Tomatoes grown with CO_2 from the industrial sources (Shell, Abengoa) and geothermal heat.

Source: www.vleestomaat.nl.

The utilization of CO_2 in greenhouses opens perspectives to more efficient food production, which is a global challenge in itself. In the years to come, the demand for food will double[85]. In the future, the productivity of Dutch horticulture is estimated to

[84] http://www.omafra.gov.on.ca/english/crops/facts/00-077.htm
[85] http://www.topcompanies.nl/en/all-magazines/1-1-horticulture-en/growing-chances-across-the-border/

result in 20 times more crop per hectare than conventional growing systems. The world may need more greenhouses and more CO_2 utilization in greenhouses in the future.

Furthermore, the utilization of industrial waste CO_2 enables an efficient and fully sustainable horticulture in temperate zones, where heating of greenhouses is required. In such greenhouses, heating may be done by industrial waste heat, heat pumps or geothermal energy, and CO_2 is from industrial waste sources (Figure 3).

3.3.2 Metrics

Today, Dutch greenhouses use about 0.4 Mt per year of industrial waste CO_2 that would otherwise be vented. This is about 7% compared to the total CO_2 emissions for the growth in greenhouses in 2011, which stood at 5.6 Mt, and about 0.2 % of the total Dutch emissions. The utilization of CO_2 leads to decreased burning of natural gas for CO_2 generation.

There are currently two networks that bring the pure industrial waste CO_2 to the horticulturists:

- The OCAP network (starting in the Botlek area): The backbone of this network is a 85 km long pipeline from Rotterdam to Amsterdam. To this existing pipeline, distribution networks are coupled, which bring the CO_2 to the various greenhouse areas (see Figure 4)[86],
- The WarmCO_2 network (south-western part of the Netherlands): Here, a new area for greenhouses is being developed within 5 km from the Yara fertilizer plant. The Yara plant supplies both waste heat and CO_2 to the greenhouses, which are therefore fully independent of fossil fuels[87].

In both cases, the CO_2 is compressed and transported in the gaseous phase. In the year 2013, OCAP is planning to install a central buffer for liquid CO_2 to deal with inbalance between supply and demand in summer. Interestingly, this CO_2 will be bought on the market for liquid CO_2.

There are two additional networks that bring CO_2 to growers, but organized differently:

- “Roca3”: The Roca3 gas-fired CHP plant, in use since 1996, supplies heat and flue gases (not pure CO_2) to 140 horticulturists north-east of Rotterdam[88].
- Plukmadese polder: The AMER power plant supplies heat to horticulturists (~130 ha greenhouses) in the Plukmadese polder. CO_2 is bought centrally from a supplier of industrial gases, but delivered per individual grower.

[86] www.ocap.nl
[87] www.warmco.nl
[88] http://eon-benelux.com/eonwww2/publishing.nsf/Content/Centrale+RoCa

Figure 4. Supply areas of OCAP

translation of legend:
Supply areas of OCAP
1 Westland
2 B-driehoek
3 Zuidplaspolder

Green line:	CO_2 pipeline
Blue line:	Planned CO_2 pipeline
Green polygons:	CO_2 supply to greenhouses
Blue polygons (in blue ovals):	Planned supply of CO_2 to greenhouses
Blue ovals:	Planned CO_2 storage

In the meantime, other greenhouse areas spread around the country also offer possibilities to construct pipelines to connect to CO_2 sources. The capacity of large point-sources of pure CO_2 in the Netherlands will be about 5 Mt by 2015[89].

The world demand for CO_2 for greenhouse growing could very well increase significantly in the years to come. The world greenhouse area is much larger than the area in the Netherlands alone, and expands rapidly in some countries. As an illustration, Table 4 shows the data for protected horticulture of vegetables worldwide in 2006.

Table 4: Estimated area protected horticulture (greenhouses/large tunnels) of vegetables (in 10000 m^2) as of 2006

	Greenhouses	Plastic greenhouses/large tunnels
Asia	2,476	926,000
Europe	28,922	171,500
Africa/Middle East	6,682	50,600
North-America	1,350	11,050
Middle/South America	-	9,510
Total	39,430	1,168,660

In the Netherlands, the greenhouse area is about 10,000 hectares. From Table 4, we can see that this is about 1% of the total permanent structures for vegetable growth. This means that the world-wide potential for CO_2 utilization could theoretically be about 100 times the potential in the Netherlands. The real potential is even higher, because fruits and flowers are not included in the table, and because greenhouse usage has increased rapidly in some countries. Mexico, for instance, had 13,000 hectares of protected tomato growth by the end of 2012[90] (a larger area for one crop than all the area in the Netherlands today) and is now the world's second-largest exporter of fresh vegetables.

The practical potential is evidently lower. In some countries, the air in greenhouses is not enriched with CO_2. Also, the need for ventilation makes enriching with CO_2 less attractive. Nevertheless, the worldwide market potential for CO_2 demand for this application is in the range of million tons to tens of million tons.

It is important to realize that the size of the market here is larger than the size of the CO_2 emission reductions. Savings come from avoided burning of natural gas, or other fuels, for CO_2 production. However, economic considerations will lead to higher-CO_2 levels in the greenhouse when the CO_2 is available in pure form and at lower cost. Further, when the reference case does not use any CO_2 at all, there are no reductions CO_2 emissions. For the Netherlands, an emission reduction of more than 50% was estimated in 2004, but changes in market conditions would lead to lower reduction numbers now[89].

[89] CO_2 Overdrachten onder het Europese systeem van emissiehandel, DHV, maart 2010, p.21; p.24 https://www.emissieautoriteit.nl/mediatheek/emissiehandel/achtergrondstudies/CO2%20overdrachten%20onder%20het%20systeem%20van%20emissiehandel%20-maart%202010.pdf

[90] Personal communication, Jan Willem de Vries, Wageningen University

For Dutch horticulturists, the cost of CO_2 is clearly outweighed by the benefits of increased, higher quality, production. This is generally speaking true for all methods of CO_2 production (burning natural gas, transport by pipeline, buying from companies selling industrial gases). The economics of using CO_2 depend on several factors, such as the cost-benefit tradeoffs for using pure CO_2 versus flue gas and investment in a CHP facility. For example, using pure CO_2 is better for plant productivity compared to using flue gas. Additionally, the conventional method of burning natural gas in a CHP cycle also generates electric power. Power generation may or may not be attractive depending on current and potential electricity supply and demand on the spot market and the relative values of prices and potential subsidies. Growers who also need electric light for their plants (typically for flowers) may be benefited by a CHP system. Nevertheless, pipeline CO_2 in Netherlands (OCAP and WarmCO_2) is a feasible alternative to on-site CHP, although growers pay a good price for the pipeline CO_2, and use both systems.

3.3.3 Current State of Technology

The utilization of CO_2 as a growth enhancer in greenhouses is applicable to many regions around the world. Utilization of pure industrial waste CO_2 started in 2005 in the Netherlands, with the OCAP project. The WarmCO_2 project followed in 2009. The extraction of the CO_2 from the industrial streams is part of the existing process. CO_2 is transported via pipelines in the gaseous phase. At night, the pressure can be increased to 30 bars, so that the pipeline acts as a buffer[91].

It is important to note that establishing both the OCAP and the WarmCO_2 network has been fully accepted by the Dutch public. The existence of a safe large-scale CO_2 transport infrastructure over the past eight years may also help the advancement of geologic storage of CO_2.

3.3.4 Economics of the technology

As already stated, the benefits of the addition of CO_2 to the greenhouse atmosphere outweigh the costs in the Netherlands, but the economics are heavily dependent on factors such as local fuel prices, and the type of operation of the greenhouse (ventilation). The Ontario Ministry of Agriculture and Food suggests that cost for liquid CO_2 range from CAD 110-200 per ton, excluding cost for hardware (tank and vaporizer units). Industrial waste CO_2 per pipeline is sold at a price below €100 per ton. Generation with natural gas depends on energy prices and, the selling price of excess electricity for a CHP system.

An important factor when dosing CO_2 is evidently the tightness of the greenhouses, and the required ventilation for cooling. In the Netherlands, there are also growers that operate hot-, and cold-storage systems in aquifers, which reduces venting.

[91] http://www.ecn.nl/fileadmin/ecn/units/bs/Optiedoc_2005/factsheets/co2-ovg-01.pdf

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3.3.5 Active International Projects, planned projects

In addition to the Dutch projects for the delivery of pure CO_2 via pipeline to greenhouses identified in 3.3.2, there are several greenhouse areas which are now considering the possibility of having their own CO_2 distribution, often with support from local or regional authorities. In Spain, Repsol performed the "CO_2 Funnels" project at Puertollano which used industrial CO_2 from the Repsol refinery complex for growing short-cycle crops in five 400 m^2 tunnel-type Mediterranean greenhouses. The study was focused on evaluating the effect of dosing CO_2 on the growth of several energy crops[92].

3.3.6 Regulatory requirements for operations

Transportation of an industrial gas by pipeline in gaseous phase is subject to existing regulation.

The work environment for personnel in a greenhouse fertilized with flue gas needs to be controlled and monitored carefully to mitigate potential risks due to high CO, NO_x and ethylene levels.

The use of industrial gases in the food industry in Europe is regulated by the European Industrial Gases Association, EIGA[93]. A similar situation will exist in other parts of the world.

3.3.7 Technology advancement needs/gaps, RD&D needs

There is a need for more insight into the use of CO_2 in greenhouses worldwide, and the benefits resulting from the use of industrial CO_2, in various parts of the world with differing climates, and for various common crops (since different crops have different needs).

Moreover, more insight or research into possibilities of new and integrated concepts that can couple surplus and demand for CO_2 as well as energy would be valuable, and could optimize the entire energy and economic system. For example, the integration of greenhouses with power generation, CO_2 (peak) demand, geothermal heat, cold storage, and solar energy is one option. Interestingly, solutions for re-use of CO_2 might enable increased use of renewables such as geothermal energy in food production, as the Dutch greenhouse example shows. A holistic approach, rather than a one-dimensional technocratic perspective is important.

3.3.8 Potential for co-production

Evidently, the advantage of the use of CO_2 in greenhouses is in the higher production. Data on productivity improvements were provided in previous paragraphs.

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[92] http://www.repsol.com/es_en/corporacion/conocer-repsol/canal-tecnologia/proyectos-casos-estudio/otros-proyectos/proyecto-funnels/

[93] Vermeulen, P.C.M., Lans, C.J.M. van der, 2010. CO_2 dosering in de biologische glastuinbouw, Rapport GTB-1085, Wageningen University & Research Centre (WUR).

4. CONSUMPTIVE APPLICATIONS

4.1 AGGREGATE, SECONDARY CONSTRUCTION MATERIAL (SCM)

4.1.1 Introduction

The development of SCMs based on carbonated matrices is an obvious-, but currently, poorly-developed route for CO_2 utilization as an alternative to CCS. At present, there are few industrial processes utilising CO_2 for the production of bulk-materials (cement and building materials) beyond the manufacture of precipitated fine powders for fillers in plastics, paint and food. This is due to:

- The cost of obtaining/transporting 'waste' CO_2;
- Market reluctance to the use of non-virgin materials; and
- The need to conform with materials performance specifications.

Until the cost of products derived from captured and sequestrated CO_2 are lower and acceptance is more widespread, processes that use CO_2 in significant quantities will not become widely developed. Additionally, 'cheap' secondary materials produced from CO_2 in high volumes have potential to disrupt established markets. As such, supply and demand might have to be controlled, thereby limiting the desired mitigating impact on emissions.

The current bottleneck for using CO_2 in viable mineral processes at an industrial scale is the rates of reaction that can be achieved[67]. Nevertheless, recent commercial initiatives utilising CO_2 emissions through carbonation of magnesium- and calcium-based feedstock to convert them into 'green' aggregates are encouraging future investment and the wider development of SCMs.

The conversion of CO_2 can be completed by various treatments including electrochemistry, dewatering and drying of carbonates/bicarbonates. In recent years, government investment into RD&D associated with the utilization of CO_2 has increased, most notably in the USA, Germany and Australia. For example, in the USA \$100 million (M) has been invested in gas scrubbing and conversion research by 2011 (including plastics). In Germany in 2009, €118 M was similarly invested in research into the use of CO_2 as a raw material. Several projects are now at the demonstration scale, with a small number of independent companies offering commercial products, although information on scale, yield and cost is difficult to obtain.

4.1.2 Metrics

Approximately 25 billion tonnes (Gt) of aggregates are used every year worldwide, with a potential value of about US\$500 billion. If these primary aggregates are replaced by secondary aggregates comprising imbibed CO_2, substantial volumes of the gas may be sequestered. However, to be successful in meeting the demands of the aggregate industry, including for use in concrete and ground engineering, SCMs must meet established technical performance requirements through national and international materials performance standards.

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It is likely that all of the produced SCMs will not always have the required physical and chemical properties for some engineering applications, and this may affect potential technology development and application. As is the case with primary materials, SCMs will need to be 'fit for purpose'.

Assuming that a 100% mineralisation process could generate annually 20bn tonnes of carbonated aggregate of the required quality and at a price that is competitive with virgin or reclaimed sources, the prospects of the technology are positive[94]. Table 5 contains metrics for potential published processes involving the production of SCMs[95].

Table 5: Metrics for aggregate production

Process (see 4.1.3)	CO_2 utilised	Products value (US\$/tCO_2)	Energy consumption	Energy penalty	CO_2 capture in-built?
Alcoa	2-23Mt[1]	10-300	n/a	n/a	yes
Calera	1,500Mt[1]	7 (aggregates) 100 (per t cement)	0.08-0.28t CO_2 emitted/t CO_2 captured	8-28%	yes
Calix	2-23Mt[1]	n/a	n/a	17% for syngas and 7% for natural gas	yes
Cambridge Carbon Capture	50-1,000Mt[1]	n/a	TBA	n/a	yes
Carbon8	3-9Kt[2]	10-18?	-44kg CO_2/t product	energy positive	yes (but not yet realised)

1: Mt: million tonnes per year
2: Actual by 2014
n/a: not available

It is worth noting that the production of SCMs can include geologically-derived materials or waste products from industrial processes. The former are abundant but not always close to potential markets, whereas many industrial residues are produced closer to urban centres and are thus potential feedstock materials for the production of SCMs. A recent

[94] Technical Group: CO_2 Utilisation Options Task Force, *CO_2 Utilisation Options - Phase 1 Report*, 2012, Carbon Sequestration Leadership Forum.
[95] Cambridge Carbon Capture. *Company Overview*. 2011 [cited 2013 25 March]; Available from: http://cambcarbcap.files.wordpress.com/2010/11/ccc_company_overview_jan-10-v4.pdf

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estimate[96] of the sequestration potential of alkaline waste materials is in the region of 875Mt on an annual basis (Table 6).

4.1.3 Current State of Technology

Commercially available processes that imbibe CO_2 into SCMs are limited in number at the present time. Table 7 gives the results of a review of published patents, indicating that processing of SCMs is technically possible, but that uptake is slower.
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Table 6: Alkaline industrial residues with potential for carbonation[96]

Waste	Annual production (Mt)	Maximum CO_2 capacity(kg/t waste)	Potential CO_2 uptake (Mt)
Bauxite residues	120	53	6.3
Waste concrete[a]	2,800	165	462
Cement kiln dust[b]	770	115	88.5
Coal fly ash	600	264	158
MSWI bottom[c, d] ashes	80	475	38.0
MSWI fly ashes[c]	20	120	2.4
Steelmaking slags	400	300	120
Total	**4,790**	**-**	**875.7**

a: Figures refer to cement production. Every tonne of concrete contains typically 10% cement
b: For every tonne of cement, 0.25-0.30 tonnes of kiln dust are produced. Thus: 0.275×2,800=770Mt
c: The annual production of municipal incineration ashes is estimated at 100Mt. If we assume that 80% comes as bottom and 20% as fly ashes then the respective figures would be 80Mt and 20Mt
d: Ambient T and P are assumed

Table 7: Assessment of technology availability from published patents/patent families

Patent Number	Year	Description	Organisation
US8367025B2 US910555882 US7906086B2*	2006 2006 2006	Method for removing CO_2 from a fluid stream and production of solid products	C-Quest *DC Comrie
US8357270B2 US8333944B2 US8137444B2 US8006446B2	2008 2007 2009 2008	Electrochemical and other methods for removal of CO_2 from waste streams and production of materials with potential for re-use	Calera Corporation
WO20011020927A2	2008	Method for oxidation and carbonation of materials producing granular material with potential for re-use in construction	PBE Descamps *et al.*

[96] Araizi, P.K., Hills, C.D.., Maries, A., Gunning, P. and Wray D.S., 2013. The current status of commercialisation of carbonation technology. 4th International Conference on Accelerated Carbonation for Environmental and Materials Engineering, April 10-12, 2013 – Leuven, Belgium.

Patent Number	Year	Description	Organisation
WO2007096671A1 WO2009024826A1	2006 2007	Method for production of construction aggregate from waste and CO_2	University of Greenwich
WO20020507008A1 GB2371298A	2001 2001	Treatment of solid contaminated materials with CO_2 to produce material for re-use or disposal	Forkers Ltd
GB2461622A	2008	Production of CO_2 absorbing materials, with potential for use in construction	Calera Corporation

CO_2 capture may involve gas compression and a reaction with water to form soluble carbonates/bicarbonates, prior to transformation into solid salts. These carbonates/bicarbonates can then be used as SCMs either as mineral fillers (such as those added to Portland cement or other bound building materials) or as primary materials in a process. Examples of processes which are currently being developed are discussed below:

The Calera process[97] uses absorbed flue gas which is captured and processed via an absorption unit into two main streams: (a) bicarbonates entering an electrochemical installation, and (b) CO_2-free flue gas. For the production of sustainable SCMs, the precipitation, dewatering and drying of calcium carbonate ($CaCO_3$) is required. Pure sodium hydroxide (NaOH) used is regenerated from the electrochemical unit.

The Carbon8 process can utilise point source emissions directly, as demonstrated with combusted landfill gas[98]. The first UK commercial plant uses CO_2 obtained in bulk from a waste source (sugar beet processing plant), located a few miles away for the production of aggregate. The solid waste that is carbonate-solidified is an air pollution control residue (APCr) supplied by powder tanker and the aggregate produced is carbon negative (-44kg CO_2/t). The CO_2 yield is 10-20% (w/w) depending on the feedstock materials, and aggregate production will increase to approximately 100 kt in 2014 with the construction of a second UK plant. Currently, the aggregate is used in the production of 'carbon negative' concrete building blocks[99].

Alcoa Inc. produces large volumes of CO_2 and alkaline waste from aluminium processing. A carbon capture system, involving flue gas from its plants and a reaction with alkaline residues produced by the aluminium production process is being

97 Calera, Calera Technology: Our Process 2010; available from: http://www.calera.com/index.php/technology
98 Carbon8. Technology Overview. 2013 [cited 2013 25 March]; Available from: http://www.c8s.co.uk/technology.php.
99 Lignacite. 1st Genuine Carbon Negative Block. http://www.lignacite.co.uk/Environmental-Centre/1st-genuine-carbon-negative-block.html

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commercially developed. The product has potential to be sold into the construction market[100].

Calix Limited is involved in minerals production and process calcium and magnesium carbonates as powder for the building, agriculture, water and power industries. The company is scaling-up its production and have recently purchase the intellectual property rights to the Novacem process (magnesia-based cement production)[101].

Cambridge Carbon and Capture's (CCC) technology is proven at laboratory scale for the carbonation of silica/metal material for use in construction and (as a by-product) the production of carbon credits due to the generation of 'carbon-free' electrical energy. Candidate feed-stocks also comprise alkaline wastes, which are digested into reactive oxides/silicates and then reacted with captured CO_2 gas[95].

4.1.4 Economics of the technology

CO2 for use in SCM production can be captured by pre-, post-, or oxy-combustion technologies[102]. The costs of CO_2 capture and compression are estimated to be US$75-90/t CO_2**Error! Bookmark not defined.**, which is high and affects the economic production of CMs. Thus, the reduction in cost, or the integration of CO_2 capture process with the SCM process (e.g., Carbon8 process), is needed.

Cost reductions might be achieved by the development of more efficient capture systems, with potential reductions in prices to US$20-US$30/tCO_2 being more favourable for the commercialisation of SCM processes[103].

4.1.5 Active International Projects, planned projects

In 2010 the US Department of Energy (DOE) approved two projects to produce sustainable aggregates for the cement industry[104]:

- Alcoa Inc. (DOE share US$ 12 M): This project was aimed at producing carbonated materials for construction fillers, soil amendments and 'green' fertilisers. The applied process focuses on the effective conversion of flue gas CO_2 into soluble carbonates/bicarbonates by an in-dust scrubber system using enzyme catalysts. The process operates at Alcoa's aluminium refining plant at Point Comfort, Texas.

[100] Alcoa Inc. Company's Overview. 2013 [cited 2013 25 March]; Available from: http://www.alcoa.com/global/en/home.asp.
[101] Calix. A World Leader in Developing Innovative Sustainable Technology. 2013 [cited 2013 25 March]; Available from: http://www.calix.com.au/calix_overview.html.
[102] Gibbins, J. and H. Chalmers, Carbon capture and storage. Energy Policy, 2008. 36(12): p. 4317-4322.
[103] IPCC special report on carbon dioxide capture and storage, in Working Group III of the Intergovernmental Panel on Climate Change, B. Metz, et al., Editors. 2005: USA, New York.
[104] DOE-Fossil Energy. Recovery Act: Innovative Concepts for Beneficial Reuse of Carbon Dioxide. 2012 [cited 2013 25 March]; Available from: http://www.fossil.energy.gov/recovery/projects/beneficial_reuse.html.

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- Calera Corporation (DOE share US$ 19.9 M): This project was aimed at capturing and processing flue gas for CO_2 conversion into aggregates suitable for construction fill or as a partial feed-stock (the limestone *input* to a cement plant) at a viable scale at Moss Landing, California.

Further projects include the Yallourn Power Station, in Victoria, Australia, where Calera is demonstrating CO_2 capture (0.3 Mt/yr) and conversion into building materials. The project is supported by the Australian Government, with aid of US$ 40M[105].

Calix is constructing a US$ 31.1 M scale-up calciner at Bacchus, outside of Melbourne, Australia[106]. In November 2012, a joint venture involving Calix, was awarded a US$ 8.8 M grant to manufacture a $3MW_e$ carbon capture system in Hatfield, Doncaster, UK, using Calix's Endex capture technology.

A Japanese consortium claims to have developed virtually-zero-emission concrete, called CO_2-SUICOM, and has applied it to balconies in a new-build construction project[107].

4.1.6 Regulatory requirements for operations

Local/regional regulations governing the capture, emissions of CO_2, and solid, liquid and gaseous emissions to the environment are pertinent for SCM production.

4.1.7 Technology advancement needs/gaps, RD&D needs

CO_2 can also be used instead of water for curing the cement to produce concrete material for buildings leading to potential energy savings, emission reductions, and lower concrete production cost. Further research and studies are needed to look into these technologies and their techno-economic feasibility.

The capture of CO_2, and its use in the building industry, is an attractive proposition considering the potential environmental and commercial benefits. However, with the current level of technological development and the high cost of CO_2 capture, the volumes of CO_2 that can be realistically utilised in the near future are low.

The development of innovative and efficient capture technologies will lead to a significant decrease in the cost of CO_2, and this will be fundamental in changing the costs of producing SCMs. Furthermore, if CO_2 is given a commercially realistic international trading price, the utilization of large amounts of CO_2 (and their conversion into sustainable construction materials) will become more attractive.

The production of carbonated products from magnesium- and calcium-based feedstock is also set with a challenge, as complete (i.e. 100%) mineralisation of liquids or solid substrates at ambient temperatures and pressures is not possible. The need for elevated

[105] Murphy, M., Calera project to get US$40, in The Age 2010: Melbourne, Australia.
[106] Global CCS Institute. Innovation to drive cuts in CCS costs. [cited 2013 25 March]; Available from: http://www.globalccsinstitute.com/institute/news/innovation-drive-cuts-ccs-costs.
[107] http://www.denka.co.jp/eng/ir/library/pdf/CSR%20REPORT%202012%20E.pdf

temperatures and pressures to obtain higher yields will have a negative impact on process costs.

However, when the benefits of utilising CO_2 in SCMs are to be defined, careful assessment of energy and CO_2 balances for processes being developed must be made. Ideally, when calculating the amount of embodied carbon in SCMs, a robust, (and accepted) methodology should be used, which is independently verifiable by a reputable third party organisation.

With the exception of the Carbon8 process, which is operating in a fully commercial environment, the main target of current projects (section 4.1.5) is to prove economic feasibility at a large-scale and that the SCMs produced meet the required technical specifications for use in construction activities and are fully accepted by the market.

4.1.8 Potential for co-production

Large emitting point sources such as power and gas plants are sources for the capture and compression of CO_2. Direct CO_2 capture ensures that CO_2 emissions are minimised, but the atmospheric release of other pollutants (such as NO_x and particulate matter) may also be prevented. A further benefit is that transportation costs are minimised, however, it is critical that the market for carbon-based SCMs is located not far from the source of their production, as the cost of transportation of dense, high-volume materials can significantly undermine the environmental benefit of sequestrating CO_2 into SCMs.

4.2 CO_2-ASSISTED GEOTHERMAL

4.2.1 Introduction

Heat generated within the Earth can be used for space heating, industrial uses and electric power generation. CO_2-assisted geothermal technologies use CO_2 as the working fluid to mine the heat for direct-use or power generation purposes. Geothermal resources are extensive and unevenly distributed globally. The technical potential for recoverable geothermal energy in the conterminous U.S. to economic drilling-accessible depths of 6.5 km has been estimated to exceed 600,000 exajoules (EJ, 10^{18} J), which is 6,000 times the current primary energy consumption in the U.S. of about 103 EJ annually[108]. In contrast, the actual global installed geothermal electric power capacity was 11.2 GW (U.S. capacity was 3.187 GW) as of May 2012, leading to total potential generation capacity per year of 0.35 EJ (worldwide) and 0.10 EJ (U.S.)[109].

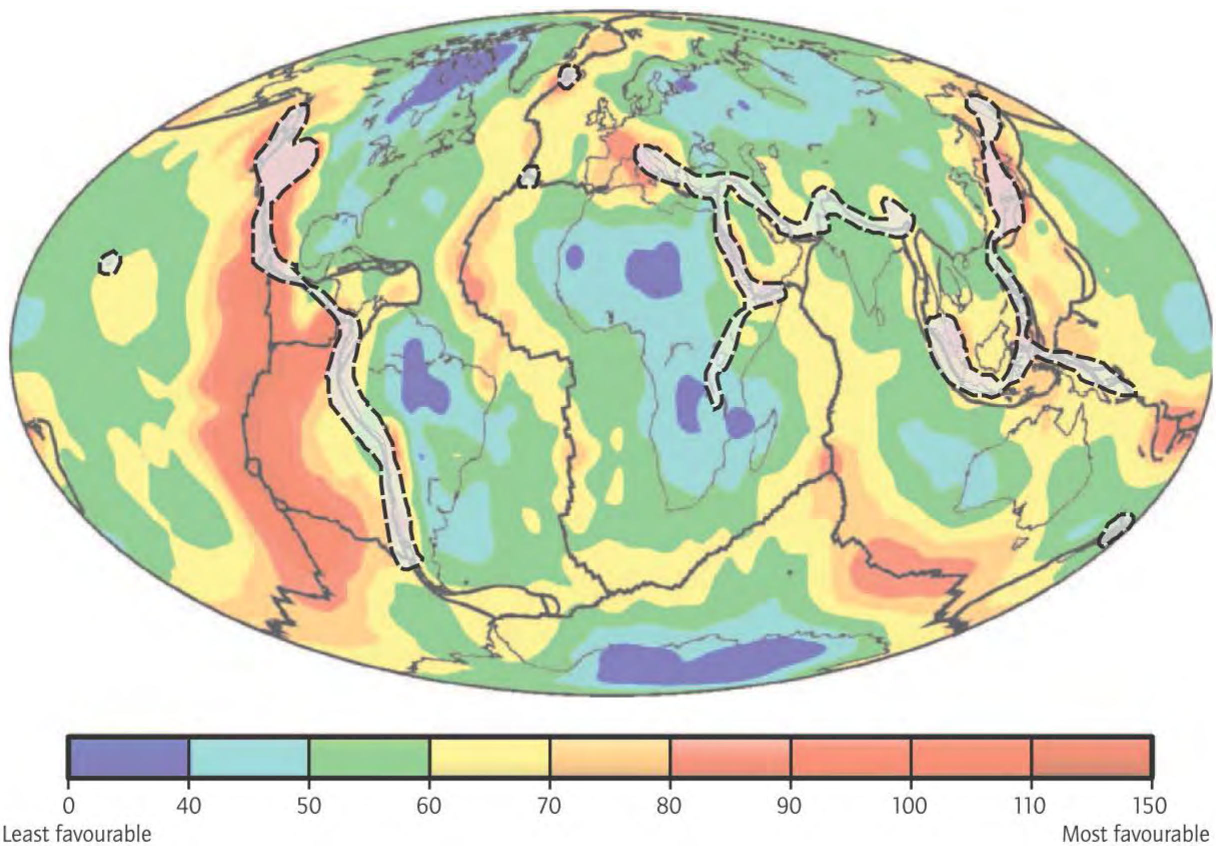

Figure 5. World resource map of convective hydrothermal reservoirs Source: IEA, 2011[130]. Note: Convective hydrothermal reservoirs are shown as light grey areas including heat flow and tectonic plate boundaries)

[108] Tester J.W., et al., 2006. The Future of Geothermal Energy in the 21 Century. Impact of Enhanced Geothermal Systems (EGS) on the United States. Available at: http://www1.eere.energy.gov/geothermal/pdfs/future_geo_energy.pdf

[109] Jennejohn D., et al., 2012. Geothermal: International Market Overview Report, Geothermal Energy Association.

Currently, large-scale commercial extraction of geothermal energy for energy production is limited to high-grade 'hydrothermal' resources found in active volcanic provinces shown in Figure 5. These systems have high-subsurface temperatures (typically exceeding 150 to 190 °C[110]) at shallow depths, and significant permeability allowing fluid circulation to occur naturally via well-connected fracture networks [108,111]. In contrast, there is a considerably larger potential resource base to be found in amagmatic settings. These resources are generally deeper and are characterised by a different heat-source and much lower natural permeability. In order to extract heat from these systems the reservoirs must be engineered to allow the flow of fluid through the hot formation by enhancing existing fractures in the rock or creating new ones. This has led to these non-volcanic resources to be known as engineered (or enhanced) geothermal systems (EGS) The total amount of heat contained in amagmatic resources around the world has been estimated to be about 800 times that of the available volcanically driven 'hydrothermal' resource[112],[108].

EGS systems are based on drilling boreholes to depths of 3 to 5 kilometers, injecting water at high pressure to enhance natural rock fractures or to create new ones, and extracting thermal energy by circulating water through a system of injection and production wells. The water can be provided by the deep reservoir itself without any supply of fresh water. For example, at the Soultz-sous-Forêt water-EGS pilot in France[134], water (175 °C at 5000 m) from the deep reservoir is used to recover heat. The EGS concept is an outgrowth of several research programs conducted around the world starting in 1973. Because water is scarce in many arid regions throughout the world, and up to 5% of the injected water may be lost to the reservoir during circulation, D.W. Brown (2000)[113] proposed that CO_2 could be used as both heat transfer fluid and fracturing/shearing fluid instead of water in EGS developments. It has been suggested that the use of CO_2 would reduce pumping costs, reduce scaling and silica dissolution issues, and result carbon sequestration in the crystalline basement rocks[113]. Supercritical CO_2 (sc.CO_2) has 60-75 percent lower specific heat (at 150 °C) compared to water. However, sc.CO_2 also has significantly lower viscosity compared to water, zero surface tension, and can access fractures not wetted by water[114]. Supercritical CO_2 also has a significantly higher mobility (density/viscosity) compared to water, and higher flow rates can be circulated through the turbine, resulting in an overall higher heat extraction rate, lower pumping costs, and higher net power output. There are two variations in CO_2-assisted geothermal power production processes (see Figure 6):

- *CO_2-engineered geothermal systems (CO_2-EGS)*

110 Dickson, M., Fanelli, M., 2004. What is Geothermal Energy?, International Geothermal Association. Available at: http://www.geothermal-energy.org/geothermal_energy/what_is_geothermal_energy.html

111 Saar, 2012. The multi-functionality of geologically sequestered carbon dioxide: From geothermal energy extraction to renewable energy storage, Presented at Midwest Groundwater Conference, Oct 2, 2012.

112 Duchane, D., Brown, D.W., 2003. Hot Dry Rock (HDR) Geothermal Energy Research and Development at Fenton Hill, New Mexico.

113 Brown,D.W., 2000. A Hot Dry Rock Geothermal Energy Concept Utilizing Supercritical CO_2 Instead of Water, Proceedings of the Twenty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, January 24-26, 2000. Available at: http://www.geothermal-energy.org/pdf/IGAstandard/SGW/2000/Brown.pdf

114 GreenFire Energy, 2011. CO_2 E™ (CO_2-based Energy): Using CO_2, pressure, and geothermal heat to provide clean, baseload electricity, energy storage and carbon sequestration.

In these systems, hydraulic fracturing or CO_2 fracturing are carried out to circulate CO_2 in crystalline, EGS resources. There are a handful of EGS projects around the world, none of which is currently injecting CO_2. For now, the effectiveness of CO_2-EGS has been studied through simulations. Pruess and coworkers further explored the CO_2-EGS concept proposed by Brown through numerical simulations[115] using a five-spot pattern with four injectors and one producer, and found CO_2 to be superior to water-based fluids in recovering heat from the hot fractured rock.

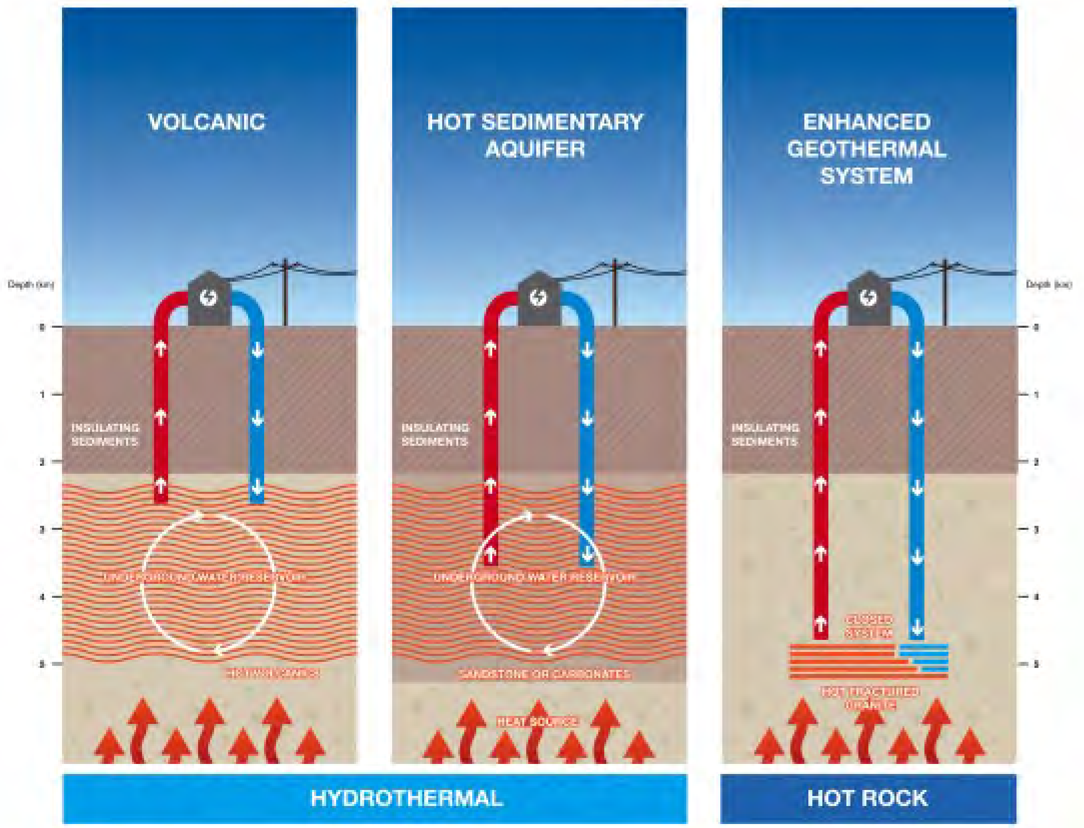

Figure 6. Illustration of the different types of geothermal energy systems.

Source: http://www.greenearthenergy.com.au/geothermal/.

- *CO_2-Deep/Hot Sedimentary Geothermal Systems*

This concept is an extension of the CO_2-EGS concept to hot, deep, saline, sedimentary formations which have high natural permeability and porosity, avoiding the need to enhance the permeability further . The geothermal energy resource in major U.S. sedimentary basins has recently been preliminarily assessed[116]. The CO_2 plume

[115] See for example, Pruess, K., 2006. Enhanced geothermal systems (EGS) using CO_2 as working fluid—A novel approach for generating renewable energy with simultaneous sequestration of carbon, Geothermics, 35(4), p.351-367, and references citing Pruess (2006).

[116] Porro, C., Augustine, C., 2012. Estimate of geothermal energy resource in major U.S. sedimentary basins. NREL/PR-6A20-55017. Available at: http://www.nrel.gov/docs/fy12osti/55017.pdf

geothermal system (CPG) proposed by Saar and coworkers[117,118,119] is an example of the use of CO_2 to extract heat from deep, hot, sedimentary formations with high thermal gradients. The concept is similar to CO_2-EOR or saline aquifer storage in that the formation brine is displaced by CO_2 during and before the start of power generation. The benefits of extracting geothermal energy from sedimentary rock are that the formations (referred to as reservoirs) are well characterized, and many geophysical data are already available from oil and gas logs. Drilling and reservoir fracturing techniques are proven in sedimentary environments. The drawbacks are that deep drilling is required to reach high temperatures, which is not yet commercial. Furthermore, formation permeability also typically decreases with depth, making deep drilling counterproductive.

4.2.2 *Metrics*

The CO_2 demand (or makeup rate) for the CO_2-assisted geothermal processes has two components: the diffusive loss of CO_2 to the formation/reservoir, and the reaction of $scCO_2$ with rock minerals to form precipitates. Loss rates of 5% to 7% have been considered in models of CO_2-EGS and CPG. The flow rate of CO_2 and the amount of electricity generated vary with time, with the net-heat extraction and power output tailing off towards the end of the project. Typical quantities of additional CO_2 injected per well from previous modeling studies are in the order of tens of kg CO_2/s[120]. Total heat reservoir volumes of ~10^8 m^3 are considered commercially viable for EGS[121].

4.2.3 *Current State of Technology*

CO_2-assisted geothermal systems consist of subsurface wells/reservoirs to allow the flow of CO_2 through hot rocks or sedimentary rocks, and the surface heat transfer, power production, and pumping equipment. There are two types of cycles used for geothermal power generation: dry steam/flash cycles for temperatures > 180 °C, and binary cycles (e.g., organic Rankine cycles) for moderate to low temperatures[122]. Binary cycle power plants have an efficiency of 10% to 13%, which is lower than that of flash steam-water based geothermal plants. Recent developments of power cycles using CO_2 as a working

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[117] Randolph, J.B. and Saar, M.O., 2011. Coupling carbon dioxide sequestration with geothermal energy capture in naturally permeable, porous geologic formations: Implications for CO_2 sequestration. Energy Procedia, 4, 2206–2213.

[118] Randolph, J.B. and Saar, M.O., 2011. Impact of reservoir permeability on the choice of subsurface geothermal heat exchange fluid: CO_2 versus water and native brine. Proceedings for the Geothermal Resources Council 35th Annual Meeting: 23–26 Oct, 2011, San Diego, CA, USA.

[119] Randolph, J.B., and Saar, M.O., 2011. Combining geothermal energy capture with geologic carbon dioxide sequestration, Geophysical Research Letters, 38, L10401, doi:10.1029/2011GL047265.

[120] See for example, Ram Mohan, A., et al., Using CO_2 from an IGCC plant as a heat transfer fluid for the extraction of geothermal energy for power generation from EGS. . Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, February 11-13, 2013.

[121] Pogacnik, J.A.,et al., 2013. CGS – Controlled wellbore-to-wellbore geothermal system flow. Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, February 11-13, 2013

[122] Eastman, A.D., Muir, M.P., 2013. CO_2-EGS and the utilization of pressurized CO_2 for purposes other than power generation. Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, February 11-13, 2013.

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fluid may further increase the heat-to-power conversion efficiency of heat sources at low temperatures[123,124].

CO_2-assisted geothermal systems are at very early stages of development. Compared to CO_2-EGS, the injection of CO_2 in hot, sedimentary geothermal systems (e.g., CPG), has lower risks due to induced seismicity, but individual technologies such as deep well drilling, brine management, heat transfer, and power production need to be integrated and optimized in smaller-scale tests before large-scale tests can be conducted.

There are two pilot-scale CO_2-assisted geothermal tests being performed in the USA. GreenFire Energy plans to demonstrate CO_2 injection in basement rocks at the St. Johns Dome in Arizona, leading to the production of 1 to 2 MW of geothermal electricity. The source of CO_2 for this project is the gas produced from shallow overlying formations at the St. Johns Dome[125]. A pilot geothermal study on CO_2 injection into deep, hot sedimentary formations is being conducted at the Southeast Regional Carbon Sequestration Partnership (SECARB) Cranfield site in Cranfield, Mississippi, USA[126]. Detailed site knowledge gained during earlier research-scale CO_2 injections at the site will be used to plan and develop the CO_2 injection into the deep (3.1 km), hot sediments using one injector and one producer.

Recent simulations of CO_2-EGS and hot-sedimentary geothermal systems have addressed the complex coupling between the flow, heat transfer, and geochemical reactions that occur when CO_2 and residual water are circulated through the HDR system. Generally, several investigators note that the five-spot pattern is suitable for operation using $scCO_2$ in EGS or CPG systems, and that the project lifetimes can exceed 25 years.

Current experimental work at the laboratory scale is focussed on understanding rock-residual brine-CO_2 interactions, and the two-phase flow of brine and supercritical CO_2 through fractures and sedimentary rocks under conditions relevant to geothermal energy extraction[127,128,129]. Some key questions addressed by such studies include the change in

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[123] Robb, D., 2012. Supercritical CO_2: The next big step? Turbomachinery International, v.53, no.5, p.22-28.
[124] $Sc.CO_2$ as a working fluid may improve the efficiency of power cycles, and is not supposed to be a means of mitigating climate change.
[125] Muir, M.P., Eastman, A.D., 2013. Single-well low temperature CO_2-based engineered geothermal system. Presented at the Geothermal Technologies Office 2013 Peer Review.
[126] Freifeld, B., et al., 2012. Geothermal energy production coupled with CCS: a field demonstration at the SECARB Cranfield Site, Cranfield, Mississippi, USA. International Conference on Greenhouse Gas Technologies (GHGT-11), 18-22 November, 2012, Kyoto, Japan.
[127] Mattson, E.D., et al., 2013. EGS-rock interactions with supercritical CO_2 saturated with water, and water saturated with supercritical CO_2. Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, February 11-13, 2013
[128] Smith M.M., et al., 2013. Experimental investigation of brine-CO_2 flow through a Natural Fracture: Permeability increases with concurrent dissolution/precipitation reactions. Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, February 11-13, 2013.
[129] Petro M., et al., 2013. Experimental study of rock-fluid interactions using automated multi-channel system operated under conditions of CO_2-based geothermal systems. Proceedings of the Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, February 11-13, 2013.

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HDR or sedimentary formation permeability as a result of CO_2 injection and CO_2 leakage to the overlying strata.

4.2.4 Economics of the technology

The levelized costs of producing CO_2-assisted geothermal heat or electricity are region specific and depend on the cost of CO_2. Eastman and Muir[122] note that the unit cost of water in the Western U.S. (~\$0.1 to \$0.2/t) is significantly lower than the cost of CO_2 (~ \$40/t to \$100/t), leading to high first-fill and operational costs[129].

The costs of EGS and the costs of conventional hydrothermal plants may be considered as lower limiting estimates for CO_2-assisted geothermal power systems. Levelized geothermal electricity generation costs for hydrothermal plants range from \$50/MWh_e to \$110/MWh_e depending on the heat content of the geothermal resource[130]. Estimated costs for EGS in the US and Europe vary from \$100/MWh_e to \$190/MWh_e and \$250/MWh_e to \$300/MWh_e respectively. The U.S. DOE aims to lower the LCOE of EGS electricity generation to \$60/MWh_e by 2030[131].

The cost of geothermal energy in Europe by 2015 is forecasted to be around 80€/MWh_e. This value has to be compared with:

- Between €50 to €130/MWh_e for nuclear electricity
- €40/MWh_e for gas
- €45/MWh_e for coal
- €40/MWh_e for wind.

In conclusion, the development of energy production from EGS systems is largely determined by its profitability. Currently, this production option is expensive because it requires very deep and costly boreholes and the financial risk is high due to the great uncertainty on reservoir productivity in unfamiliar geological media. The current scenarios do not expect an industrial deployment before 2020-2030.

In this context and because of the additional cost induced by the introduction of CO_2 into the system, the use of CO_2 in the primary loop would raise the threshold of profitability of the geothermal installation.

4.2.5 Active International Projects, planned projects

In the US, GreenFire Energy was awarded a DOE grant in 2010 to implement a 1 to 2 MW-scale CO_2-EGS project at the Springerville-St. Johns Dome in eastern Arizona. CO_2 produced from shallow formations would be compressed and re-injected into granie/schist-containing basement rocks. The project involves drilling a test well to 6,500 ft depth, performing a huff-and-puff test by injecting and producing CO_2 to obtain

[130] IEA, 2011. Technology Roadmap: Geothermal Heat and Power,. Available at: http://www.iea.org/publications/freepublications/publication/Geothermal_Roadmap.pdf
[131] http://www1.eere.energy.gov/geothermal/vision_mission_goals.html

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and revise data on formation characteristics, and finally installing and testing a 1 to 2 MW geothermal electric generation system[132].

As discussed in section 4.2.3, the Cranfield geothermal pilot aims to demonstrate concurrent CO_2 storage and geothermal electricity generation.

Europe has 11 EGS projects under development in Croatia, France, Germany, Hungary, Ireland, United Kingdom, Slovakia, Slovenia, and Spain[133]. The lessons learned from the water-EGS pilot at Soultz-Sous-Forêts may be applicable for CO_2-EGS projects in other parts of Europe and around the world[134].

There are 6 or more EGS projects of various styles which are at a range of stages of development in Australia. None of these projects are currently considering using CO_2 as the primary fluid.

Other countries such as India and China are known to be investigating potential EGS developments, although their exact progress and plans are unknown. It is not known if CO_2-EGS is being considered.

4.2.6 Regulatory requirements for operations

One of the concerns with EGS projects is the potential for induced seismicity. For example, heightened public perceptions due to earthquakes generated concurrent with water injection at an EGS project in Basel, Switzerland resulted in the project's suspension in 2006. A protocol for addressing induced seismicity associated with EGS, based on experiences from several projects, was developed by the U.S. DOE to address the concerns of public and policymakers[135]. The steps suggested to address induced seismicity involve implementing a preliminary screening study, community outreach, selecting criteria for ground vibration and noise, establishing local seismic monitoring, quantifying the hazard from natural-, and induced-seismic events, characterizing the risk of induced-seismic events, and developing risk-based mitigation plans.

Regulators may require the injection rates to be below that which can lead to observable seismicity. One example of regulatory requirements for CO_2-EGS can be gleaned from the GreenFire Energy project which required mineral exploration, site access, well drilling, underground injection control (UIC) class V, and aquifer protection permits. This project is located in an area of low seismicity. A passive seismic network would be used for obtaining a seismic background before drilling and injection, and to monitor

[132] Eastman, Muir, 2012. Update of a Trial of CO_2-based Geothermal at the St. Johns Dome. Proceedings of the Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, Jan 30 - Feb 1, 2012.
[133] Gibaud, J.P., 2011. Geothermal Electricity Market in Europe, European Geothermal Energy Council, Available at: http://egec.info/wp-content/uploads/2011/12/Geo-Elec-Market-Report-2011-.pdf
[134] http://www.rets-project.eu/UserFiles/File/pdf/Best%20practices/ADEC/BP_SOULTZ_EN_v2.pdf
[135] Majer, E., et al., 2012. Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems, DOE/EE-0662. Available at: http://www1.eere.energy.gov/geothermal/pdfs/geothermal_seismicity_protocol_012012.pdf

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fracture formation and fluid movement during fracturing, injection and production operations.

4.2.7 Technology advancement needs/gaps, RD&D needs

Although sc.CO_2 can result in a higher-net power output compared to water, uncertainties associated with CO_2 transport and reactions in the subsurface, long-term mechanical integrity of injection and production wells, reliability of the power plant, and reservoir response to CO_2 injection may lead to the operators choosing water as a heat-exchange medium over sc.CO_2.

One of the main impediments to CO_2-EGS is the risk of induced seismicity due to CO_2 injection. Multiple monitoring technologies (e.g., microseismic, isotopes, tracers) need be deployed to ensure that the project managers have an accurate understanding of fracture development and flow in the subsurface. Community outreach and public acceptance are critical to project success.

Creating and controlling permeability in basement rocks for large-scale CO_2-EGS (wellbore-wellbore offset of ~100 m) to ensure that a large rock volume contacts the CO_2 is a challenge[121]. If rock volume contacting the cold CO_2 is inadequate, the project life would be limited due to the cooling of the active volume upon scCO_2 circulation.

Water management during EGS and CPG is a critical issue. Water produced from deep subsurface as a result of CO_2 injection is typically saline, and may also contain high proportions of metal ions and needs to be properly handled and disposed. A surface reverse osmosis (RO) system may be used to produce fresh water, but requires additional capital and operating expenditures.

As CO_2 is injected in an EGS reservoir, the composition of the produced fluid would change from brine, brine+CO_2, to CO_2 because the injected CO_2 displaces any existing fluids within the formation or fracture. In the case of CO_2-EGS, water may be present as a result of fraccing performed to create the fracture flow paths. The displacement of brine by CO_2 may lead to the precipitation of salts around the wellbore, reducing permeability[136]. Overcoming such problems may require the co-injection of CO_2 and brine.

A majority of the pressure drop for water-based EGS systems occurs as frictional losses in the reservoir. In contrast, the majority of pressure loss in CO_2-EGS occurs in the wellbore. Wellbores need to be designed for CO_2 to minimize pressure losses and pumping costs[137].

[136] Borgia, A., Pruess, K., Kneafsey, T.J., Oldenburg, C.M. and Pan L., 2012. Simulation of CO_2-EGS in a fractured reservoir with salt precipitations, Proceedings of the ThirtySeventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California.

[137] Atrens A.D., et al., 2010. Electricity generation using a carbon-dioxide thermosiphon, Geothermics, v.39, p.161-169.

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The water saturation of sc.CO_2 has a detrimental effect on the conversion of silicates to carbonates and needs to be studied further as a carbonates may be formed in the reservoir formation and in wellbores, further increasing the risk of reduced permeability. Corrosion prevention certainly has to be considered and included in cost estimates when estimating the feasibility of CO_2-EGS or CO_2-CPG. Furthermore, the addition of even small impurities to CO_2 changes the temperature and pressure at which the gas will transform to a liquid, solid or supercritical fluid. The addition of some gases (eg. N_2, O_2) provokes the transformation of the gas or the supercritical fluid into a liquid-gas mixture. These changes in phase behavior provoke corresponding changes in the transport and compressibility of the injected gas which can have dramatic effects on gas transport in the subsurface..

4.2.8 Potential for co-production

CO_2-assisted geothermal has a high potential for the concurrent recovery of geothermal energy with simultaneous geologic storage of CO_2, as discussed in the previous paragraphs. The extent to which this can be realized depends on the developments in each technology area and public perceptions of the injection of CO_2 in the subsurface.

5. SUMMARY AND CONCLUSIONS

This report provides a more detailed summary and analysis of selected options to utilize carbon dioxide (CO_2) from the Phase I report. As identified in the Phase I report, market potential for many of the utilization options is limited (i.e., small, and/or ‘niche’), with some exceptions (e.g., enhanced oil recovery - not a subject of this report - or the conversion of CO_2 to fuels or chemicals). However, when taken cumulatively, the sum of these options can provide a number of technological mechanisms to utilize CO_2 in a manner that has potential to provide economic benefits for fossil fuel fired power plants or industrial processes: As such, they may well be a means of supporting the early deployment of carbon capture and storage (CCS) in certain circumstances and accelerating deployment.

CO_2 has the potential to be used in the extraction of other energy resources, as a working fluid, and as a chemical feedstock. These applications have some market potential, although the technology maturity varies widely. Some applications, such as urea production, already have an existing global market, while others have the potential for significant markets but technical and economic challenges must be addressed.

5.1 MAIN TECHNICAL CHALLENGES

The primary technical challenges surrounding several of the CO_2 utilization options identified in this report center around research, development, and demonstration (RD&D) efforts to validate the utilization of CO_2 as an option, reduce the cost and improve the efficiency.

The main technical challenges for the specific options are:

CO_2 for enhanced gas recovery (CO_2-EGR): Numerous desk studies on CO_2-EGR exist in the literature, but only a very limited number of field tests has been performed so far (both for CO_2-EGR, as well as for N_2-EGR). In general these field tests, with the nearly depleted K12-B gas field in the Dutch offshore sector being the most well-known (if not the only one), have injected too little amounts of CO_2 to draw firm conclusions on the EGR potential. The primary technical challenges are to predict (early) breakthrough of CO_2 (or any other driving gas like N_2) at production wells, to predict the mixing of the gasses and to monitor the process. The lack of experience around this technology makes it difficult to assess its economic potential, though recently two projects in preparation for industrial (N_2-)EGR have been announced, demonstrating at least the commercial interests.

CO_2 for shale gas recovery: Laboratory studies and some field tests have been performed using CO_2 to preferentially displace methane and adsorb on shale formations. Further, tests have been performed using CO_2 as a replacement fluid for water in the fracturing process. The primary technical issue with CO_2 for shale gas recovery, utilizing CO_2 as both the fracturing fluid and for methane displacement, is the lack of testing to understand the dynamics of the process and assess the costs.

CO_2 for shale oil recovery: The primary issue with utilizing CO_2 as a fracturing fluid is cost relative to other alternatives. The technical challenges associated with CO_2 use are the lack of appropriate viscosity enhancers that can improve stimulation operations or open opportunities for otherwise uneconomic reservoirs.

Urea production: Urea is commercially produced today and there are no significant technical challenges. The technical challenges that do exist for urea are primarily related to the feedstock that is used to produce hydrogen and ammonia. For example, coal-derived feedstock is typically at the higher end of current global prices. Technology improvements in synthesis gas production are needed, but not advancements in urea synthesis/production.

Algal routes to fuel, chemicals and animal feed stocks: The key technical challenges associated with using CO_2 to enhance the cultivation of microalgae species as a precursor to various fuels, chemicals and animal feed stock are maximizing the lipid productivity, addressing possible contamination issues and developing cost-effective harvesting, processing, and dewatering techniques. Also, different system designs (e.g., open raceway ponds versus photobioreactors) pose different challenges relative to land use and process control (ponds), and gas-liquid mass transfer, prevention of wall-growth and energy efficiency for mixing/cooling (photobioreactors).

<u>CO_2 utilization in greenhouses</u>: The primary technical issues with utilization of CO_2 in greenhouses are their integration with various CO_2 sources and quantifying the potential regional benefits from this utilization option.

<u>Aggregate and secondary construction material production</u>: The key technical challenge for the utilization of CO_2 for the production of building materials such as concrete is to improve the rate of reaction for the conversion/synthesis to optimize the process and product yields. Another challenge is ensuring that the products meet established cost and technical performance requirements and standards.

<u>CO_2-assisted geothermal systems (CO_2-EGS)</u>: There are several issues related to the use of CO_2 in enhanced geothermal systems. These include limited knowledge of the geochemical impacts of CO_2 and long-term retention of CO_2 in the reservoir and the design and optimization of systems that utilize CO_2 for heat extraction and subsequent power generation. Similar to other areas of utilization or storage of CO_2 in the subsurface discussed in this report, CO_2-EGS is not well understood.

5.2 RECOMMENDATIONS

In summary, there are a wide range of CO_2 utilization options available, which can serve as additional mechanisms for deployment and commercialization of CCS by providing an economic return for the capture and utilization of CO_2. This Phase II report results in several recommendations that can assist with the continued development and deployment of non-EOR CO_2 utilization options in this context.

1. For technologies which are commercially and technologically mature, such as urea production and utilization in greenhouses, efforts should be on demonstration projects. For urea production, the focus should be on the use of non-traditional feedstocks (such as coal) or 'polygeneration' concepts (e.g., those based on integrated gasification combined cycle (IGCC) concepts) which can help facilitate CCS deployment by diversifying the product mix and providing a mechanism for return on investment. For utilization in greenhouses, new and integrated concepts that can couple surplus and demand for CO_2 as well as energy, thus optimizing the whole energy and economic system would be valuable.

2. Efforts that are focused on hydrocarbon recovery, such as CO_2 for enhanced gas recovery (via methane displacement), or CO_2 utilization as a fracturing fluid, should focus on field tests to validate existing technologies and capabilities, and to understand the dynamics of CO_2 interactions in the reservoir. R&D efforts on CO_2 as a fracturing fluid should focus on the development of viscosity enhancers that can improve efficiency and optimize the process. Issues such as wellbore construction, monitoring and simulations should leverage those tools and technologies that currently exist in industry or are under development through existing CCS R&D efforts.

3. For algal routes to fuels and aggregate/secondary construction materials production, the primary focus should be on R&D activities that address the key techno-economic challenges previously identified for these particular utilization options. Independent tests to verify the performance of these products compared to technical requirements and standards should be conducted. Support of small, pilot-scale tests of first generation technologies and designs could help provide initial data on engineering and process challenges of these options.

4. For CO_2-assisted geothermal systems, more R&D and studies are necessary to address the subsurface impacts of utilizing CO_2 in this application. Additionally, small pilot-scale tests could provide some initial data on actual operational impacts and key engineering challenges that need to be addressed.

5. Finally, more detailed technical, economic, and environmental analyses should be conducted to better quantify the potential impacts and economic potential of these

technologies and to clarify how R&D could potentially expand the market for these utilization options (e.g., in enhanced gas recovery) and improve the economic and environmental performance of the system. A holistic approach, incorporating several distinct perspectives, is important.

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TECHNICAL GROUP

2013 Annual Report by the CSLF Task Force on Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2

Background

At the September 2011 CSLF Ministerial Meeting in Beijing, a Task Force was formed to investigate CCS Technology Opportunities and Gaps. The Task Force mandate was to perform initial identification and review of best practices and standards for storage and monitoring of injected CO_2. This document is the 2013 Annual Report from the Task Force.

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Reviewing Best Practices and Standards for Geologic Storage and Monitoring of CO_2

Initial Compilation of Standards, Best Practices and Guidelines for CO_2 Storage and Monitoring

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Executive Summary

This report is the delivery of from Phase 1 of Task Force 6 of the Carbon Sequestration Leadership Forum (CSLF) Technical Group. As such it is an update of a report from CO2CRC (2011), which presented a list of standards, guidelines and best practice manuals (BPMs) related to carbon capture and storage (CCS). It gives an initial compilation of BPMs and similar documents and contains brief reviews of documents issued after the CO2CRC report.

So far (June 2013) only one standard on CCS has been identified, the Canadian CSA Z741-12. It is also the only identified document that appears to cover all topics listed. This initial compilation shows that site selection, monitoring and verification and risk assessment are well covered by existing standards, BPMs or guidance documents.

Recommendations for follow-up

It is recommended that Task Force 6 carries its work into a Phase 2. The objective of this phase will be to:
- Identify the applicability and the shortcomings of the various BPMs
- Communicate the results to ISO TC265 (ISO committee for development of a CCS standard).

The scope of the work in Phase 2 will be:
1. Remove documents which are outdated (this may apply to most documents more than five years old) or have been issued in revised/updated versions
2. Sort the BPMs and guidelines according to topic (monitoring, risk assessment, etc.)
3. Link the BPMs and guidelines to topics in the Canadian Standard on geological storage of carbon dioxide (CSA Z741-12) and stakeholders (operators, regulators, technology providers)
4. Suggest layout of a web based solution for annual updates, e.g. using the web site proposed by the CSLF Projects Interaction and Review Team (PIRT).

Points 3 and 4 will be the most important contribution of the Task Force. They will help users of the standard to find more detailed assistance in a concise way, e.g. in form of a matrix, and will reveal shortcomings of the suite of PBMs and guidelines.

Deliverables
- A brief report describing the relevance of the various BPMs and guidelines to existing standards on CCS and various stakeholders
- A proposal for further updates using a web based solution

Schedule
- Approval of further work: November 2013
- Commitment by Task Force members by November 2013 (essential to complete the suggested programme)
- Annual report: December 2013
- Deliverables: End of march 2014.

1. Background

At the meeting of the CSLF technical Group in Bergen, Norway June 12, 2012, it was agreed that the new Task Force on "Monitoring of Geologic Storage for Commercial Projects" (TF6) should:

1. Identify and review existing standards for geological CO_2 storage and monitoring on an annual basis;
2. Identify and review existing guidelines for communication with and engagement of involved communities and regulators on an annual basis;
3. Identify shortcomings and/or weaknesses in standards/guidelines;
4. Communicate findings to the ISO TC 265 that has been established to produce a standards on CCS;
5. 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; and
6. Follow the work of other task forces related to CO_2 storage, e.g.:
   a. Task Force on Action Plan #7 – Technical Challenges for Conversion of CO_2-EOR to CCS (Chaired by Canada).
   b. Task Force on Action Plan #1 – Technology Gap Closure (Chaired by Australia)^

A list of Task Force members can be found in Appendix H.

The following schedule was agreed following the Bergen meeting in June 2012:

- Early Sept 2012. Draft of initial compilation of standards etc to TF
- Mid-Dec. 2012 Interim report
- 15. May 2013 Draft of compilation of standards, guidelines etc
- 01. July 2013 Comments from TF on draft
- Mid Sept. 2013 Report to Secretariat
- Oct. 2013 Report to Ministerial Meeting

It was also agreed that the fall 2013 report should be a decision gate for termination or continuation, depending on e.g. progress made by ISO. Further deliverables will be decided after the decision gate in fall 2013.

Thus it will be useful to divide the work of the Task Force into phases as follows:

- Phase 1: The initial compilation of BPMs, to be delivered in September 2013
- Phase 2: Identifying the applicability and the shortcomings of the various BPMs, with a report to be delivered in time for the fall CSLF meeting 2014
- Phase 3: Annual updates of the compilation.

Each phase will represent a decision gate, with recommendation on continuation or termination of the Task Force. The final report will in any circumstance be completed no later than by fall 2016. Communication with ISO TC265 will be a continuous process.

2. Scope of this note

This is the report from Phase 1 of the Task Force, the initial compilation of standards, Best Practices Manuals (BPMs) and guidelines for technical aspects of geologic storage of CO_2. Hereafter the term BPM is used for all three concepts. The report lists relevant BPMs on geologic storage of CO_2 and gives a very brief summary of the contents.

As stated at the Bergen meeting in June 2012, the report is an update of a summary by CO2CRC (2011), issued in March 2011, in which BPMs issued after March 2011 have been added.

The BPMs and other documents listed in the various tables and appendices of this report have been carefully compiled and are publicly available. Nevertheless, the lists may not be exhaustive.

Some guidelines and BPMs concerned with regulatory issues, community engagement and communication are listed in Appendices A and B, respectively but not discussed further.

Appendix C gives a list of monitoring methods used in some storage projects and Appendices D, E and F list some publications related to, respectively, risk assessment methods, CO_2 storage atlases and BPMs for CO_2 pipelines. These have been included as a result of input from inside and outside the Task Force but will not pursued further unless the proponents take on to do the work.

There is a substantial body of general literature (lessons learned, experiences, etc) with content that may contribute to improving or supplementing best practices, standards etc. Such literature is not included in this first overview but a selection of publications will be included in an update.

3. Identified standards, best practices manuals and guidelines for CO_2 storage

Table 1 lists the short names used for the BPMs that are included in Tables 2-5.. Tables 2 – 5 show the following:

- Table 2: This is a copy CO2CRC's summaries, with the exception of CO2NET Work Package 7 Best Practice Review from 2004, which is not included here due to its age and very limited scope
- Table 3: This table gives brief summaries of content of BPMs not included in the CO2CRC report or issued after March 2011
- Table 4: A selection of guidance documents or guidelines that have been published as annexes or similar to regulations on CO_2 storage
- Table 5: This table repeats CO2CRC's assessment of the BPMs in Table 2 and supplements it with *suggested* assessment of the BPMs and guidelines in Tables 3 and 4.

CO2CRC (2011) has assessed the scope and content of the BPMs listed in Table 2 with respect level of details for the following aspects: pre-feasibility, site selection, capacity estimation, simulation and modelling, construction, operation, closure, monitoring and verification, risk assessment, community consultation and regulation.

Table 1. Short name of BPMs listed in Tables 2 – 5.

Short name used in Table 2	Full name
CO2STORE	Best practice for the storage of CO_2 in saline aquifers
CCP	A technical basis for carbon dioxide storage
DNV CO2QUAL	Guideline for selection and qualification of sites and projects for geologic storage of CO_2
DNV CO2WELLS	CO2WELLSGuideline for the risk management of existing wells at CO_2 geological storage site
DNV RP-J203	Geological Storage of Carbon Dioxide (DNV-RP-J203)
LBNL/GEOSEQ	Geologic carbon dioxide sequestration: Site evaluation to implementation
NETL MVA	Best practices for: Monitoring, verification, and accounting of CO_2 stored in deep geologic formation
NETL GS	Best practices for: Geologic storage formation classification: Understanding its importance and impacts on CCS opportunities in the United States
NETL SS	Best practices for: Site screening, site selection, and initial characterization for storage of CO_2 in deep geologic formations
NETL RA	Risk analysis and simulation for geologic storage of CO_2
NETL WM	Best practices for: Carbon Storage Systems and Well Management Activities
WRI CCS	Guidelines for CCS
IEA Weyburn	Best Practice Manual developed through learning from Weyburn project
CSA	Z741-12 Geological storage of carbon dioxide
AU1	Australian Guiding Principles for Carbon Dioxide Capture and Geological Storage(Guiding Principles)
AU2	Environmental Guidelines for Carbon Dioxide Capture and Geological Storage – 2009
EC1	Guidance Document 1. CO_2 Storage Life Cycle Risk Management Framework
EC2	Guidance Document 2. Characterization of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures
OSPAR	OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations
London	London Convention and Protocol: Specific Guidelines to Risk Assessment and Management Framework (RAMF) 2006
EPA	Geologic Sequestration of Carbon Dioxide: Underground Injection Control (UIC) Program Class VI Well Project Plan Development Guidance

Table 2. Most relevant best practice manuals listed in CO2CRC (2011), excluding those addressing regulatory and public engagement issues as well as those purely addressing capacity estimation, sorted alphabetically by issuing organization and then chronologically. Comments are based on CO2CRC (2011).

Date	Issued by	Title (Short name used in Table 5, followed by full name and link)	Contents	Comment
2008	BGS	CO2STORE: Best practice for the storage of CO_2 in saline aquifers (http://nora.nerc.ac.uk/2959/)	First published in 2003. The latest version (2008) covers all aspects of storage in saline aquifers: • Identifying ideal reservoir • Seal properties • Capacity estimation • Predictive flow modelling, • Geochemical and geomechanical site characterization • Operating the site • Cost estimation • Transport needs • Monitoring plan design • History matching based on monitoring data • Safety and risk assessment procedures.	The information is presented through case studies of what was done and learned at 5 separate projects, offshore and onshore, including Sleipner and Schwarze Pumpe.
Jan. 2009	CO_2 Capture Project (CCP)	CCP: A technical basis for carbon dioxide storage (http://www.co2captureproject.org/co2_storage_technical_book.html)	Covers: • Background and site selection • Operation • Closure • Monitoring • Detailed guide for well construction and completion that contains discussions on materials and the factors that govern which you can use and when (a significant addition that this publication includes and others do not). The BPM covers, with enough detail to be considered beyond basic, a technical understanding of the aspects of CO_2storage.	Based on experiences from participating companies in CO_2injection. Use a large number of case studies, separated from the text as standalone examples, to illustrate how the advice given in each section was used in reality. It is a guide to developing a storage project.

Feb. 2010	DNV	DNV CO2QUAL: Guideline for selection and qualification of sites and projects for geological storage of CO_2 (http://www.dnv.com.au/binaries/CO2QUALSTORE_guideline_tcm162-412142.pdf)	A step by step guide to selecting a CO_2 storage site that covers • Pre-feasibility stages of developing a screening plan • Data acquisition • Capacity estimation • Modelling and simulation • Risk assessment • Regulation • Operation and closure (but majority of the BPM is on site selection and characterization).	Covers the many different aspects that need to be considered and provides best practice for accomplishing each step often providing deliverables that could be expected. However, although it must be assumed that the best practices are based on lessons-learned; there are few direct case studies or examples that are mentioned as proof of the success of the best practices provided.
Sept. 2004	LBNL (GEO-SEQ Project Team)	GEOSEQ: Geologic carbon dioxide sequestration: Site evaluation to implementation (http://www.netl.doe.gov/technologies/carbon_seq/refshelf/GEO-SEQ_BestPract_Rev1-1.pdf)	This manual covers • A non-detailed discussion on capacity estimation. Also covers • A section dedicated to EOR. • Characterization of brine-formation sequestration. • Monitoring • Verification • Disposal of impure CO_2 streams • Modelling and simulation	An early manual that covers many aspects.
Jan. 2009	NETL	NETL MVA: Best practices for: Monitoring, verification, and accounting of CO_2 stored in deep geologic formations (http://www.netl.doe.gov/technologies/carbon_seq/refshelf/MVA_Document.pdf)	Comprehensive BPM addressing the need for and requirements of a monitoring program at a CCS project. Covers: • Atmospheric, near-surface, and subsurface monitoring • Simulation techniques • Geophysical techniques, geochemical techniques and crustal and surface techniques • Pre-operational, operational, and post-operational phases of monitoring • Discussion on possible regulatory requirements.	Utilizes numerous case studies and international projects to address what has been achieved so far and what will be required in the future.

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Sept. 2010	NETL	NETL GS: Best practices for: Geologic storage formation classification: Understanding its importance and impacts on CCS opportunities in the United States (http://www.netl.doe.gov/technologies/carbon_seq/refshelf/BPM_GeologicStorageClassification.pdf)	Written for the purpose of understanding and applying geology to a CCS project. Covers background on: • Geological terminology, • Rock types and how they fit into CCS and which are most suitable. As well as more technical issues including different depositional environments and what each one means for CCS.	This BPM covers only a very specific topic: understanding how geology affects a CCS project.
Nov. 2010	NETL	NETL SS: Best practices for: Site screening, site selection, and initial characterization for storage of CO_2indeep geologic formations (http://www.netl.doe.gov/technologies/carbon_seq/refshelf/BPM-SiteScreening.pdf)	Relates specifically to the needs of a generic CCS project covering all possible opportunities and what is necessary to select and characterize a site. Covers • Identifying and developing all potential injection sites and requirements for each type (saline/depleted reservoir/coal) • Data analysis • Injection strategies • Model development and refinement • Capacity estimation and overall suitability analysis • Social and environmental considerations in developing and operating a site.	A 110 page comprehensive discussion of 'what you need to know with regard to storage. It addresses this from a fundamental standpoint covering basic scientific understanding and only occasionally inserting application examples. It does not cover simulation, risk and monitoring to a technical level as there are separate BPMs published to cover these.

2008	WRI	WRI CCS: Guidelines for CCS (http://pdf.wri.org/ccs_guidelines.pdf)	Covers the entire CCS process (Capture, transport, storage). Storage topics addressed are Recommended guidelines for: • MMV • Risk assessment • Financial Responsibility • Property rights and ownership • Site selection and characterization • Injection operations • Site closure • Post-closure	Unable to achieve the same level of detail as other BPMs, more an overview of a theoretical project development and what proponents 'should' consider and do to be successful. It is best described as a dictionary of CCS project aspects as opposed to a BPM. That being said, it does not call itself directly a best practice manual.

Table 3. Relevant best practice manuals published after the CO2CRC (2011) report (March 2011). Sorted alphabetically by issuing organization and then chronologically..

Date	Issued by	Title (Short name used in Table 5, followed by full name and link)	Contents	Comment
Oct. 2012	CSA Group	CSA: Z741-12 - Geological storage of carbon dioxide	This standard addresses: • Management systems • Site screening, selection and characterisation • Risk management Well infrastructure • Well infrastructure development • Monitoring and verification • Closure	The first edition CSA Z741, *Geological storage of carbon dioxide*. It was developed by the Technical Committee on Geological Storage of Carbon dioxide, which is a joint Canada – USA Technical Committee, with support from IPAC-CO2 research Inc.
June 2011	DNV	DNV CO2WELLS: Guideline for the risk management of existing wells at CO_2 geological	Describes a transparent methodology to evaluate the integrity of wells, and risk-based procedure for re-qualification of wells for CO_2-injection. Content includes: • Well integrity risk	The guideline provides a tool for independent validation and verification. Contributes to build confidence among regulators and stakeholders in risk informed approaches to selection and

		storage site (http://www.dnv.com/industry/energy/segments/carbon_capture_storage/recommended_practice_guidelines/co2qualstore_co2wells/index.asp)	o Risk assessment and risk criteria o Identification, analyses and evaluation of well risks o Communication • Qualification of existing wells • Assess performance of and qualification of wells	management of storage sites.
April 2012	DNV	DNV RP-J203: Geological Storage of Carbon Dioxide (DNV-RP-J203) (http://www.dnv.com/news_events/news/2012/newcertificationframeworkforco2storage.asp)	This Recommended Practice (RP) is part of DNV´s series of RPs. The main objective is to provide a systematic approach to the selection, qualification and management of geological CO_2 storage sites. It covers: • Storage screening and appraisal • Permitting o Context and requirements o Risk performance targets o Storage and closure permits • Risk management, assessment and treatment • Well qualification	The RP incorporates and combines the guidance given in: • CO2QUALSTORE • CO2WELLS These two guidelines were the final deliverables from joint industry projects whereas this RP has been developed, and will be maintained, by DNV. Monitoring and verification is mentioned only indirectly as part of permitting.
June 2012	DNV	DNV DSS-402 (not in table 5): Qualification Management for Geological Storage of CO_2 (DNV-DSS-402) (http://www.dnv.com/news_events/news/2012/newcertificationframeworkforco2storage.asp)	This DNV Service Specification (DSS) provides a framework for the certification of geological storage sites for CO_2. It covers: • Principles for selection, qualification and management of geological storage sites for CO_2 • Service overview (basically what services DNV can provide) • Examples of CO_2 storage certification documents	Not really a BPM but a description of DNV's services within selection, qualification and management of geological storage sites. As such it provides some guidance for CO_2storage project developers and other parties, but the most important document is DNV-Rp-J203.
March 2011	NETL	NETL RA: Risk analysis and simulation for geologic storage ofCO_2 (http://www.netl.doe.g	The BPM includes elements that are required for accurate simulation for risk: • Fundamentals • Identification • Assessment (including quantifying) and characterization	A generic publication that provides an understanding of what risk and numerical simulation is and why it is an essential aspect to CCS. This BPM was developed from the lessons learned at numerous projects run by the

		ov/technologies/carbon_seq/refshelf/BPM_RiskAnalysisSimulation.pdf)	• Mitigation; • And for simulation the many different processes (thermal, chemical, biological, etc…). The BPM also covers how risk plans and numerical simulations can be applied separately and together to a CCS project in order to handle the potential risks of a CCS site.	Regional Carbon Sequestration Partnership (RCSP).
April 2012	NETL	NETL WM: Best practices for: Carbon Storage Systems and Well Management Activities (http://www.netl.doe.gov/technologies/carbon_seq/refshelf/BPM-Carbon-Storage-Systems-and-Well-Mgt.pdf)	This BPM covers: • Assessment Initial Site characterization • Injection design • Project cost revisions • Permitting • Establishing site security and access • Well and facility layout • Well pad preparations • Well drilling • Formation evaluation • Well construction • Well testing • Suitability of well • Pre-injection baseline • Injection system completion • Injection • Post-injection operations, including well and site closure and MVA	Purpose: to share lessons learned regarding site-specific management activities for carbon storage well systems. Builds on the experiences of the RCSPs and the petroleum and other private industry. The BPM is part of NETL's series of BPMs for CCUS.

Oct. 2012	NETL	Best Practices for Monitoring, Verification, and Accounting of CO2 Stored in Deep Geologic Formations – 2012 Update http://www.netl.doe.gov/technologies/carbon_seq/refshelf/BPM-MVA-2012.pdf	Addressing the Objectives and Goals of Monitoring Overview of Existing MVA Technologies Field Readiness of CO2 Monitoring Tools Applicability to Regulatory and Reservoir Management Needs Monitoring Plan Monitoring of CO2 in the Atmosphere Near-Surface Monitoring Techniques Subsurface Monitoring MVA Data Integration and Analysis Technologies Review of EPA Permitting Requirements	Update of 2009 version
Oct. 2012	IEAGHG/PTRC	Hitchon, B. (ed), 2012, Best Practices for Validating CO_2 Geological Storage. Geoscience Publishing	This book addresses • Characterization • Storage performance predictions • Geochemical monitoring • Geophysical monitoring • History matching and performance validation • Well integrity • Risk assessment • Community outreach -	This "Best Practices manual" provides a summary of key knowledge gained from research during the IEAGHG Weyburn-Midale Monitoring and Storage project in Saskatchewan, Canada over 12 years. The project was managed by Petroleum Technology Research Centre (PTRC) and the research was carried out in two distinct phases. The first, 2000 – 2004, demonstrated that he Weyburn reservoir provided a suitable site for storage of CO_2; the second, 2005 – 2012, incorporated the Midale oilfield. The book aims to provide technical guidance to future operators, regulators and other stakeholders.
Jan. 2013	DNV	CO2RISKMAN Levels 1 – 4. http://www.dnv.com/industry/energy/segments/carbon_capture_storage/recommended_practice_guidelines/co2riskman/co2riskman_guidance.asp	This is basically a risk management guidance document for most of the CCS chain, in four parts. Storage related items are found in Level 4 and covers management of well risk, injection facility risk and intermediate storage risk.	The CO2RISKMAN Guidance document (is intended to provide a robust knowledge source to assist CCS projects with the development and implementation of their hazard management processes.

Table 3 may later be supplemented by project specific BPM like documents, as the EU funded projects CASTOR[1], CO2REMOVE[2], CO2CARE[3], SITECHAR[4], MUSTANG[5] and PANACEA[6] have issued or plan to issue such publications.

It is outside the scope of TF6 to venture into CCS legislation. However, it is deemed relevant to include a list of guidance documents or guidelines that have been published as annexes or similar to regulations on CO_2 storage. Such guidelines often have contents and structure that resemble standards. A selection of such guidelines is shown in Table 4. The relevant regulations and legislation is given in Appendix A. More information on legal aspects of CCS can be found at the general website of the Carbon Capture Legal Programme (CCLP) of the University College of London (UCL)[7] and more directly related to dedicated CCUS legislation[8]. The websites provide summarizations, analyses, and responses to global CCUS legislation and regulations. The CCLP offers both their own interpretation of the legal works as well as links to the legislation and links to position and discussion papers from other organizations. Along with the section dedicated to existing legislation, the CCLP provides several short-report style papers and presentations that address particular issues surrounding the workings of regulatory issues. Additionally, CCLP mentions also the status in selected Member States of the transposition of the EU CCS Directive[9].

Table 5 repeats CO2CRC's assessment of the BPMs in Table 2 and supplements it with *suggested* assessment of the BPMs and guidelines in Tables 3 and 4. We have also excluded the DNV DSS-402 Qualification management for geological storage of CO_2.

Table 5 indicates that only one of the identified documents (CSA Z741-12) covers all topics listed. This is the only standard issued on CCS by June 2013. Table 5 also shows that site selection, monitoring and verification and risk assessment are covered by existing standards, BPMs or guidance documents. Strengths, weaknesses and needs for additions or improvements of the documents listed in Tables 2– 4 will be examined in Phase 2.

Monitoring is an important part of CO_2 storage. A useful tool for selection of monitoring methods and technologies has been developed by the IEA Greenhouse Ga R&D Programme[10].

Appendix B gives a preliminary list of monitoring tools used in operative storage projects (Table B.1) and links to the websites of some large scale integrated CCS projects under execution, where it may be possible to find information on planned monitoring (Table B.2).

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1 http://www.castor-project.eu/
2 http://www.co2remove.eu/
3 http://www.co2care.org/
4 http://www.sitechar-co2.eu/
5 http://www.co2mustang.eu/
6 http://panacea-co2.org/
7 http://www.ucl.ac.uk/cclp/,
8 http://www.ucl.ac.uk/cclp/ccsdedleg.php
9 http://www.ucl.ac.uk/cclp/ccseutransposition.php
10 http://www.ieaghg.org/index.php?/Monitoring-Selection-Tool.html; users have to register

Appendix C gives an overview of some risk assessment (RA) methodologies. These are generally classified in two main groups: qualitative and quantitative. Most common qualitative methods, which do not provide concrete or numerical results, are the features, events, and processes (FEP), and the Vulnerability Evaluation Framework (VEF). The quantitative methods are used in well-known systems where the level of uncertainty is relatively low. Two main kinds of methods belong to this group: Deterministic Risk Assessment (DRA) and Probabilistic Risk Assessment (PRA).

Appendix E lists some relevant BPMs or related documents for storage capacity estimation. Community consultation and engagement is important to achieve understanding of CCUS has a greenhouse gas mitigating option. Appendix F lists some BPMs related to the topic. These will not be pursued further until a decision has been made on whether or not this is the responsibility of the CSLF TG. Comments are by CO2CRC (2011).

Table 4. Guidelines included as annexes etc to regulations

Date	Issued by	Title (Short name used in Table 5, followed by full name and link)	Contents	Comment
2005	Australian Government	AU1: Australian Guiding Principles for Carbon Dioxide Capture and Geological Storage(Guiding Principles) (http://www.ret.gov.au/resources/Documents/ccs/CCS_Aust_Regulatory_Guiding_Principles.pdf)	The purpose of the Guiding Principles is to promote consistency in the development of a CCS regulatory framework across the Australian states and territories. The Guiding Principles address six areas of CCS activities: 1. Assessment and approval processes 2. Access and property rights 3. Transportation issues 4. Monitoring and verification 5. Liability and post-closure responsibilities 6. Financial issues The Guiding principles are non-binding.	The Australian Government has developed a regulatory framework for offshore CO_2 storage based on amendments to existing petroleum legislation. (See e.g. http://www.ucl.ac.uk/cclp/ccsoffnational-AUS.php#envregs). Two sets of non-binding guidelines have been developed to promote a consistent approach to the application of CCS activities in Australia, including offshore storage activities. These guidelines are summarised briefly in the column to the left.
2009	Australian Government	AU2: Environmental Guidelines for Carbon Dioxide Capture and Geological Storage - 2009 (http://www.ephc.gov.au/sites/default/files/Climate_GL__Environmental_Guidelines_for_CCS_200905_0.pdf)	Environmental Guidelines are non-binding but do provide some high level supplementary information on 1. Environmental assessment of CCS activities 2. Monitoring of injected GHG substances 3. Site closure 4. The need for co-ordination across jurisdictions.	

2011	European Commission	EC1: Guidance Document 1 CO_2Storage Life Cycle Risk Management Framework (http://ec.europa.eu/clima/policies/lowcarbon/ccs/implementation/docs/gd1_en.pdf)	Of the four guidance documents Directive 2009/31/EC nos. 1 and 2 are relevant for this overview. The purpose of the Guidance Documents is to assist stakeholders to implement the Directive (so-called CCS Directive Guidance). Document 1 (GD1) addresses the overall framework for geological storage in the CCS Directive for the entire life cycle of geological CO_2storageactivities including 1. The phases 2. Main activities 3. Major regulatory milestones. 4. High-level approach to risk assessment and management	The European Commission has issued a directive, DIRECTIVE 2009/31/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the geological storage of carbon dioxide and amending. The directive has four guidance documents, on 1. Risk management 2. Characterization and monitoring 3. Transfer of responsibility 4. Financial security and mechanism
2011	European Commission	EC2: Guidance Document 2 Characterisation of the Storage Complex, CO_2Stream Composition, Monitoring and Corrective Measures (http://ec.europa.eu/clima/policies/lowcarbon/ccs/implementation/docs/gd2_en.pdf)	Guidance Document 2 (GD2) builds on GD1 provides guidance on: 1. Site selection; 2. Composition of the CO_2stream; 3. Monitoring; 4. Corrective measures. The Guidance documents are non- legally binding.	
June 2007	OSPAR Convention	OSPAR: Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations (http://www.ucl.ac.uk/cclp/pdf/OSPAR2007-Annex-7.pdf)	The Guidelines provide generic guidance for Contracting Parties when considering applications for permits to store CO_2in geological formations under the seabed. The Guidelines have four Annexes, whereof Annex 1 – Framework for Risk Assessment and management of Storage of CO_2 Streams in Geological Formations (FRAM) – is relevant for this overview. It addresses: 1. Problem formulation 2. Site selection and characterisation 3. Exposure assessment 4. Effects assessment 5. Risk characterization 6. Risk management	The OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic has issued Decision 2007/2 on the Storage of Carbon Dioxide Streams in Geological Formations with Guidelines (http://www.ucl.ac.uk/cclp/pdf/OSPAR2007-Annex-6.pdf)

2006, 2007, and 2012	London Convention and Protocol	Risk Assessment and Management Framework (RAMF) 2006 CO2 Specific Guidelines 2007 CO2 Specific Guidelines revised 2012	The RAMF 2006 provides generic guidance in order to characterize the risks to the marine environment on a site-specific basis, and collect the necessary information to develop a management strategy to address uncertainties and any residual risks. The Guidelines cover: • Carbon Dioxide Stream Characterization • Site Selection and Characterization); • Assessment of Potential Impacts • Permit and Permit Conditions); • Monitoring and Risk Management); • Mitigation or Remediation Plan The Guidelines were updated in 2012 to include transboundary movement subsurface.	The RAMF forms the basis for the OSPAR Guidelines. The CO2 Specific Guidelines are to be followed by London Protocol Parties when issuing a permit for CO2 geological storage in the marine environment and ensure compliance with Annex 2 of the Protocol (Assessment of wastes or other matter that may be considered for dumping). Work is ongoing on including transboundary movement above-surface.
August 2012	EPA (US Government)	EPA: Geologic Sequestration of Carbon Dioxide: Underground Injection Control (UIC) Program Class VI Well Project Plan Development Guidance (http://water.epa.gov/type/groundwater/uic/class6/upload/epa816r11017.pdf)	This document describes the required elements of each of the five plans prospective Class VI injection well owners and operators must submit with a permit application under the Class VI Rule requirements: o Area of Review and Corrective Action Plan, o Testing and Monitoring Plan, o Injection Well Plugging Plan, o Post-Injection Site Care (PISC) and o Site Closure Plan, and Emergency and Remedial Response Plan	This is a basic and non-technical guidance document with some emphasis on corrective action plans and emergency and remedial response plans. It is adapted to the US regulation for Class VI Wells and therefore also has guidance on how to prepare plans that relate specifically to US regulations.

Table 5. Assessment of scope and content of BPMs listed in Tables 1 –4. For BPMs listed in Table 3 the assessment is by CO2CRC (2011). For the other BPMs the assessment is by TF6 and is to be regarded as suggestions.

BPM	Planning/pre-feasibility	Site screening, selection and characterisation	Simulation and modelling	Well construction/ integrity	Operation	Closure	Monitoring and verification	Risk management, incl. assessment
CO2STORE	Basic	Technical	Technical	-	Basic	Detailed	Technical	Detailed
CCP	-	Basic	-	Detailed	Detailed	Basic	Technical	Basic
DNV CO2QUAL	Detailed	Detailed	Basic	-	Detailed	Detailed	Basic	Detailed
DNV CO2WELLS	-	Technical (existing wells)	-	-	-	-	-	Technical (existing wells)
DNV RP-J203	Basic	Detailed	Basic	Detailed	-	-	Detailed	Detailed
DVN CO2RISKMAN	-	-	-	-	-	-	-	Detailed
GEOSEQ	-	Basic	Basic	-	-	-	Detailed	-
NETL MVA	-	-	-	-	Technical	Technical	Technical	Basic
NETL GS	Technical	Technical	-	-	-	-	-	-
NETL SS	Basic	Detailed	Basic	-	-	-	-	Technical
NETL RA+update	-	-	Technical	-	-	-	-	Technical
NETL WM	-	-	-	Technical	Technical	Technical	-	-
WRI CCS	Basic	Detailed	Basic	Basic	Basic	Detailed	Detailed	Detailed
IEA Weyburn	-	Technical	Technical	Technical	-	-	Technical	Technical
CSA	Basic	Detailed	Detailed	Detailed	Basic	Detailed	Detailed	Detailed
AU1	-	-	-	-	-	-	-	-
AU2	-	-	-	-	-	-	(Very) Basic	(Env. risk very basic)
EC1	-	-	-	-	-	-	-	Detailed
EC2	-	Detailed	Basic	-	-	-	Detailed	(only corrective part)
OSPAR	Basic	Basic	-	-	-	-	-	Basic
London	-	Very basic	-	-	-	-	Very basic	Very basic
EPA	-	-	-	-	-	Basic	Basic	Basic

The following assessment grades have been used. Some BPM have limited cope and the assigned "grade" applies to the topic of the BPM.

-	Not covered specifically	Technical	Provides technical details of projects, generally comprehensive
Basic	Briefly covered in a generic way	Detailed	Comprehensive discussion, generally generic

4. Other related documents

Appendix D lists relevant documents and related references for storage capacity of CO_2 in different regions of the world. The list is a combination of atlases and GIS (geo databases and tools). Each of them bears specificity due to regional coverage (e.g. South Africa, Brazil) but also methodology (e.g. BGR, ETI, Caprock Italy). The references may not lead to the document or database itself but to a website where more information may be found.

Pipelines are outside the scope for TF6 but some standards, BPMs and guidance documents are shown in Appendix G as it was suggested to include this.

5. ISO TC 265 Carbon capture and storage (CCS)

At the Bergen meeting, the Task Force on Monitoring Geologic Storage for Commercial Projects had recommended that the CSLF request a formal liaison with the ISO Technical Committee on CO_2 Capture, Transportation and Geological Storage (ISO/TC 265). To that end, the CSLF Policy Group Chair, in August, sent a letter to the ISO/TC 265 Secretariat that requested liaison status, which has been accepted. The CSLF Secretariat will coordinate communication between ISO/TC265 and the CSLT Technical Group Executive Committee in that regard.

As of June 2013 the status of ISO/TC65 is:

There are currently 16 participating member countries, 10 observing members, and 6 liaison organisations involved in ISO/TC 265. 13 of the participating and three of the observing members countries are also members of the CSLF.

A business plan and a preliminary scoping document have been developed and work is continuing to further develop and refine the scope of work. The scope of work is anticipated to include not only elements that require standardisation now, but also be forward looking and include elements that will require standardisation in the future. Initially the following working groups (WGs) have been defined:

1. Capture, secretariat Japan
2. Transport, secretariat Germany
3. Storage, secretariat Canada
4. Quantification and verification, secretariat China
5. Cross cutting issues, secretariat France

A call for experts to the working groups has been issued. Detailed strategies and priorities will be established for each of the working groups and the business plan will be updated as work progresses.

On this background it is suggested to continue the work of CSLF Task Force 6, as its work will complement ISO TC265.

6. References

CO2CRC (2011) A review of best practice manuals for carbon dioxide storage and regulation. http://www.globalccsinstitute.com/publications/review-existing-best-practice-manuals-carbon-dioxide-storage-and-regulation

Appendix A. Regulations

Table A.1. Legislation and regulations to which the guidelines of Chapter 3, table 4, are associated. Comments are not provided, as legislation is outside the scope for Task Force 6 "Monitoring of Geologic Storage for Commercial Projects".

Date	Issued by	Title
2008 - 2011	Australian Government	Offshore Petroleum Amendment (Greenhouse Gas Storage) Act 2008 (OPGGS Act); Offshore Petroleum and Greenhouse Gas Storage (Environment) Regulations 2009; Offshore Petroleum and Greenhouse Gas Storage (Management of Greenhouse Gas Well Operations) Regulations 2010; Offshore Petroleum and Greenhouse Gas Storage (Management of Greenhouse Gas Well Operations) Regulations 2010; Offshore Petroleum and Greenhouse Gas Storage (Resource Management and Administration) Regulations 2011 (RMA Regs); Offshore Petroleum and Greenhouse Gas Storage (Injection and Storage) Regulations 2010 Draft), see also http://www.ucl.ac.uk/cclp/ccsdedlegnat-AUS.php.
Dec. 2010	Alberta, Canada	Carbon Capture and Storage Statutes Amendments Act 2010, see also http://www.ucl.ac.uk/cclp/ccsdedlegnat-CAN.php
April 2009	European Commission	DIRECTIVE 2009/31/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF)
2006, 2007 and 2012	International Maritime Organization (IMO)	London Convention and Protocal. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 and 1996 Protocol Thereto http://www.imo.org/OurWork/Environment/SpecialProgrammesAndInitiatives/Pages/London-Convention-and-Protocol.aspx
June 2007	OSPAR Convention	OSPAR Decision 2007/2 on the Storage of Carbon Dioxide Streams in Geological Formations (http://www.ucl.ac.uk/cclp/pdf/OSPAR2007-Annex-6.pdf);(http://www.ucl.ac.uk/cclp/ccsoffeuropeospar.php) (http://www.ucl.ac.uk/cclp/pdf/OSPAR_Convention_e_updated_text_2007.pdf); 8 http://www.ucl.ac.uk/cclp/pdf/OSPAR2007-Annex-5.pdf)
2008	UK	Energy Act 2008 (http://www.legislation.gov.uk/ukpga/2008/32/pdfs/ukpga_20080032_en.pdf). See also .ucl.ac.uk/cclp/ccsdedlegnat-UK.php
July 2008	EPA (US Government)	Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO_2) Geologic Sequestration (GS) Wells; see also http://www.ucl.ac.uk/cclp/ccsdedlegnat-US-Federal.php
Dec. 2010	EPA (US Government)	Final rule for Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO_2) Geologic Sequestration (GS) Wells (http://water.epa.gov/type/groundwater/uic/class6/gsregulations.cfm)

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Appendix B. Monitoring tools and techniques used in some projects

Table B.1.Monitoring technologies used at some present storage sites. The list is based on the references supplemented by Myer (2011) and should not be regarded as complete. Supplemented by information from Jones and Chadwick (2012; http://www.cgseurope.net/UserFiles/file/Ankara%20workshop_june%202012/presentations/DavidJones.pdf). There may also be differences in how the monitoring approaches are described by the project; thus, there may be some inconsistencies and not completely corrects marks in the table.

	Site											
	Sleipner [1]	Weyburn [2]	In Salah [3]	Snøhvit [4]	K12-B	Otway [5]	Ketzin [6]	Decatuar[7]	Quest	Lacq[8]	Gorgon	Aquistore
Seismic surface (2D/3D)	x	x	x	x		x	x	x	x			x
Seismic surface (3C/9C)		x										
Seismic downhole (VSP, Crosshole)		x				x	x	x	x			x
Electrical (EM, ERT) surface	x						x					
Electrical (EM, ERT) downhole		x					x		x			
Gravity surface / seabed	x	x										x
Tiltmeters			x									x
Satellite interferometry (InSAR)		x	x				x	x	x			x
Downhole P, T		x		x	x	x	x	x	x	x		x
Continuous downhole temperature							x		x	x		
Acoustic seabed imaging (echosounder, sonar)	x			x								
Acoustic water column imaging	x											
Geophones								x				
Water column chemistry	x											
Seabed video (ROV/AUV)	x											
Soil gas		x	x			x	x	x		x		x
Surface gas flux		x	x			x		x		x		
Passive CO_2 detectors			x			x						
Ecosystem & biomarkers	x		x	x						x		
Microseismic (passive seismic)		x	x			x	x			x		
Observation wells		x	x		x	x	x	x	x			x
Tracers		x	x		x		x		x			
Microbiology			x				x					

Wireline logs			x		x		x					
Fluid samples (reservoir, aquifers, groundwater)		x	x		x	x	x	x	x	x		x
Atmospheric CO_2 mobile/spatial		x	x			x		x	x	x		
Atmospheric CO_2 flux tower		x	x			x				x		
Well head pressure	x	x	x	x	x	x	x	x	x	x		x
Temperature	x	x	x	x	x	x	x	x	x	x		x
Well integrity monitoring (EMIT, PMIT)					x				x			
Well integrity downhole camera log					x		x					

[1] CO2STORE (2006) Best Practice for the storage CO2 in saline Aquifers. Observations and guidelines from the SACS and CO2STORE projects. http://www.co2store.org/TEK/FOT/SVG03178.nsf/web/092d69538cd9be22c1256db8003e59d1?opendocument

[2] Wilson and Monea, (2005) IEA GHG Weyburn CO2 Monitoring & Storage Project. Summary Report 2000 – 2004. Petroleum Research Centre, Regina, Canada. OSBN 0-9736290-0-2

Hitchon, B. (ed), 2012, Best Practices for Validating CO_2 Geological Storage.
Geoscience Publishing

[3] Mathieson, A., J. Midgely, I. Wright, N. Saoula, and P. Ringrose (2010), *In Salah CO2 Storage JIP: CO2 sequestration monitoring and verification technologies applied at Krechba,Algeri.* Energy Procedia, © Elsevier, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies, IEA Greenhouse Gas Programme, Amsterdam, The Netherlands.

[3] Wright, I., A. Mathieson, F. Riddiford, and C. Bishop (2010), In Salah CO2 JIP: Site Selection, Management, Field Development Plan and Monitoring Overview. Energy Procedia, © Elsevier, Proceedings of 10th International Conference on Greenhouse Gas Control Technologies, IEA Greenhouse Gas Programme, Amsterdam, The Netherlands.

[4] Myer (2011) Global Status of Geologic CO2 Storage Technology Development. Report from the United States Carbon sequestration Council July 25 2011. http://www.uscsc.org/Files/Admin/Educational_Papers/Global_Status_of_Geologic_CO2_Storage_Technology_Development_Updated_Final_Edition%5B1%5D.pdf

[5] CO2CRC (2012) (Cooperative Research Centre for Greenhouse Gas Technologies) Stage 1 results from the CO2CRC Otway Project. (http://www.co2crc.com.au/dls/otway/Otway_Project_stage_1_results.pdf)

[6] Würdemann, H., Moeller, F., Kuehn, M., Heidug, W., Christensen, N.P., Borm, G., Schilling, F.R., and the CO2Sink Group, 2010. CO2SINK—From site characterisation and risk assessment to monitoring and verification: One year of operational experience with the field laboratory for CO2storage at Ketzin, Germany. International Journal of Greenhouse Gas Control Volume 4.

[7]http://www.cslforum.org/projects/illinoisbasin.html

[8]Jacques Monne, Total (personal communication)

Table B.2.Links to some large scale integrated CCS project where information on monitoring technologies used at the storage may be found

Site	Link to web-site
Quest	http://www.shell.ca/en/aboutshell/our-business-tpkg/business-in-canada/upstream/oil-sands/quest.html
Gorgon	
Boundary Dam (EOR)	
Kemper County (EOR)	
Longannet - Golden-Eye	http://www.decc.gov.uk/en/content/cms/emissions/ccs/ukccscomm_prog/feed/scottish_power/scottish_power.aspx
Kingsnorth – storage in natural gas reservoirs	http://www.decc.gov.uk/en/content/cms/emissions/ccs/ukccscomm_prog/feed/e_on_feed_/e_on_feed_.aspx

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Appendix C. Risk Assessment (RA) Methods

Table C.1. Some methodologies for risk assessment of geological storage of CO2 (Condor et a.,, Energy Procedia 4(2011) 4036-4043)

Method	Goal	Data needed	Industrial application	Application for GSC
DRA	Analytical point estimate calculations	Numerical and qualitative expert estimation for scenario development and model development	Safety engineering (sensitivity analysis)	Initial risk assessment. No uncertainty estimations
PRA	Predict the probability of safety failures of complex system	Numerical qualitative expert estimation for scenario development, model development quantifying PDFs	Safety engineering	Detailed risk assessment. Uncertainty estimation
FEP	Scenario development	Qualitative expert estimation for scenario development	Scenario analysis	Screening and Site selection
VEF	Conceptual framework for regulators and technical experts	Qualitative expert estimation to identify which areas should be in-depth studied	Hazard identification and potential consequences	Framework for site selection and regulator guidance
SWIFT	Elaborate hypothesis	Qualitative expert estimation to identify hazards	Hazard identification in engineering	Hazard and consequence mapping
MCA/MAUT	Evaluation of alternatives in multiple objective	Qualitative and numerical expert estimation for data input utility	Decision making	Framework for screening and site selection
RISQUE	Systemic process with participation of expert panels estimation in event-tree approach	Qualitative and numerical expert	Hazard identification and potential consequences	Hazard and consequence mapping
CFA/SRF	Estimation of risk based on probabilities of occurrence in individual features	Qualitative and quantitative estimation of risk and uncertainty	Development of simple probabilistic models	Managing risks in GSC sites
MOSAR	Identifying and preventing risks	Qualitative and quantitative data for a well-known system	Risk reduction in complex systems	Systematic risk analysis for well-known sites
ESL	Identification of uncertainties in decisions	Qualitative and quantitative understanding of uncertainties	Reduction of uncertainties in well-known systems	Detailed PRA and dealing with uncertainties
P&R	Risk mapping in wellbores under the criteria of degradation scenarios	Qualitative and quantitative data for wellbores	Risk evaluation under the concept of ALARP	Long-term well integrity
SMA	Estimation of risk based on probabilities.	Quantitative estimation of risk and PDFs	Development of complex models in well-known systems	PRA for the whole CCS chain

Appendix D. Selection of CO_2 Storage Atlases

This list is a combination of Atlases and GIS (geo databases and tools). Each of them beares specificity due to regional coverage (e.g. South Africa, Brazil) but also methodology (e.g. BGR, ETI, Caprock Italy).

Carbon Sequestration Atlas of the United States and Canada I, II and III (http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasIII/index.html)

The North American Carbon Storage Atlas 2012 (http://www.netl.doe.gov/technologies/carbon_seq/refshelf/NACSA2012.pdf)

The CO2 Storage Atlas Norwegian North Sea 2011 (http://www.npd.no/Global/Norsk/3-Publikasjoner/Rapporter/PDF/CO2-ATLAS-lav.pdf)

Queensland carbon dioxide geological storage atlas. Compiled by Greenhouse Gas Storage Solutions on behalf of Queensland Department of Employment, Economic Development and Innovation. (http://www.cgss.com.au/Assessement%20of%20Qlds%20CO2%20geological%20storage%20prospectivity_web%20version.pdf)

South Africa CO2 Storage Atlas (http://www.sacccs.org.za/wp-content/uploads/2010/11/Atlas.pdf)

BGR Germany CO2 Storage "Atlas" (GIS) (http://www.bgr.bund.de/DE/Themen/CO2Speicherung/Downloads/Speicherkataster_Kartenanwendung.html. Description in: http://www.bgr.bund.de/DE/Themen/CO2Speicherung/Downloads/Speicherkataster_synthese.pdf?__blob=publicationFile&v=4;http://www.bgr.bund.de/DE/Themen/CO2Speicherung/Downloads/Speicherkataster_Nachweissystem.pdf?__blob=publicationFile&v=1)

ETI/The Crown Estate/BGS (in prep) CO2STORED – the UK Storage Appraisal Project. Online database/GIS.

The Brazilian Carbon Geological Sequestration Map (CARBMAP Project, some info at http://www.pucrs.br/cepac/index_e.php?p=programas)

The geo-database of caprock quality and deep saline aquifers distribution for geological storage of CO2 in Italy (GIS) (http://www.sciencedirect.com/science/article/pii/S036054421100137X)

Appendix E. BPMs on CO_2 storage capacity

Table E.1. Best practices and similar that relates to capacity estimation

Date	Issued by	Title	Contents	Comment
March 2003	Stefan Bachu	Screening and Ranking of sedimentary basins for sequestration of CO2 (http://www.geology.wmich.edu/bachu_Barnes_2003.pdf) Screening and Ranking of hydrocarbon reservoirs for CO2storage (http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/p21.pdf)		One of the first articles on the subject of site selection for CO2 storage. The subject matter is very broad and applied to regional scale assessment. It represents a thorough attempt to provide a guide and understanding to CCS site screening.
March 2008	CO2CRC	Storage Capacity Estimation, Site Selection and Characterisation for CO_2Storage Projects (http://www.ukerc.ac.uk/support/tiki-download_file.php?fileId=2395)		A comprehensive, although generic, report on what is necessary to select and characterize a site and assess the storage capacity. We have not considered it a best practice manual because, although it provides a thorough and valuable resource on site selection, it is presented as more of a 'what to consider' as opposed to what practices should be undertaken.
2005, 2007 and 2008	CSLF Task Force for Review and Identification of Standards for CO_2 Storage Capacity	Measurement, Phase I, II and III (http://www.cslforum.org/publications/index.html?cid=nav_publications)		
2008	NETL	Methodology for Development of Geologic Storage Estimates for Carbon Dioxide (http://www.netl.doe.gov/technologies/carbon_seq/refshelf/methodology2008.pdf)in		Included as an additional reference but it is limited in scope and has been superseded by NETL's site screening BPM, which contains a technical section on storage capacity.

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2008	Netherlands Oil and Gas Exploration And Production Association	Potential for CO2 storage in depleted gas fields on the Netherlands Continental Shelf http://www.nogepa.nl/en/Home/OliegasinNederland/Energieklimaatverandering/CO2opslag.aspx	This report has two parts: Phase 1: Technical assessment Phase 2: Costs of transport and storage	
2010	CHINA(country based not BPM)	Chinese methodologies of storage capacity estimation. Near-term mega-scale CO2 capture and storage demonstration opportunities in China Zheng et. al., 2010. doi:10.1016/j.fuel.2011.07.004		
2011	JAPAN (country based not BPM)	Japanese methodology of storage capacity estimation. Saline-aquifer CO2 sequestration in Japan-methodology of storage capacity assessment. Ogawa et al., 2011. http://dx.doi.org/10.1016/j.ijggc.2010.09.009	National onshore and offshore assessment for Japan	A nationwide saline-aquifer CO2 storage capacity assessment carried out in Japan. The multiplication of S_f and S_g is analogous to efficiency factor in US DOE methodology and Capacity coefficient of CSLF methodology ranges from 1% to 20%
Others[1]	UK (country based not BPM)	UK CO2 Storage Appraisal Project (ETI 2011)	National offshore resource estimate for UK	Estimate of the storage resource that is theoretically accessible without recurse to pressure management and chase water injection. Chances of success and economics of each storage unit assessed.
	DE (country based not BPM) (http://www.bgr.bund.de/DE/Themen/CO2Speicherung/Downloads/Speicherkataster_Kartenanwendung.html)	GIS-basierte Kartenanwendung „Informationssystem Speicher-Kataster Deutschland" (ArcReader 10 erforderlich, issued by BGR	Regional capacity assessment onshore and offshore for Germany	Capacity in structural and stratigraphic traps estimated. GIS/Spreadsheet

[1] *Source S. Holloway (IEA Seminar 2011). Please note also ongoing efforts towards a common methodology worldwide for CO2 Storage Capacity Assessment* – S. Brennan et al, 2011. GHG 11 Abstract. Towards international guidelines for CO2 storage capacity estimation.

Appendix F. BPMs on regulatory issues, community engagement and communication

Table F.1. Best practices etc. that considers regulatory issues, community engagement and similar (based on CO2CRC, 2011)

Date	Issued by	Title	Contents	Comment
Nov. 2010	CCP	Update on Selected Regulation Issues for CO_2Capture and Geological Storage (http://www.co2capturep roject.org/reports/regulat ory_report.pdf)	Covers the following sections • Carbon capture readiness • permitting and licensing, • impurities in injected CO_2 streams • pore space ownership, • liability issues • Monitoring, reporting and verification requirements Each section has a general overview followed by a country by country description of how some nations handle the particular issue.	Dedicated to understanding regulation, this manual is structured by regulatory subject. Although it does not cover as many issues as the IEA framework, the inclusion of thorough reviews of existing legislation on key issues merits regarding this BPM as a valuable resource.
Nov. 2010	IEA	CCS Model Regulatory Framework (http://www.iea.org/ccs/l egal/model_framework.p df)	Covers • the entire CCS chain from capture through to storage site closure and provides a comprehensive discussion of the issues regulators face • reporting and classification issues, liability, hazards and risk, inspections and monitoring, financial aspects • areas that need to be standardized such as fluid composition.	This framework provides a guideline for understanding what must go into developing regulations for CCS. It uses existing regulations as examples of how the guidelines proposed have been used. Although, focused on only one aspect of storage (regulation) it does so thoroughly.
Dec. 2009.	NETL	Best Practices for: Public outreach and education for carbon storage projects (http://www.netl.doe.gov /technologies/carbon_seq /refshelf/BPM_PublicOu treach.pdf)	This BPM covers • The importance of public outreach • How public outreach should be integrated into the development of the project • Identifying stakeholders, an information gathering practice termed 'social characterization • Developing plans and strategies, • Clarification on what key messages should be and how to tailor them to a public audience.	This BPM takes the short social outreach discussion from the site screening BPM and expands it using a generic approach combining lessons learned from numerous projects in a non-specific way.

Oct. 2010	WRI	Guidelines for community engagement in CCS (http://pdf.wri.org/ccs_and_community_engagement.pdf)	Includes understanding • The importance of community engagement • The needs of different stakeholders • of applying community engagement to the specifics of CCS throughout the entire life of a project • Of how to cover impacts and risks effectively and what reactions to expect • The best practice for presenting and exchanging information.	Comprehensive review of the CCS community engagement process. Provides numerous examples from around the world of the case studies where these lessons were learned.
2010	USGS	A probabilistic assessment methodology for the evaluation of geologic carbon dioxide storage: U.S. Geological Survey Open-File Report 2010–1127, 31 p., (http://pubs.usgs.gov/of/2010/1127)		

Appendix G. BPMs and current guidance and standards related to CO_2 pipelines in connection with CCS projects

Table G.1. Some standards, BMPs and guidelines related to CO_2 transport in pipelines

Date	Issued by	Title	Contents
ALARP	HSE (UK)	Reducing risk As Low As Reasonably Practicable http://www.hse.gov.uk/pipelines/co2conveying.htm#a9	Application of good practice at the design stage is essential to demonstrating reduction of (ALARP). HSE expects duty holders to apply relevant good practice. Depending on the level of risk and complexity involved, it is possible the adoption of good practice alone may not be sufficient to comply with the law.
1996	PSR	Pipelines Safety Regulations	Regulation 5 requires that the design of a pipeline, or any modification to it, takes account of the operating regime of the pipeline and the conditions under which the fluid is to be conveyed as well as the environment to which the pipeline will be subjected. In particular with regard to the re-use of existing pipelines, any proposal to change the fluid conveyed will require a re-assessment of the original pipeline design to ensure that the pipeline is capable of conveying the fluid safely. European Standards implemented in the UK as British Normative Standards (BS EN series) and supported by published documents (such as the British Standards PD series) provide a sound basis for the design of pipelines. Other national or international codes e.g. a relevant standard or code of practice of a national standards body or equivalent body of any member state of the European Union are likely to be acceptable provided the proposed standard, code of practice, technical specification or procedure provides equivalent levels of safety.
	European Standards	PD 8010: 2004; BS EN 14161: 2003; Institute of Petroleum Pipeline Code IP6; DNV OS-F101 - Submarine Pipeline Systems (2007)	Codes IP6, BS EN 14161, BS PD 8010 and DNV OS-F101 are all applicable to pipelines transporting CO2; the last three categorising it as a non- flammable, non-toxic fluid which is gaseous at ambient temperature and pressure. IP6 also treats CO2 as a gas.

	US Pipeline Codes	US Federal Code of Regulations, Title 49, Volume 3, Part 195 – Transportation of Hazardous Liquids by Pipeline and the associated ASME standards B31.4 and B31.8	Main American codes which address the transportation of liquids and gases by pipeline respectively. The US Federal Code only applies to pipelines transporting CO2 in the supercritical phase and is therefore only relevant to proposals to use pipelines to convey supercritical CO2. There does not appear to be any equivalent code, which addresses the transport of gaseous or liquid CO2.
April 2010	DNV	Recommended Practice DNV-RP-J202. Design and operation of CO2 pipelines	The Recommended Practice (RP) was developed to address the need for guidance for how to manage risks and uncertainties specifically related to transportation of CO_2 in pipelines. The document provides guidance and sets out criteria for the concept development, design, construction and operation of steel pipelines for the transportation of CO_2. It is written to be a supplement to existing pipeline standards and is applicable to both onshore and offshore pipelines. The RP is intended to assist in delivering pipelines in compliance with international laws and regulations. The pipeline operator will also have to ensure that the project is in compliance with local laws and regulations.

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