2015

CSLF Mid-Year Meeting and Technology Workshop

Regina, Saskatchewan, Canada

June 15-19, 2015

carbon sequestration leadership forum

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2015 CSLF Mid-Year Meeting
Regina, Saskatchewan, Canada
15-19 June 2015

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2015 CSLF MID-YEAR MEETING DOCUMENTS BOOK

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2015 CSLF Mid-Year Meeting

Regina, Saskatchewan, Canada

15-19 June 2015

	Monday **15 June 2015** Hotel Saskatchewan	**Tuesday** **16 June 2015** Hotel Saskatchewan	**Wednesday** **17 June 2015** Hotel Saskatchewan	**Thursday** **18 June 2015**	**Friday** **19 June 2015** Hotel Saskatchewan
Morning		CSLF Technical Group Meeting	CSLF Technology Workshop	Visit to Boundary Dam Project and SaskPower CCS Test Facility	CSLF Policy Group Meeting
Afternoon	CSLF Projects Interaction and Review Team (PIRT) Meeting	CSLF Technical Group Meeting (continues)	CSLF Technology Workshop (continues)	Visit to Boundary Dam Project and SaskPower CCS Test Facility (continues)	CSLF Policy Group Meeting (continues)

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Carbon Sequestration Leadership Forum
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CSLF-P-2015-01
Draft: 04 June 2015
Prepared by CSLF Secretariat

DRAFT AGENDA
CSLF Policy Group Meeting

Regency Ballroom of Radisson Hotel Saskatchewan
Regina, Saskatchewan, Canada

June 19, 2015

07:30-08:30 Meeting Registration / Breakfast

08:30-10:30 Policy Group Meeting

1. **Welcome and Opening Statement**
   Christopher Smith, Policy Group Chair, United States
2. **Meeting Host's Welcome**
   Michael Marsh, President and CEO, SaskPower
3. **Introduction of Delegates**
   Delegates
4. **Adoption of Agenda**
   Christopher Smith, Policy Group Chair, United States
5. **Review and Approval of Minutes from Warsaw** CSLF-P-2014-09
   Christopher Smith, Policy Group Chair, United States
6. **Review of Warsaw Meeting Action Items**
   Jarad Daniels, Director, CSLF Secretariat
7. **Report from CSLF Technical Group**
   Trygve Riis, Technical Group Chair, Norway
8. **Report from the CCS in the Academic Community Task Force** CSLF-P-2015-02
   Edward S. Rubin, Department of Engineering and Public Policy, Carnegie Mellon University
9. **Assessing Barriers to High-Level Geological CO_2 Storage**
   Tony Ripley, United Kingdom
10. **Discussion of Exploratory Committee Work Plan Status:**
    1. **Financing for CCS Projects**
       Bernard Frois, France
       Delegates

10:30-10:45 Refreshment Break

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10:45-12:15 Continuation of Meeting

b. **Supporting Development of 2nd and 3rd Generation CCS Technologies** CSLF-P-2015-03
Trygve Riis, Technical Group Chair, Norway
Geoff Murphy, Canada
Kathryn Gagnon, Canada
Tone Skogen, Norway
Delegates

c. **Global Collaboration on Large-Scale CCS Projects**
Jarad Daniels, Director, CSLF Secretariat
Sizhen Peng, China
Delegates

12:15-13:00 Lunch

13:00-14:30 Continuation of Meeting

d. **Communications**
Khalid Abuleif, Saudi Arabia
Delegates

11. **Stakeholder Recommendations to CSLF**
Barry Worthington, United States Energy Association
Other Stakeholders TBD
Delegates

12. **Report from the CSLF Capacity Building Governing Council**
Tone Skogen, Capacity Building Governing Council Chair, Norway
Delegates

13. **Report on UNFCCC Bonn Climate Change Conference**
Khalid Abuleif, Saudi Arabia

14:30-14:45 Refreshment Break

14:45-17:00 Continuation of Meeting

14. **Planning for 2015 CSLF Ministerial Meeting**
Khalid Abuleif, Saudi Arabia
Jarad Daniels, Director, CSLF Secretariat
Delegates

15. **Ministerial Communiqué** CSLF-P-2015-04
Jarad Daniels, Director, CSLF Secretariat
Delegates

16. **Open Discussion and New Business**
Delegates

17. **Action Items and Next Steps**
Jarad Daniels, Director, CSLF Secretariat

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

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2015-01
Draft: 03 June 2015
Prepared by CSLF Secretariat

DRAFT AGENDA
CSLF Technical Group Meeting

Regency Ballroom of Radisson Hotel Saskatchewan
Regina, Saskatchewan, Canada

Tuesday, June 16, 2015

08:00-09:00 Meeting Registration / Breakfast

09:00-10:30 Technical Group Meeting

1. **Welcome and Opening Statement**
   Trygve Riis, Technical Group Chair, Norway
2. **Meeting Host's Welcome**
   Michael Monea, President, Carbon Capture & Storage Initiatives, SaskPower
3. **Introduction of Delegates**
   Delegates
4. **Adoption of Agenda**
   Trygve Riis, Technical Group Chair, Norway
5. **Review and Approval of Minutes from Warsaw Meeting** CSLF-T-2014-09
   Trygve Riis, Technical Group Chair, Norway
6. **Report from Secretariat**
   - Review of Warsaw Meeting Action Items
   - Highlights from October 2014 Technical Group Meeting

   Richard Lynch, CSLF Secretariat
7. **Overview of CCS Activities in Canada**
   Eddy Chui, Director, Clean Fossil Fuels, CanmetENERGY, Natural Resources Canada
8. **Coal Industry Perspectives in a CCS-Enabled Environment**
   John Schadan, President – Canada Operations, Westmoreland Coal Co.

10:30-10:45 Refreshment Break

10:45-12:30 Continuation of Meeting

9. **Update from the IEA Greenhouse Gas R&D Programme**
   Tim Dixon, Manager – Technical Programme, IEA GHG
10. **Update from the Global CCS Institute**
    Neil Wildgust, Principal Manager – CO_2 Storage, GCCSI
11. **CSLF-recognized Carbon Capture Project – Phase 3 Results**
    Mark Crombie, CCP3 Programme Manager, BP Group Technology
12. **Report from Projects Interaction and Review Team**
    Clinton Foster, PIRT Chair, Australia
13. **Progress Report on CSLF Technology Roadmap** CSLF-T-2015-02
    Clinton Foster, PIRT Chair, Australia

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12:30-13:30 **Lunch**
Luncheon Presentation: "Full-Scale Design of a Post-Combustion CO_2 Capture Process for a Gas-Fired Plant"
David Bernier, Senior Principal Power Discipline Leader, Stantec

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

14. Review of Project Nominated for CSLF Recognition: Jingbian CCS Project
Jinfeng Ma, Northwest University
Hong Wang, Shaanxi Yanchang Petroleum Group

15. Final Report from Review of CO_2 Storage Efficiency in Deep Saline Aquifers Task Force
Stefan Bachu, Task Force Chair, Canada

16. Report from Sub-Seabed Storage of CO_2 Task Force
Mark Ackiewicz, Task Force Chair, United States

17. Report on the ISO and its CCS-related Activities
Tim Dixon, Manager – Technical Programme, IEA GHG

18. The Outlook for Improved Carbon Capture Technology
Edward S. Rubin, Department of Engineering and Public Policy, Carnegie Mellon University

15:30-15:45 **Refreshment Break**

15:45-18:00 **Continuation of Meeting**

19. Injectivity – A Dose of Reality?
Wayne Rowe, Senior Project Manager, Schlumberger

20. Enzymatic Technology for Low-Cost Carbon Capture
Jonathan Carley, Vice-President – Business Development, CO_2 Solutions, Inc.

21. Review of Technical Group Action Plan CSLF-T-2015-03
Trygve Riis, Technical Group Chair, Norway
Delegates

22. Update from Joint Task Force on the Development of 2nd and 3rd Generation CCS Technologies CSLF-P-2015-03
Lars Ingolf Eide, Norway
Trygve Riis, Technical Group Chair, Norway

23. Technical Group Deliverables for 6th CSLF Ministerial Conference
Trygve Riis, Technical Group Chair, Norway
Richard Lynch. CSLF Secretariat

24. Update on International CO_2 Capture Test Centre Network
Lars Ingolf Eide, Test Centre Network Chair, Norway

25. Preview of Technology Workshop and Update on Future CSLF Meetings
Richard Lynch, CSLF Secretariat

26. Open Discussion and New Business
Delegates

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27. Action Items and Next Steps
Richard Lynch, CSLF Secretariat

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

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Carbon Sequestration Leadership Forum

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Draft: 19 May 2015
Prepared by CSLF Secretariat

Agenda

CSLF PROJECTS INTERACTION AND REVIEW TEAM (PIRT)

Radisson Hotel Saskatchewan
Regina, Saskatchewan, Canada
15 June 2015

Room: Blue Lounge
14:00-16:30

1. **Welcome and Opening Remarks**
   Clinton Foster, PIRT Chair, Australia

2. **Introduction of Attendees**
   Meeting Attendees

3. **Approval of Summary from Warsaw PIRT Meeting**
   Clinton Foster, PIRT Chair, Australia

4. **Report from Secretariat**
   - Review of Action Items from Warsaw Meeting
   - CSLF Technology Roadmap (TRM) Interim Report

   Richard Lynch, CSLF Secretariat

5. **Review of Initial Draft of 2015 TRM Interim Report**
   Clinton Foster, PIRT Chair, Australia
   PIRT Members

6. **Review of Project Proposed for CSLF Recognition: Jingbian CCS Project**
   Jinfeng Ma, Northwest University, China
   Hong Wang, Shaanxi Yanchang Petroleum Group, China

7. **Future PIRT Activities**
   - Technology Workshops
   - TRM Progress Reports
   - 2017 TRM

   Clinton Foster, PIRT Chair, Australia

8. **Open Discussion and New Business**
   Meeting Attendees

9. **Action Items and Next Steps**
   Richard Lynch, CSLF Secretariat

10. **Closing Comments / Adjourn**
    Clinton Foster, PIRT Chair, Australia

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2015 CSLF Technology Workshop

Lessons Learned from Large-Scale CCS

Regency Ballroom of the Radisson Hotel Saskatchewan
Regina, Saskatchewan, Canada

17 June 2015

08:00-09:00
Breakfast

09:00-09:15
Plenary Session

Workshop Introduction and Background
Richard Lynch, CSLF Secretariat

Welcoming and Keynote Address
Michael Monea, President, Carbon Capture & Storage Initiatives, SaskPower

09:15-12:30
Session 1: Project Siting and Construction

Session Co-Chairs:
Lars Ingolf Eide and Philip Sharman

- **Rotterdam Opslag en Afvand Demonstratieproject (ROAD)**
  Hans Schoenmakers, MCP
- **Illinois Industrial CCS Project**
  Scott McDonald, ADM
- **Kemper County Energy Facility**
  Richard Esposito, Southern Company
- **Shell Quest Project**
  Luc Rock, Shell

Messages and Takeaways from Session
Session Co-Chairs

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12:30-13:30

Lunch

Luncheon Presentation: "Advancements of Shell Cansolv in Post-Combustion CO_2 Capture Technology" by Farhang Abdollahi, Licensing Technology Manager - Global CCS Projects, Shell Cansolv

13:30-16:30

Session 2: Project Operations

Session Co-Chairs:

Clinton Foster and Philip Sharman

- ***Experience from EOR Operations*: PCOR Bell Creek Project**
  Edward Steadman, EERC
- ***Experience from Utility Sector Operations*: SaskPower Boundary Dam Project**
  Michael Monea, SaskPower
  Aquistore Project
  Kyle Worth, PTRC
- ***Experience from Natural Gas Operations*: Offshore Norway**
  Britta Paasch, Statoil
- ***Experience from Industry Operations*: Summary of Dakota Gasification Company's CO_2 Capture and Transport, and Future Options for Gasification Systems**
  Mike Holmes, EERC

Messages and Takeaways from Session

Session Co-Chairs

Workshop Concept

- Following presentations, there will be a discussion among the panelists facilitated by the session co-chairs.
- Following the panelist discussion, there will be an Audience Interaction Q&A session.

18:00-21:00

Reception / Dinner

Government House (4607 Dewdney Avenue, Regina)

Dinner Remarks by Warren Stanley, Member of the Legislative Assembly of the Province of Saskatchewan

Transportation will be provided to Government House from the Radisson Hotel Saskatchewan starting at 18:00. Shuttles will return from Government House to the Radisson Hotel Saskatchewan starting at 21:00.

Reception: 18:00 to 19:00
Dinner: 19:00 to 21:00

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SaskPower Site Visit Agenda

June 18, 2015

07:00 am	Depart for Boundary Dam (*note: Buses depart from Hotel Sask*)
09:30 am	Arrive at Boundary Dam Power Plant
10:00 am	Safety Orientation
10:30 am	Tours of Power Plant and Carbon Capture Project
12:00 pm	Leave Boundary Dam and travel to Carbon Capture Test Facility at Shand Power Plant
12:30 pm	Lunch at Shand
13:00 pm	Dedication Ceremony for Carbon Capture Test Facility
15:00 pm	Buses Depart for Regina
17:30 pm	Arrive at Hotel Sask

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-P-2014-07
Draft: 06 April 2015
Prepared by CSLF Secretariat

DRAFT

Draft Minutes of the Policy Group Meeting
Warsaw, Poland
Thursday, 30 October 2014

LIST OF ATTENDEES

Chair	Christopher Smith, United States

Policy Group Delegates

Australia:	Zoe Naden
Brazil:	Giuliano Ventura
Canada:	Kathryn Gagnon, Eddy Chui
China:	Sizhen Peng, Xian Zhang, Chenyong Sun
France:	Bernard Frois
Japan:	Ryozo Tanaka, Takashi Kawabata
Korea:	Chang Keun Yi, Seung Phill Choi
Mexico:	Giselle Pérez
Norway:	Tone Skogen, Fredrik Netland
Poland:	Marcin Korolec, Piotr Kisiel
Saudi Arabia:	Hamoud Al-Otaibi
South Africa:	Gina Downes, Landi Themba
United Kingdom:	Tony Ripley
United States:	Jarad Daniels, John Litynski

Representatives of Allied Organizations

Global CCS Institute:	Andrew Purvis
IEA:	Juho Lipponen, Tristan Stanley

CSLF Secretariat

Richard Lynch, Adam Wong

Invited Speakers

Tomasz Dąbrowski, Director, Department of Energy, Ministry of Economy, Poland
Trygve Riis, Technical Group Chair, Norway

Observers

Netherlands:	Tim Bertels
Poland:	Adam Normark, Anna Madyniak, Janusz Reiter, Adam Wócicki
South Africa:	Tony Surridge
United Kingdom:	Luke Warren
United States:	Damian Bednarz, Geoffrey Lyon, Jim Wood, Barry Worthington

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1. Welcome and Opening Statement

Christopher Smith

The Chairman of the Policy Group, Christopher Smith, called the meeting to order and welcomed delegates and observers to Warsaw. He thanked Poland for hosting the 2014 CSLF Annual Meeting, and also acknowledged the hard work by the various CSLF Task Forces, the CSLF Technical Group, and the CSLF Secretariat.

2. Introduction of Delegates

Policy Group delegates introduced themselves. Fourteen of the twenty-three CSLF Members were present, including representatives from Australia, Brazil, Canada, China, France, Japan, Korea, Mexico, Norway, Poland, Saudi Arabia, South Africa, the United Kingdom, and the United States. Observers representing the International Energy Agency, Global CCS Institute, the Netherlands, Poland, South Africa, the United Kingdom, and the United States were also present.

3. Host Country Welcome

Tomasz Dąbrowski

Tomasz Dąbrowski, Director of the Energy Department at Poland's Ministry of Economy, welcomed the CSLF Policy Group to Warsaw and thanked the CSLF for allowing Poland the opportunity to host. Mr. Dąbrowski provided remarks regarding Poland's use of coal, and noted the interest Poland has in all clean coal technologies. Mr. Dąbrowski stressed that now is an important time for the world to provide serious attention and huge investments to reduce carbon emissions.

4. Adoption of Agenda

The Agenda was adopted without change.

5. Review and Approval of Minutes from London

The Minutes from the CSLF Policy Group Meeting on 5 June 2014 in London were approved without change.

6. Secretariat Report on London Meeting Action Items

Adam Wong provided a brief summary of the action items from the CSLF Policy Group Meeting on 5 June 2014 in London. All action items have been completed.

7. Recent and Current CCS Issues

Juho Lipponen

Juho Lipponen provided a thorough background framing of recent climate policy meetings, including the United Nations Climate Summit 2014, the Greenhouse Gas Control Technologies (GHGT-12) Conference, and the United Nations Framework

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Convention on Climate Change (UNFCCC) Technical Expert Meeting on CCUS. Mr. Lipponen noted that the recent opening of Canada's Boundary Dam Project, the world's first commercial-scale power plant retrofit with CCS, has changed the CCS conversation, as the argument against CCS in now off the table.

8. Update from CSLF Technical Group


Trygve Riis

Trygve Riis provided an update from the CSLF Technical Group. At its on Tuesday, 28 October 2014, the Technical Group voted to recommend the Norcem CO_2 Capture Project to the Policy Group for CSLF recognition. The Technical Group is also planning to produce an update report on the CSLF Technology Roadmap in time for the next CSLF Ministerial Meeting in 2015. The Technical Group will also continue its collaboration with the Policy Group on "Supporting Development of 2nd and 3rd Generation CCS Technologies" with Canada and Norway as leads. Other task force members will include Japan, Korea, the United Kingdom, the United States, and the IEA GHG.

Other consensuses reached from the recent Technical Group Meeting included an announcement that the Review of CO_2 Storage Efficiency in Deep Saline Aquifers Task Force has concluded its work and will disband following the publication of its journal paper, the Technical Group will not form a task force to address the Action Plan item on "CCS with the Industrial Emissions Sources", and the Technical Group will not yet form a task force to address the Action Plan item on "Energy Penalty Reduction".

After the update from Mr. Riis, there was consensus to approve the Norcem CO_2 Capture Project for CSLF recognition.

9. Discussion of Exploratory Committee Work Plan:

a. Supporting Development of 2nd and 3rd Generation CCS Technologies


Kathryn Gagnon

Trygve Riis began the discussion by providing an overview of 2nd and 3rd generation technologies, along with challenges and suggested actions. Kathryn Gagnon presented on the possibility of a site map for 2nd and 3rd generation CCS technologies. Ms. Gagnon suggested that this site map could be a living document that would be updated by projects and developers as the technologies evolve. It was agreed that Canada would lead the effort to include mapping initiatives and funding mechanisms, while Norway would lead the efforts to both identify promising technologies, along with how to efficiently test these new technologies. The ultimate goal would be for this group to prepare and present a policy document on how to accelerate implementation of 2nd and 3rd generation capture technologies. Canada will lead this policy-facing effort, with the expectation that all countries supporting this task will actively be involved in the drafting of this document. The European Commission, Japan, Korea, the United Kingdom, and the United States will also support this effort. This task group will draft deliverables to

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discuss at the next Policy Group meeting, with an overall goal of a policy-facing document to present to the Ministers.

b. Global Collaboration on Large-Scale CCS Projects

Jarad Daniels

Sizhen Peng

Jarad Daniels and Sizhen Peng led a discussion on how the CSLF might facilitate global collaboration on large scale integrated projects. There is an interest in deep saline formations, as there is plenty of enhanced oil recovery data. After the discussion, a consensus was reached that the United States and China should continue working to identify opportunities for the CSLF to add significant value to large saline projects, to include both projects that were discussed and other projects that members might identify in the coming months. This effort shall include discussions with countries on potential in-kind and financial resources that might be brought to the table. The work should also include discussions with project developers on opportunities to add or expand technical value to existing efforts. The goal will be to provide specific opportunities to discuss at the next Policy Group meeting, with an eventual target towards deliverables for the CSLF Ministers to announce at the Ministerial Meeting in 2015.

c. Financing for CCS Projects

Bernard Frois

James Wood

The Financing CCS Task Force Chair, Bernard Frois, and Jim Wood of the U.S.-China Clean Energy Research Center then framed the conversation on financing for CCS projects. Dr. Frois provided a review and summary of his recent financing workshop held on 15 October 2014, in Washington, D.C. This workshop demonstrated that there is growing interest in CCS, but that government assistance is still essential. Discussions included the potential effects of recent draft United States Environmental Protection Agency regulations impacting CCS. Mr. Wood highlighted the importance of partnerships for financing CCS projects in Asia, and provided thoughts on the opportunities to actively manage reservoir pressures though water withdrawal and freshwater co-production. Dr. Frois concluded that lessons learned from existing projects have important impact, and that stable government systems are requisite for projects to succeed. It was noted that dialogue with financial institutions are increasing, and understanding and trust are

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building. CSLF participants were encouraged to provide input to Dr. Frois on how to best continue engaging the financial communities, while also working to progress financing opportunities for CCS projects.

d. Communications

Juho Lipponen started the discussion on CSLF Communications and provided suggestions from the Communications Task Force, which is led by Saudi Arabia with support from the IEA and the Global CCS Institute. A recommendation was made to hire a communications professional to help frame a communications strategy, and the task force was asked to pursue member contributions to enable this. It is estimated that the cost for a communications professional would be between US $30,000-60,000. It was noted that the CSLF should strive to pass the CSLF message to other multilateral meetings. The task force was asked to continue to refine key messages to focus on and deliver at a variety of levels and thru various potential international mechanisms, such as the UNFCCC.

10. Stakeholder Recommendations to CSLF

Barry Worthington

Barry Worthington of the United States Energy Association and Luke Warren of the Carbon Capture and Storage Association provided stakeholder recommendations to the CSLF. Mr. Worthington highlighted recommendations for CCS being pursued by the United Nations Economic Commission for Europe. The recommendations included policy parity for CCS, the need for protection of intellectual property under any crediting mechanism, that a broad array of fiscal instruments should be made available to support CCS (but the selection should not be mandated), and the need for government support for CCS demonstration projects, particularly between developed and developing nations. Recommendations are also being put forward for CCS specifically in developing countries, the sharing of credits, credit for CCS thru enhanced oil recovery, public outreach and communications for CCS as part of a carbon reduction strategy, etc.

Luke Warren

Mr. Warren detailed the recent European 2030 Climate and Energy Framework agreed to last week on 23 October, which includes explicit recognition of CCS, and the need for additional funding for innovative technologies, such as the NER 400. Mr. Warren also summarized the U.K. CCS Commercialization program, which has many merits to support CCS. He also provided updates on several CCS projects being pursued in the United Kingdom, and noted the U.K.'s CCS Policy Scoping Document that will provide stakeholder input for consideration from the United Kingdom's Department of Energy and Climate Change. Mr. Warren also mentioned that the U.K. is keen on pursuing industrial CCS opportunities and highlighted the Tees Valley City Deal.

Mr. Worthington congratulated the CSLF for the decision to actively pursue better communications, although much work is still required. Mr. Worthington suggested that

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the CSLF should consider stakeholder corporations to both help support CSLF communication efforts, and also move communications on CCS forward. Mr. Worthington recommended that the CSLF consider changing its name to remove the word "sequestration." The stakeholders also commended the CSLF financing efforts. Stakeholders seek to improve and increase their engagement at next year's Ministerial Meeting, and look forward to presenting their thoughts and ideas at the next CSLF Meeting in Canada. The stakeholders suggested that a core ministerial theme or message should be on public acceptance, supported by better communications.

11. CSLF Input to the Next CEM Meeting

Jarad Daniels stressed the need for CCS to be included in the key messages document at the upcoming CEM meeting. The United States will work on getting a CCS session on the agenda. The CEM preparatory meeting, hosted by the United States, will take place on 25-26 March 2015 in Washington, D.C. CEM6 (minister-level meeting), will take place 27-28 May 2015 in Mexico, with the specific location still to be determined.

12. Planning for 2015 CSLF Meetings

Richard Lynch announced that the next CSLF meeting will be in June 2015 in Regina, Saskatchewan, Canada. This will be a five day meeting, organized as follows:

- Day 1: PIRT meeting (in afternoon)
- Day 2: Technical Group Meeting
- Day 3: Technology Workshop
- Day 4: Visit to CSLF-recognized Boundary Dam Project
- Day 5: Policy Group Meeting

Mr. Lynch stated that further details concerning the Regina meeting would be forthcoming soon. Hamoud Al-Otaibi announced that Saudi Arabia will be hosting the 6th CSLF Ministerial in the fourth quarter of 2015. Exact dates for this meeting will be announced when available.

13. Action Items and Next Steps

The Policy Group reached a consensus on the following items:

- The Norcem CO_2 Capture Project was approved for CSLF recognition.
- Any input regarding financing CCS should be provided to France.

Action items from the meeting are as follows:

Item	Lead	Action
1	Canada and Norway	Prepare a draft policy document on how to achieve accelerated implementation of 2nd and 3rd generation CCS technologies, to also include CCS outside of the power sector
2	China and United States	Provide specific recommendations regarding how the Policy Group can propose that the CSLF Ministers support a large-scale integrated project, whether it a new or existing project

Item	Lead	Action
3	Saudi Arabia, IEA, Global CCS Institute	Investigate potentially funding a professional for CCS communications, while also finding a way to get key CSLF messages to a wider audience
4	United States	Engage to get CCS on the agenda for the Clean Energy Ministerial
5	Saudi Arabia and CSLF Secretariat	Announce a date for the 2015 CSLF Ministerial Meeting
6	CSLF Secretariat	Distribute more information on UNFCCC recognition
7	Canada and CSLF Secretariat	Explore changing the dates for the 2015 CSLF Mid-Year Meeting in Regina, Canada

14. Open Discussion and New Business

Tone Skogen summarized the status of the CSLF Capacity Building Program, which is undergoing a transition of the remaining Capacity Building Program Funds from the United States Department of Energy to the Global CCS Institute. Once this transition is complete, the CSLF Capacity Building Program can then proceed with new capacity building efforts.

A conversation was also held regarding UNFCCC recognition, and it was agreed that the CSLF Secretariat would research this and provide the necessary information.

15. Closing Remarks / Adjourn

Jarad Daniels provided a summary of the day's meetings, and noted the significant recommendations and action items. Chris Smith provided the closing remarks. Mr. Smith stressed the need for the CSLF to continue to engage all countries, including countries outside of the CSLF. He thanked the host country Poland, the CSLF Secretariat, and all the meeting attendees.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-P-2015-02
18 May 2015

POLICY GROUP

Report and Recommendations from the CCS in the Academic Community Task Force

Background

The CCS in the Academic Community Task Force was formed in 2009 at the CSLF Policy Group's meeting in San Francisco. The mission of the Task Force was to identify and engage academic programs on CCS throughout the world, and help determine the path forward for CSLF in this area. Accomplishments to date include a mapping and gap analysis of CCS post-graduate academic courses worldwide and links to the CSLF Capacity Building Task Force.

This paper represents a proposed forward action plan for the Task Force.

Action Requested

The Policy Group is requested to review the Task Force's report.

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Report and Recommendations from the CCS in the Academic Community Task Force

The CCS in the Academic Community Task Force was created in 2009 at the CSLF Policy Group's meeting in San Francisco. It was formed because there was consensus that engaging the academic community is vital to the overall success of the CSLF. This Task Force has been given the mission to identify and engage academic programs on CCS throughout the world, and help determine the path forward for CSLF in this area. Accomplishments to date include a mapping and gap analysis of CCS post-graduate academic courses worldwide and links to the CSLF Capacity Building Task Force.

The Task Force has not been active since the 4th CSLF Ministerial Meeting in 2011. Resumption of the Task Force is being undertaken with the following structure:

Chair: Prof. Edward Rubin, Carnegie Mellon University
Co-Chair: Pamela Tomski, Global CCS Institute
Co-Chair: CSLF Policy Group delegate

Many governments do not yet have mechanisms established to support international collaborations, research exchanges, or summer school experiences among the academic community. Where programs do exist, they are not well coordinated. Therefore, the Task Force recommends to the Policy Group that governments:

- Review and assess available programs for international CCS collaborative research, student exchanges and summer school experiences available for the academic community, including their scope and objectives, current funding levels, sources of support, and key contacts;
- Where CCS programs do not exist, determine if member countries may be receptive to adding such activities on various aspects of CCS; and
- Consider commitments to fund specific solicitations to expand and enhance international CCS collaborative research, student exchanges, and summer school experiences.

Pursuant to concurrence by the Policy Group that it will assist in providing information on existing and potential mechanisms to support international collaborations, research exchanges, and summer school experiences among the academic community, the Task Force will prepare a written report summarizing the information provided. Based on this information, the report will recommend specific solicitations and funding commitments needed to substantially enhance the mission of the CSLF via support for collaborative activities among the international academic community.

The Task Force report with its recommendations will be presented to the Policy Group at the 6th CSLF Ministerial Meeting in Riyadh, Saudi Arabia.

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Task Force Action Items:

- Identify an academic champion from each CSLF member country and secure input to the Task Force concept;
- Socialize the Task Force concept among Policy Group delegates and secure agreement among governments to provide the Task Force with information as requested;
- Determine how CSLF Capacity Building resources can best support Task Force efforts; and
- Prepare a Task Force report which will be a deliverable at the 6th CSLF Ministerial Meeting.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-P-2015-03
20 May 2015

POLICY GROUP

Supporting Development of 2nd and 3rd Generation Carbon Capture Technologies

Background

One of the four main thematic focal points for the upcoming 6th CSLF Ministerial Meeting is "Supporting Development of 2nd and 3rd Generation Carbon Capture Technologies". To that end, a joint Policy Group-Technical Group Task Force for was formed in 2014 at the CSLF Policy Group's meeting in Warsaw. Canada is leading the effort to include mapping initiatives and funding mechanisms, while Norway is leading the efforts to both identify promising technologies, along with how to efficiently test these new technologies. The ultimate goal would be for this joint task force to prepare and present a policy document on how to accelerate implementation of 2nd and 3rd generation capture technologies.

This paper, prepared by Norway's Technical Group delegation, is a draft-in-progress which describes efforts to identify 2nd and 3rd generation emerging technologies for CO_2 capture and identify potential testing facilities that can help bring the technologies out of laboratory and pilot-scale testing to demonstration size testing. A final version of this document will be ready in time for the 6th CSLF Ministerial Meeting.

Action Requested

The Policy Group is requested to review the Task Force's draft-in-progress report.

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Carbon Sequestration Leadership Forum
SUPPORTING DEVELOPMENT OF 2ND AND 3RD GENERATION CARBON CAPTURE TECHNOLOGIES:
Mapping technologies and relevant test facilities

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Executive Summary

Results

This report describes efforts to identify emerging technologies (2nd and 3rd generation) of CO_2 capture and identify potential testing facilities that can help bring the technologies out of laboratory and pilot-scale testing to demonstration size testing, i.e. capture rates of order *100* tonnes per day and more. The results are summarized in Table 1 below.

Table 1. Identified emerging (2nd and 3rd generation) CO_2 capture technologies and the possibilities to use existing testing facilities. Note that the spread in TRL for some groups reflects variations of individual technologies within the group.
Green=Commercial
Yellow=2nd generation
Red=3rd generation

Capture approach (Post-, pre- or oxy-combustion	Technology group	Tecchnology Readiness Level (TRL)	Generation	Application (power and industry)	Potential testing facilities for demo-scale w/capacity
Post-, solvents	Amine-based solvents	Commercially available from several vendors (Fluor, MHI, Aker to mention a few)			
	Precipitating solvents	4 – 5	2nd - 3rd	Power, cement, steel	
	Two phase liquid system	3 - 4	2nd - 3rd	Power, cement, steel	
	Enzymes	1 – 2	3rd	Power, cement, steel	
	Ionic fluids	1 – 4	2nd - 3rd	Power, cement, steel	
	Novel systems - Encapsulated solvent - Electrochemical (EMAR)	1 – 2	3rd	Power, cement; EMAR also steel & aluminum	
Post-, sorbents	Calcium looping system	5 – 6	2nd	Power, cement, steel	
	Other sorbent looping systems	1 – 6	2nd - 3rd	Power, cement,steel	
	Vacuum Pressure Swing	2 – 3	3rd	Power, cement	
	Temperature swing	1 – 2	3rd	Power, cement	
Post-, membranes	Polymeric	5 – 6	2nd	Power, cement, steel	
	Other (electrochemical, ceramic and composites)	2 - 4	3rd	Power, cement, steel	
	Polymeric membranes combined with low temperature separation	2 – 6	2nd	Power, cement, steel	
Post- other	Low temperature	3 - 5	2nd - 3rd	Power	

	(cryogenic)				
	CO$_2$ enrichment in flue gas	5 – 6	2nd	Power	
	Hydrates	1 - 3	3rd	Power	
	Algae	1 - 3	3rd	Flue gases from power and most other industries	
	Supersonic	1 - 2	3rd	Power	
	Pressurized post-combustion capture	2 - 5	2nd -3rd	Power	
Pre-, solvents	Solvents for pre-combustion	Applies to commercially available solvents, e.g. Selexol™ process and Rectisol® process used in steam methane reforming in e.g. hydrogen production in the fertilizing and refining industries			
Pre-, sorbents	Sorption Enhanced Water Gas Shift (SEWGS)	4 - 5	2nd	Power, refinery, hydrogen production	
	Sorption Enhanced Steam-Methane reforming (SE-SMR)	1 - 2	3rd	Power, refinery, hydrogen production	
Pre-, membranes	Metal and composite	3 - 5	2nd – 3rd	Power, refinery, hydrogen production	
	Ceramic	2 - 4	2nd - 3rd	Power, refinery, hydrogen production	
Pre-, other	Low temperature	1 - 3	3rd	Power, refinery, hydrogen production	
	Concepts with fuel cells	3 – 6	2nd – 3rd	Coal and biomass based power, hydrogen production	
	Other improvements		NA		
Oxy-combustion	Chemical Looping Combustion	2 - 3	3rd	Power	
	Oxygen transport membranes (OTM) Power Cycle	2 – 3	3rd	Power	
Oxygen production for oxy-combustion	Cryogenic air separation	Commercially available			
	O$_2$ separation using membranes		NA		

	Advanced Cryogenic air separation		NA		
Oxy-, other	High pressure oxy-combustion		NA		
	Oxy-combustion gas turbine		NA		
	Oxygen production boilers		NA		
	CO_2 processing and clean-up		NA		

Recommendations for Follow-Up

1. Background and Objectives

At the CSLF Ministerial Meeting in Washington DC in November 2013 the Exploratory Committee of the CSLF Policy Group identified the following topics of great interest to CSLF that should be moved forward in Task Forces:

1. Communications
2. Global collaboration on large-scale CCS project(s)
3. Financing for CCS projects
4. Supporting development of 2nd and 3rd generation ccs technologies
5. Transitioning from CO_2-EOR to CCS.

The fourth task is the topic of this report. More specifically, the Policy Group stated that:
"Efforts should be taken to better understand the role of 2nd and 3rd generation technologies for CCS deployment, and policies and approaches identified among individual CSLF member countries that can stimulate 2nd and 3rd generation CCS project proposals to improve the outlook for successful Large Scale Integrated Project deployment in the 2020 to 2030 timeframe. Development of these technologies will benefit from the CCS Pilot Scale Testing Network, which is in the process of being stood up. "

2. Scope and Approach

To achieve the fourth task, the following activities were agreed to be performed jointly by the CSLF Policy and Technical Groups:

1. Map initiatives and funding mechanisms for 2nd and 3rd generation technologies in CSLF member countries. US DOE/NETL Advanced Carbon Dioxide Capture R&D Program, Norwegian CLIMIT and UK Innovation Fund for Carbon Capture Projects are examples that should be summarized for the benefit of CSLF members. Provide perspective on how these initiatives parallel with market mechanisms which would drive the adoption of these technologies. The effort should also include
    1.1 mapping/exploring the criteria that industry around the world may use to adopt technologies, i.e., market pull
    1.2 identifying the specific financial challenges associated with scale-up and deployment of 2nd and 3rd generation capture technologies
    1.3 exploring the understanding of what those challenges might be, particularly if government funds are used, as well as the interest in joint funding/international collaboration

   Responsible: Policy Group
2. Map/Identify 2nd and 3rd generation technologies under consideration in CSLF member countries, and identify technologies that may mature in the 2020 –2030 timeframe, their development plans to scale from current readiness levels to prepare for demonstration, and the major challenges facing technology development. Good starting points are technology updates from DOE/NETL Advanced Carbon Dioxide Capture R&D Program, report from UK Advanced Power generation technology Forum, projects and reports from the IEA Greenhouse Gas R&D Program, CLIMIT projects and reports from SINTEF on behalf of CSLF and TCM. Responsible: Technical Group
3. Use existing networks, e.g. the established International CCS Test Centre Network and ECCSEL, to map potential for testing 2nd and 3rd generation technologies at existing test facilities. There is

knowledge from a limited number of test facilities (e.g. NCCC, CanmetENERGY and TCM) on the possibilities to test 2nd generation technologies in scale 1 - 5 MW_{th}. The list of test facilities needs to be expanded. Responsible for liaising with the networks: Technical Group

4. Prepare a Policy document on how to achieve an accelerated implementation of 2nd and 3rd generation CO_2 capture technologies. Responsible: Policy Group.

This report answers points 2 and 3 above by compiling and summarizing information that is already available but spread on several publications.

We will not delve into each single technology provider and its technology. Rather, the technologies are grouped according to common principles and a common template is used to describe the technology group.

Chapter 3 of the report gives the definitions of 2nd and 3rd generation capture technologies and Chapters 4 – 6 give summaries of the identified 2nd and 3rd generation technologies, sorted by technology approach/route and groups. Chapter 7 give brief summaries of novel technologies of which detailed descriptions are not yet available in the open literature, and Chapter 8 gives summary descriptions of the capabilities of identified test facilities to perform demonstration scale test of 2nd and 3rd generation CO_2 capture technologies.

Appendix A gives a summary of how CO_2 capture technologies can be applied in industries other than power production, in support of the possible applications given for each identified technology.

This report summarises several review papers and is NOT an original work. In particular, the grouping of capture technologies as well as the descriptions rely heavily on reports by SINTEF (2013)[1], DOE/NETL (2013)[2] and IEAGHG (2014)[3]. Other review documents that have been used are ZEP (2013)[4], CSLF (2013a)[5] and GCCSI (2014)[6]. References to these documents are usually not given in the general descriptions, nor are references to papers and articles used by the mentioned references. The reader is referred to the above references for more details.

3. What are 2nd and 3rd generation capture technologies?

3.1 Definition

Different definitions and/or classifications of emerging capture technologies are in use, see e.g. APGTF (2011)[7], CSLF (2013a, 2013b[8]), US DOE/NETL (2013), ZEP (2013), GCCSI (2014) and

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[1] http://www.tcmda.com/PageFiles/1544/SINTEF%20report.pdf

[2] http://www.netl.doe.gov/File%20Library/Research/Coal/carbon%20capture/handbook/CO2-Capture-Tech-Update-2013.pdf

[3] IEAGHG (2014) Assessment of emerging CO_2 capture technologies and their potential to reduce costs. 2014/TR4, December 2014

[4] http://www.zeroemissionsplatform.eu/library.html

[5] http://www.cslforum.org/publications/documents/CCSTechnologyOpportunitiesGaps_FinalReport.pdf

[6] GCCSI (2014) Global Status of CCS 2014. http://www.globalccsinstitute.com/publications/global-status-ccs-2014-summary-report

[7] http://www.apgtf-uk.com/index.php/publications/publications-2011

IEAGHG (2014). This report will use the following definitions, basically adapted from DOE/NETL (2013), to describe the maturity of the technologies:

- 2nd generation technologies—include technology components currently in R&D that will be validated and ready for demonstration in the 2020–2025 timeframe
- 3rd generation technologies, or "Transformational" technologies in DOE/NETL, —include technology components that are in the early stage of development or are conceptual that offer the potential for improvements in cost and performance beyond those expected from 2nd generation technologies. The development and scale-up of 3rdgeneration technologies are expected to occur in the 2016–2030 timeframe, and demonstration projects are expected to be initiated in the 2030–2035 time period.

The term "emerging" will be used to include both 2nd and 3rd generation technologies.

3.2 Classification of technologies

The reports by SINTEF (2013), DOE/NETL (2013), IEAGHG (2014) and GCCSI (2014) use different definitions of technology maturity. SINTEF (2013) defines technology maturity according to the five groups:

- Idea/theoretical investigations only
- Proof of concept/lab scale testing
- Pilot scale testing
- Demonstration
- Commercial.

DOE/NETL (2013) uses similar maturity descriptions in the capture technology sheets but add whether the tests imply slip streams with real flue gas, syngas or simulated gas.

IEAGHG (2014) has a different approach, using Technology readiness Levels (TRL), Table 2.

Table 2. TRL definitions according to IEAGHG (2014)

Maturity	TRL	Definition
Demonstration	9	Normal commercial service
	8	Commercial demonstration, full scale deployment in final form
	7	Sub-scale demonstration, fully functional prototype
Development	6	Fully integrated pilot tested in a relevant environment
	5	Sub-system validation in a relevant environment
	4	System validation in a laboratory environment
Research	3	Proof-of-concept tests, component level
	2	Formulation of the application
	1	Basic principles, observed, initial concept

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[8] http://www.cslforum.org/publications/documents/CSLF_Technology_Roadmap_2013.pdf

GCCSI (2014) also uses TRL but groups them differently, as in the Table 3. GCCSI (2014) operates with some overlap between the TRL and maturity levels to account for unavoidable uncertainties of a high-level evaluation.

Table 3. TRL definitions according to GCCSI (2014)

Maturity	TRL	Definition
Demonstration	9	The process is implemented at full or reduced scale but is representative of a commercial plant in performance and complexity. The process is engineered in the same manner as a commercial project and fully integrated with the flue gas source process. Flue gas is derived from a source representative of the commercial application. The plant operates over the full range of operating conditions.
	8	
Pilot/demonstration	7	The overlap between pilot and demonstration
Pilot	6	The main parts are integrated and tested in a complete process to conduct performance tests and sensitivity analyses. First engineering design takes place. Real flue gas e.g. derived from a new or existing source, conditioned to meet actual characteristics if necessary (e.g. dedicated burner).
Lab/bench/pilot	5	The overlap between lab/bench and pilot
Lab/bench	4	The core process components are tested in a lab facility or at bench-scale to demonstrate the working principle on single components or limited integration (main parts of the process). Flue gas is artificial.
	3	
Concept/lab-bench	2	The overlap between concept and lab/bench
Concept	1	The idea is demonstrated using theoretical calculations and/ or observation of basic principles in laboratory.

Table 4 shows how the classifications of the four reports correspond to the definition of 2nd and 3rd generation used in this report.

Table 4. Maturity definitions in relation to emerging (2nd and 3rd) generation capture technologies

Classification used in this report, generation	SINTEF (2013)	DOE/NETL (2013)	IEAGHG (2014)	GCCSI (2014)
2nd	Pilot scale testing	Pilot scale testing (real and simulated gases)	Development (TRL 4 – 6)	Pilot (TRL 5-7)
3rd	Proof of concept/lab scale testing; Idea/theoretical investigations only	Proof of concept/lab scale testing; Idea/theoretical investigations only (real and simulated gases)	Research (TRL 1 – 3)	Concept and lab/bench (TRL 1 – 5)

Several factors contribute to an inevitable degree of subjectivity when evaluating the maturity level of technologies. These include:

- The reviewers (and vendors) will have different views on how far a technology has come or how promising it is. E.g., among the post-combustion technologies, Temperature Swing Adsorption (TSA) and Pressure Swing Adsorption (PSA) are classified by GCCSI (2014) at TRL 5-7, whereas IEAGHG (2014) classify them as, respectively, TRL 1 and 3
- Reviewers use different classifications, as described above. The terms 2nd and 3rd generation technologies are generally not used in the reviewed documents
- Reviewers are not always precise as to which maturity level a technology is and indicate a maturity between two categories
- The boundary between "pilot" and "demonstration" is indeed floating and un-precise, in terms of quantity as well as units. SINTEF (2012) may be interpreted to include technologies with CO_2 capture rates of a few kg/hour to several tons/hour as pilot, whereas GCCSI (2014) mentions both technologies with 1 – 2 MW_{th} and 35 MW_{th} as pilots.

In Chapters 4 - 6 we have classified technologies according to estimated TRL, basically using the IEAGHG (2014) definitions in Tables 2 and 4. We have strived to find a balance when there are different views among the referenced sources, realizing that some of our classifications may be open for dispute.

NOTE: The TRL grading is based on technical status, not on feasibility or whether this approach is CCS or CCUS)

3.3 Excluded from this report: Overall process development and integration, materials

Several measures to improve technologies and reduce energy penalties and costs will be common to all types of CO_2 capture technologies. Such measures include but are not limited to:

- General energy efficiency measures, e.g. for turbines
- Optimized integration a CO_2 capture system with the power or processing plant, e.g. heat integration
- Improvement of 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
- Materials choice and improvements
- Improved process equipment like heat exchangers, pumps fans and other auxiliary equipment.

These measures are not connected to any particular CO_2 capture technology or technology generation but improving them are processes that need to be going on continuously. They are not considered here.

4. Summary of Identified Technologies - Post-combustion

In post-combustion CO_2 capture, the CO_2 is removed from the combustion or industrial process flue gas. CO_2 concentration in the flue gas varies from 3-4% for gas power to well above 20% for some industrial processes. The principle of the post-combustion process is illustrated in Figure 1.

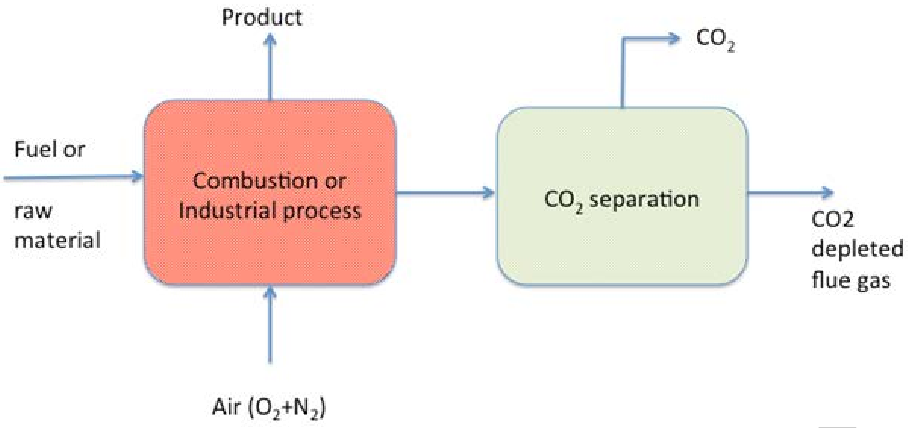

Figure 1. Schematic illustration of the post-combustion process

The separation process itself can be achieved by using solvents, sorbents or membranes. Each variety comes in several alternative fashions. Presently, use of solvents is the most mature approach. For solvents and sorbents two reactors are required: one for absorption/adsorption in which the CO_2 is captured, and one for release of the CO_2. A main hurdle is the energy required for the release.

An alternative to solvents and sorbents is using membranes, which selectively let the CO_2 to pass through. Hybrid solutions and solutions that cannot be classified as either of the three above also exist and are briefly described in the report.

4.1 Post-combustion solvents

Solvent-based CO_2 capture involves chemical or physical absorption of CO_2 from combustion flue gas into a liquid carrier. Chemical solvents rely on a chemical reaction of CO_2 in the solvent whereas physical solvents absorb molecular CO_2 without a chemical reaction. Chemical solvents are most attractive for post-combustion with dilute low-pressure flue gases. The absorption liquid is re-generated by increasing its temperature or reducing its pressure.

Solvents for use in post-combustion CO_2 capture are commercially available from several vendors. The world's first commercial scale capture plant, SaskPower's Boundary Dam, Saskatchewan, Canada, is the best example, with a process by Shell Cansolv. Other vendors include Aker Solutions (earlier Aker Clean Carbon), Fluor, Mitsubishi Hitachi, Linde-BASF and Alstom, all have amine based solutions, just to mention some. Alstom also has a technology based on ammonia.

Important objectives for the improvement of post-combustion solvents, including the commercial ones, are development of low cost, non-corrosive solvents that have a high CO_2 loading capacity, high absorption rate, low regeneration energy, improved reaction kinetics, low environmental impact and are resistant to degradation. This is ongoing research by vendors, research institutes and universities and is excluded from this summary, which focuses on new concepts not yet at the demonstration level.

4.1.1 Precipitating solvents

Certain solvent systems form a precipitate when absorbing CO_2. Amino acid salts and inorganic carbonate solvent systems are among the examples, in which precipitation of neutral amino acid or bicarbonate salts occur. The precipitation leads to a concentrated slurry of salts, which is sent to re-generation, while part of the solvent is sent back to the absorber. The use of precipitating solvents has potentially several advantages over traditional solvents. As the equilibrium CO_2 pressure remains constant when the CO_2 loading continues to increase the absorption can be maintained, potentially leading to improved absorber performance such as increased stability and absorption capacity, increased kinetics, higher cyclic loading, and reduced energy consumption during regeneration (can be regenerated at higher pressure) compared to amine systems.

- **Maturity**: 2nd to 3rd generation; TRL 4-5 (Lab scale testing to small pilot-scale with real flue gas)
- **Challenges:** The impact of SO_2 and NO_x; the need for reclaiming of solvent needs further investigation; the operation of packed absorbers with precipitation requires some development; optimization of packing materials; and tendency for solids to build up and slowly block the process will need to be checked by long pilot plant runs
- **Some players**: Shell Global Solutions, Alstom, CSIRO, SINTEF/NTNU, TNO, University of Melbourne
- **Pathway to technology qualification**: On-site testing with real flue gas at e.g. a few tenths of tonnes of CO_2/hour. Further research on packing materials and optimization of liquid/gas ratios is recommended
- **Infrastructure required**: Further lab and pilot testing is recommended. This requires basic equipment for characterization of crystals formation. Equipment for solid-liquid separation and heat exchangers is also needed. Infrastructure like access to real flue gas, water, electricity and other utilites.
- **Environmental impact**: Low impact if inorganic carbonates are used. Potential Health, safety and Environment (HSE) issues must be addressed if NH_3 is used.
- **Applications**: Power industry, cement industry, steel industry

4.1.2 Two phase liquid phase solvents

Biphasic mixtures consist of two immiscible phases. In the case of CO_2 capture certain solvents form two liquid phases at absorption or when heated. Examples are blends of amine with different dissolution between the components. When two liquid phases are formed the lower phase will contain most of the bound CO_2 at very high concentration. This lower phase is separated out and sent for desorption.

The two liquid phase systems studied show a great degree of flexibility in operation and have advantages over working with solids/precipitates, e.g. it is believed that a re-boiler energy requirement of 2.0 GJ/tonne CO_2 is within reach and that the CO_2 can be released at higher pressures.

- **Maturity**: 2nd to 3rd generation; TRL 3 - 4 (Proof-of-concept with material testing at lab-scale, some testing planned or carried out in pilots)
- **Challenges:** Tailoring and characterizing the system to minimize the energy requirement; firmer validation
- **Some players**: IFPEN, SINTEF/NTNU, Technical University of Dortmund
- **Pathway to technology qualification**: Further lab and pilot should be performed in terms of optimizing solvent formulation and composition based upon operability, degradation and

emissions. For firmer validation of process Pilot scale tests were planned for ENEL plant at Brindisi in 2015 but have been cancelled.

- **Infrastructure required:** The concept utilizes a similar infrastructure as in conventional absorption/desorption cycles, i.e. access to real flue gas, water, electricity and other utilities, but requires some additional equipment like gas/liquid and liquid/liquid separators.
- **Environmental impact:** Very limited evaluation so far. Use of amines with low aqueous solubility may potentially lead to high emissions and might require special mitigation steps.
- **Applications**: Power industry, cement industry, steel industry

4.1.3 Enzymes

The enzyme carbonic anhydrase (CA) is known to accelerate the hydration of neutral aqueous CO_2 molecules to ionic bicarbonate species. CA is amongst the most well-known enzymes, since it operates in most living organisms, including human beings. By adding a soluble enzyme to an energy efficient solvent one may be able to achieve a lower cost process for carbon capture and mimicking nature's own process. Increasing the kinetic rates of the hydration of CO_2 and dehydration, as CA does, results in enhanced absorption and desorption of CO_2 into and out of a CO_2 solvent and/or in various membrane processes with immobilized CA. Novozymes applies ultrasonic energy to increase the overall driving force of the solvent re-generation reaction.

- **Maturity**: 3rd generation; TRL 1 - 2 (Bench scale testing with real flue gas)
- **Challenges:** Understanding the level of enzyme activation; increasing the chemical and physical stability of the enzymes (mainly thermal stability); advancing the limited cyclic capacity (for carbonates)
- **Some players**: CO_2 Solutions, Novozymes, Carbozymes, Akermin
- **Pathway to technology qualification**: Further basic research to understand the level of enzyme activation and to increase the chemical and physical stability of the enzymes (mainly thermal stability). In addition, the limited cyclic capacity (for carbonates) needs further advancements. Scale-up to lab and small pilot.
- **Infrastructure required**: The concept can utilize the existing infrastructure for post-combustion as found at many larger test facilities, such as access to real flue gas, water, electricity and other utilities. Some modifications may be required, depending on the need for recycling enzymes to avoid high temperature exposure.
- **Environmental impact**: Potentially low impact. If inorganic carbonates are use as main component and there are no other activators than the enzyme, there should be no emissions.
- **Applications**: Power industry, cement industry, steel industry

4.1.4 Ionic liquids

Ionic liquids (ILs) are inorganic or organic salts in a liquid state, with low melting usually below 100 °C. Ionic liquids are largely made of ions and short-lived ion pairs. The physical and chemical properties of ILs can be tuned to achieve high physical and chemical solubility for CO_2 to reduce the energy demand, increase stability, and to lower the flue gas losses compared to standard amine solvents (they are non-volatile), thereby reducing the costs of capture while also reducing the environmental impact. They are often termed "designer solvents". In reversible IL neutral molecules react with CO_2 to form a liquid that dissolves additional CO_2 by a physisorption mechanism. A modest rise in temperature reverses the reaction and releases pure CO_2. Another type of IL, polyionic liquids, made from ionic liquid monomers, have enhanced CO_2 sorption capacities and achieved fast sorption/desorption rates compared with room temperature ionic liquids.

IL have also been proposed for use in liquid membranes, supported on e.g. a porous alumina membrane.

- **Maturity**: 2nd to 3rd; TRL 1 – 4 (Lab scale testing with simulated flue gas to small pilot-scale with real flue gas. Pilot) scale (0.5 – 1 MW_e) with slipstream was proposed in October 2013, fate unknown.
- **Challenges:** Optimization of chemical/physical properties to overcome high viscosity problems, lowering the thermal energy requirements for CO_2 desorption and reduce costs.
- **Some players**: ION Engineering, Dupont, Xcel Energy, Evonik, Eltraon R&D, University of Notre Dame, University of Alabama, Georgia Tech Research Corporation, University of Colorado and many Chinese research groups (materials development).
- **Pathway to technology qualification**: Pursue an active research to optimize physical and chemical properties of ILs by expanding the lab-scale units to pilot scale. In addition, more work is needed on lowering the thermal energy requirements for desorption of CO_2 and investigations on the stability and regeneration of the solvent.
- **Infrastructure required**: The concept utilizes a similar infrastructure as in conventional absorption/desorption cycles, i.e. access to real flue gas, water, electricity and other utilities, and is usually described as a drop-in replacement for aqueous amine solvent systems.
- **Environmental impact**: More work is needed to evaluate toxicity, "green label" is not straight forward due many unknowns related to effects of long-chain ILs and cations/anions. The non-volatile nature of ILs indicates lower exposure risk than for volatile solvents. ILs are non-flammable at ambient and higher temperatures.
- **Applications**: Power industry, cement industry, steel industry

4.1.5 Novel solvent systems – encapsulated and electrochemical

These are processes that use amine-based solvents with novel system designs that should minimize the known disadvantages of standard amine systems. This can be done through solvent development and/or novel process configurations. Two examples are encapsulated solvent and electrochemically-mediated amine regeneration systems.

Encapsulated solvent involves encapsulating the solvent, e.g. an amine or a carbonate, in thin polymeric membrane or shell, forming beads of size 200 – 400 µm, thereby given a large increase in contact surface area between flue gas and solvent. The inner solvent will perform the selectivity role. The shell must be highly permeable to carbon dioxide and strong enough to survive capture, and presumably release pure CO_2 via heating, over thousands of cycles. With the capacity of liquids and the physical behaviour of solid sorbents, encapsulated solvents may be useful in both conventional-style capture applications, as well as new approaches. The liquid, as well as any degradation products or precipitates, remains encapsulated within the beads.

In electrochemically-mediated amine regeneration (EMAR) systems, the heat exchanger and stripper is replaced with an electrochemical cell. As integration is required with the plant steam cycle this concept offers the advantage of easier retrofitting than traditional amine or other solvent systems. It may also achieve lower CO_2 lean loading. The process has potential to improve the overall process economics by reducing absorber size and lowering system energy penalty.

- **Maturity**: 3rd generation; TRL 1 - 2 (Encapsulated solvents: Proof of concept; Electrochemically-mediated amine regeneration: Bench to lab scale testing)
- **Challenges:** Scale-up from lab
- **Some players**:
    - Encapsulated solvents: Lawrence Livermore National Laboratory, University of IL Urbana-Champaign, Babcock and Wilcox Co.
    - Electrochemically-mediated amines: Mass. Institute of Technology, Siemens, Topchiev Institute of Petrochemical Synthesis, Russia
    - Addition of organic acid: NTNU
- **Pathway to technology qualification**: On-site testing with real flue gas at e.g. a few tenths of tonnes of CO_2/hour. The impact of SO_2 and NO_X and the need for reclaiming of solvent needs further investigation. Further research on packing materials and optimization of liquid/gas ratios is recommended
- **Infrastructure required**: The concept can utilize the existing infrastructure for post-combustion as found at many larger test facilities i.e. access to real flue gas, water, electricity and other utilities. Some modifications will be required, such as cathodic systems. Sufficient electricity must be secured.
- **Environmental impact**: For the encapsulated solvent concept, leakage of amines degradation to the surroundings may be reduced if the encapsulated amines remain structurally intact. This will require further research. In general, an improved efficiency may reduce the environmental foot-print.
- **Applications**: Power industry, cement industry; EMAR also steel and aluminum.

4.2 Post-combustion sorbents

4.2.1 Calcium looping systems

In this process 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 in which $CaCO_3$ is converted back to CaO and CO_2 under the addition of air or oxygen, heat and fuel. CO_2 can thereafter be captured. Temperatures in the carbonator are 600 - 650 ^{o}C and in the calciner 850 – 1000 ^{o}C. Advantages of the calcium looping process is that the output from the calciner is the high purity CO_2; that the exothermic heat of the CO_2 absorption reaction can be recovered for use in steam generation, which reduces the energy penalty; and that the raw material ($CaO/CaCO_3$ found in e.g. dolomite and natural gypsum) is abundant and inexpensive.

The calcium looping process has mainly been studied for post-combustion application in coal fired power plants and les so for gas fired power plants. In coal fired plants there are good opportunities for heat integration for both carbonator and the steam leaving the calciner. In gas fired plants, one looses the good heat integration that can be obtained for coal fired plants.

- **Maturity**: 2nd generation; TRL 5 - 6 (Pilot scale:
    - At 1 – 2 MW_e on real flue gas from coal fired power plant (Darmstadt, smaller one in Stuttgart and China);
    - 8000 – 9000 tonnes CO_2/year at cement plant by Taiwan Cement Group)
- **Challenges:** The rapid degradation of the sorbent, CaO, requires continuous substitution of $CaCO_3$ (which also degrades). As the CO_2 from the "fresh" CaO also must be captured, the degradation leads to an increased amount of CO2 that must be captured, compressed and

transported. This, in combination with the low residual activity, requires studies on more advanced sorbents. Further, the design and operation of the solid-solid heat exchanger required between the carbonator and calciner to recuperate heat and improve energy efficiency must be improved.

- **Some players**: Foster Wheeler, Alstom, SINTEF, IFE, TU Darmstadt, University of Stuttgart, INCAR (Oviedo, Spain), CSIC, SINTEF, IFE, Chalmers University of Technology, other universities in Europe, North America, and China.
- **Pathway to technology qualification**: Scale up to large pilot scale in the order of $10MW_e$ is needed.
- **Infrastructure required:** CO_2-containing flue gas is required. Infrastructure is required for continuous supply and makeup of $CaCO_3$ sorbent as the sorbent deactivation rate is high, and for disposal of degraded CaO.
- **Environmental impact:** CaO and $CaCO_3$ can be safely stored at atmospheric conditions (CaO is also a saleable product) since they are stable and non-volatile materials. The impact of the calcium looping process regarding the fine dust emission must be evaluated.
- **Applications**: Power industry, cement industry, steel industry

4.2.2 Other sorbent looping systems

Due to the rapid degeneration of $CaO/CaCO_3$ and the large need for make-up, one will seek to find other options. This can be done in several ways, including:

- By improving the lifetime of natural Ca-based minerals by promoting the minerals with other elements or processing with other inorganics
- By preparating supported Ca-based sorbents by wet impregnation of calcium-containing solutions onto a porous substrate followed by calcination
- By developing sorbents based on nano technology, such as nanoparticles of e.g. CaO, LiO, Na_2O that are stabilized by other nano-sized particles made from e.g. ZrO, CeO_2, TiO_2, SiO_2, Al_2O_3
- By loading CO_2-philic polymers onto high surface nanoporous materials (molecular Basket sorbents, MBS)
- By modifying mesoporous carbon material with surface functional groups that adsorb CO_2.

- **Maturity**: Demonstration to 2nd or 3rd generation; TRL 1 - 6 (Depends on adsorbent: From lab scale testing on simulated flue gas via 1 MW pilot on slip stream of actual flue gas (ADA-ES at Southern Company Miller Plant, unknown sorbent) to 10 MW slip stream from coal fired power plant KEPCO's Hadong, Korea)
- **Key Challenges**: Increase stability and reduce degradation while at the same time have high CO_2 absorbing/desorbing capacity and heat requirements; large scale manufacturing
- **Some Players**: Toshiba, CanMet, Imperial College, ECN, SINTEF, Mitsubishi, ETH, ADA-ES, TDA Research, RTI International, University of North Dakota, SRI International, KEPCO RI, Korea
- **Pathway to technology qualification**: Depends on sorbent. Once qualified in lab the possibilities of larger scale testing in facilities as used t NCCC for the SRI sorbent, at Southern Company Miller Plant for ADA-ES sorbent and the Hadong plant in Korea should be explored
- **Infrastructure required**: Slip stream of flue gas from full scale power plant and possibilities for make-up and disposal of deactivated sorbent. Possibilities to analyze for potential emissions or hazardous waste.

- **Environmental impact:** Sorbent depending
- **Applications**: Power industry, cement industry, steel industry

4.2.3 Vacuum pressure swing adsorption (VPSA)

VPSA is a version of Pressure Swing Absorption (PSA) that uses vacuum to desorb the adsorbed gas.. Two or more columns, which are filled with adsorbent pellets, are needed to achieve a continuous process. In each column a sequence of adsorption, rinse, evacuation and purge to desorb the adsorbed gas is carried out. The adsorbent will be a high surface area material with moderate adsorption energy with the adsorbing gas and high selectivity for CO_2 compared to gases like NO_X and O_2. The energy required in this process is the electric power for the vacuum pumps and the valves as well as the energy needed to compress the CO_2 from below atmospheric pressure. There is no need for steam. Overall, the energy requirement is believed to be lower than that for amine solvent solutions. The VPSA (vacuum pressure swing adsorption) process is best suited for flue gases with CO_2 content >10%, i.e. for coal fired power plants and several industrial processes.

Zeolites are often used as adsorbents in the VPSA process but Metal Organic Frameworks (MOFs) and other tuneable materials with high surface may result in significantly improved performance provided they have high cyclic capacity and can work at high relative humidities.

- **Maturity:** 3rd generation; TRL 2 - 3 (Lab Scale testing with real flue gas)
- **Key Challenges**: Need to investigate the impact of SO_2 and NO_X and the need for reclaiming of solvent. Further development of optimised adsorbents.
- **Some Players**: Engineering companies: Air Products, Linde, UOP, Wärtsilä Hamworthy, Zeolite producers: UOP, Grace, Zeolyst. Academic and research institutions: SINTEF and University of Oslo, Monash University/CSIRO, University of Ottawa, Georgia Tech, ETH, RTI International.
- **Pathway to technology qualification**: Scale-up to pilot-scale on-site testing with real flue gas at e.g. a few tenths of tonnes of CO_2/hour.. Further research on packing materials and optimization of liquid/gas ratios is recommended
- **Infrastructure required**: Access to real flue gas with CO_2 concentration >10%.
- **Environmental impact**: No specific impacts are expected as the sorbents are stable non-volatile solid materials that contain no trace-metals.
- **Applications**: Power industry, cement industry, steel industry

4.2.4 Temperature swing adsorption (TSA)

In a TSA process, CO_2 is adsorbed on a high surface area material at low temperature (40-60^{o}C) in an adsorber. Two solutions exist for the desorption process:

- The adsorbent is in a contained in two or more columns and each column undergoes a cycle with adsorbing and desorbing that leads to the release of CO_2. Energy for the desorption is usually heat in form of steam but electric current can also be used. The latter is referred to as Electric Swing Adsorption (ESA).
- Adsorption and desorption are performed in the same column by first absorbing CO_2, followed by heating (to 80-150^{o}C) to desorb CO_2

Several materials are being tested as adsorbent for the TSA process. These include zeolites, sorbents based on sodium, silica and alumina based sorbents, activated carbon and polymeric hollow fiber contactors filled with CO_2 adsorbent.

An amine-impregnated sorbent developed by RITE and NAIST of Japan has been tested successfully in a moving bed system utilizing low-temperature steam. The system (KCC) has been designed by Kawasaki Heavy Industries and tested with promising results on exhaust gas from a 7800 kW gas engine, producing 3.2 t/h of CO_2.

TSA can be combined with a Pressure Swing Adsorption (PSA) in a PTSA process where both reduced pressure and increased temperature are used to regenerate the adsorbent.

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- **Maturity**: 2nd to 3rd generation; TRL 1 - 4 (TRL 4: the amine impregnated sorbents in a TSA moving bed system; other sorbents mainly TRL 1-2, i.e. bench scale with real flue gas, lab scale with simulated flue gas)
- **Key Challenges**: Depends on the sorbent but include: Increase the CO_2 adsorption capacity of some sorbents; reduce the impact of contaminants, particularly SO_X; reduce heat of adsorption.
- **Some Players**: RITE; NAIST and Kawasaki Heavy Indistries, Japan, Adsorption Research Inc (SRI) and Inventys, adsorbent producers Grace, UOP, and Zeolyst, Georigia Institute of Technology, InnoSepra, TDA Research and ETH
- **Pathway to technology qualification**: On-site testing at pilot scale with real flue gas at e.g. a few tenths of tonnes of CO_2/hour.
- **Infrastructure required**: A CO_2 containing real flue gas preferably with CO_2 concentration < 10%. Some moving bed concepts need the flue gas at at > 200 °C (for regeneration). The KCC system may use steam at 60 °C.
- **Environmental impact:** No specific impacts are expected as the sorbents are stable non-volatile solid materials that contain no trace-metals
- **Applications**: Power industry, cement industry, steel industry

4.3 Post-combustions Membranes

4.3.1 Membranes general

Membrane-based post-combustion CO_2 capture uses permeable or semi-permeable materials that allow for the selective separation of CO_2 from flue gas. While membranes are more advantageous for separating CO_2 in high-pressure applications, such as coal gasification, there is also significant work going on in developing highly selective and permeable membrane systems designed specifically for CO_2 separation from low partial pressure, post-combustion flue gas streams. Membranes potentially could be a more energy efficient and cost-effective technology option for post-combustion CO_2 capture than solvents or sorbents

Membranes for post-combustion come as polymeric, glassy as well as rubbery; as hybrids of polymeric and nano-particles; electrochemical membranes; as ceramic; and as composites. Polymeric membranes have long been used in a number of industrial gas separation processes including air separation; hydrogen recovery from ammonia; dehydration of air; and CO_2 separation from natural gas. Of the polymeric membranes, rubbery membranes have higher permeability and lower selectivity while glass membranes have higher selectivity and lower permeability. Improvements of polymeric performance may be achieved by use of chemical reactions, in which a CO_2-reactive functionality is attached to the polymer.

Liquid membrane (LM) is a prospective separation system consisting of a liquid film through which selective mass transfers of gases, ions, or molecules occur via permeation and transport processes. LM can be both non-supported and supported. In the latter microporous films are used as the solid support and they are either flat sheet or hollow fiber LMs.

Post-combustion membranes can be in the shape of both sheets and hollow fibers. They can be used as a contactor between the CO_2-containing flue gas and an absorption liquid.

The process and material design research focuses on ensuring a large driving force for sufficient flux across the membrane and membrane selectivity.

Membranes have advantages that include:

- Simple passive operation with no moving parts
- Energy-efficient with low operating costs
- No hazardous waste streams
- Modular design that makes them suitable for retrofit and scale-up
- Simple and easy maintenance provided sufficiently long lifetime

- **Maturity:**
    - 2nd generation; TRL 5 – 6 (Polymeric membranes for separation of CO_2 from natural gas are commercially available but are still in need of pilot and demo-scale testing for post-combustion capture)
    - 3rd generation; TRL 2 – 4 (Other membranes range from bench scale with synthetic flue gas to small-scale pilot (1 MW) stage testing with real flues gas)
- **Key Challenges:** Increase and prove long term membrane stability; increase selectivity and permeability for the low partial pressure of CO_2 in the flue gas from power production to reduce compression work and need for multi-stage membrane design may be required; optimize process design;
- **Some Players**: Membrane Technology and Research Inc., RTI International, NTNU, SINTEF, University of Twente, New Jersey Institute of Technology, FuelCell Energy, General Electric, Ohio State University, Gas technology Institute, American Air Liquide, University of New Mexico, Carbozyme
- **Pathway to technology qualification**: Continue material development and better understanding of membranes other than polymeric. Scale-up to pilot and thereafter small-scale demo on-site with real flue gas at e.g. a few tenths of tonnes of CO_2/hour.
- **Infrastructure required**: The concept can utilize the existing infrastructure for post-combustion as found at many larger test facilities. Some modifications will be required.
- **Applications**: Power industry, cement industry, steel industry

4.3.2 Polymeric membranes combined with low temperature separation

This is a hybrid system where the stream with a high concentration of CO_2 from a polymeric membrane is sent to a low temperature "cryogenic" unit to obtain high capture rates and CO_2 transport specifications. Another concept operates also the membrane at low temperature (-25 ^{o}C to – 45 ^{o}C), as membrane selectivity and permaeance increases significantly at these temperatures. However, this process is more complicated and more energy consuming than the simpler configuration and not competitive.

- **Maturity**:
    - 2nd to 3rd generation; TRL 3 – 5 (Hybrid concept, membranes at somewhat higher level).

- **Key Challenges**: For membranes as described in 4.3.1; for the refrigeration system – bring down energy requirements
- **Some Players**: Membranes: Membrane Technology and Research Inc (MTR), RTI International,Air Liquide, NTNU, University of Twente, NJIT. Low-temperature CO_2 purification: Air Liquide, Air Products and Chemicals Inc., Praxair, Linde Engineering
- **Pathway to technology qualification**: Perform pilot tests on the membrane systems at 1 – 10 MW. As the low-temperature systems have been are being tested at the pilot scale, the hybrid system will can be tested at pilot scale once the membranes are qualified for pilot scale.
- **Infrastructure required**:. The concept can utilize the existing infrastructure at TCM but cooling possibilities down to – 130 °C must be added.
- **Environmental impact**: None is expected as there are no chemicals involved
- **Applications**: Power industry, cement industry, steel industry

4.4 Post-combustion Low temperature (Cryogenic) CO_2 separation from flue gas

Low-temperature separation is also known as anti-sublimation, cold separation, cryogenic separation, freeze-out separation, and frosting separation. Low-temperature separation is possible since the flue gas constituents have different freezing temperatures. The process includes the freeze-out of CO_2 and separation of the solid particles from other flue gas components through solidification on cold surfaces or through expansion of pressurized and cooled gas into CO_2 freeze-out region. While low-temperature separation is physically possible, its cost-effectiveness is limited due to the large quantity of energy necessary to accomplish the flue gas cooling. The energy consumption is inversely proportional to the CO_2 concentration in the flue gas. Thus, cryogenic separation is not well suited for gas power. Under any circumstances, tight heat integration is necessary to keep energy penalty low. However, some simulations claim lower specific capture work than the conventional MEA-based capture.

- **Maturity**: 3rd generation; TRL 2 - 3 (Large lab/small pilot scale at 240 kg CO_2/day)
- **Key Challenges**: Pilot testing is needed to determine the specific capture work and efficiency.
- **Some Players**: GE, Shell Global Solutions, Alstom, Endhoven University of Technology, MINES ParisTech.
- **Pathway to technology qualification**: Process equipment is available for larger scale that hitherto tested, thus scale-up will be the natural next step
- **Infrastructure required**: Real flue gas is needed, power and refrigeration possibilities down to – 130 °C.
- **Environmental impact**: None is expected as there are no chemicals involved
- **Applications**: Power industry, cement industry, steel industry, refineries

4.5 CO_2 enrichment in flue gas from gas turbines

The basic idea behind this concept is to recirculate part of the flue gas prior to the CO_2 capture unit to increase CO_2 content in the flue gas, which will facilitate post-combustion CO_2 capture. Concepts with oxygen-enriched air are also envisaged for producing flue gases with a further increase in CO_2 concentration.

- **Maturity**: 2nd generation (Process optimization may be validated by 2020, turbine by mid-2020'ies)

- **Key challenges**: Develop optimal process configuration; obtain stable and complete combustion in CO_2- and/or oxygen-enriched atmosphere by adaptation of gas turbines
- **Some players**: Turbine manufacturers
- **Pathway to technology qualification**: Further testing on large existing gas turbines
- **Infrastructure required**: None special
- **Environmental impact**: None
- **Applications**: Power production

4.6 Hydrates

Gas hydrates are crystallines composed of water and gas under suitable conditions of low temperature and high pressure. When gas hydrate is formed from a mixture of gases, the component that forms hydrate most easily might be enriched in hydrate phase. Due to hydrates having the capacity to store a large amount of gas and to separate a gas mixture, hydrate technology has attracted much attention as a potential means of capturing CO_2. One advantage of the technology is the modest energy penalty, thus hydrate technology for gas separation seems to be cheap compared to other post-combustion alternatives in case of a CO_2 rich source gas. It may be competitive in application fields where the inlet gas has a high pressure such as the oil and gas industry

- **Maturity**: 3rd generation (Concept studies to bench-scale)
- **Key challenges**: Further reduction of energy consumption; increase hydrate formation rate; improve separation efficiency; reduce induction time before hydrate production start.
- **Some players**: IFE, University of Peruga, several research institutions in China, Technical University of Denmark
- **Pathway to technology qualification**: Improve computation models; improve additives; Much laboratory work is still needed
- **Infrastructure required**: Too early
- **Environmental impact**: To be investigated
- **Applications**: Power production

4.7 Algae

Algae are found in fresh as well as salt water. Like plants, they draw energy from photosynthesis, using light from the sun and carbon dioxide from the air. They efficiently capture carbon by taking it out of the air and locking it away in solid biomass. Thus, they are considered suitable for taking the CO_2 out of flue gases. Two types of microalgae can be envisaged: (1) One type that grows rapidly and puts on sufficiently weight to sink to the sea bed ; and (2) a second type that can be used as a raw material for making products or as a renewable fuel itself.

Algae technologies use plantonic algae in water solution in Vertical Bioreactors (VB) or in algae farms with large ponds. However, most are currently not economically viable, especially on a large scale. Limitations to these systems include: sub-optimal productivity, expensive installation, large footprint (surface area), high water demand and the requirement for a highly trained end-user.

- **Maturity**: 3rd generation/TRL 1 – 3 (Small units exist for both bioreactors and open ponds, but amount CO_2 captured is very small.
- **Key challenges**: Reducing the need for water during production and for space; collecting the CO_2, as it is released through bubbling in the liquid phase and harvesting is difficult, time consuming and

inefficient. In addition, the present operation is difficult to scale up, leaves a large foot print, may have problems with light supply at night (open outdoor ponds), understandin impacts of trace contaminants (e.g. heavy metals)

- **Some players**: University of Bergen, University of Kentucky, CESFAC (Confederación Española de Fabricantes de Alimentos Compuestos Para Animales), partners in EU project ALGADISK, Macquarie Generation (Australia), Seambiotic, Israel
- **Pathway to technology qualification**: Develop systems with lower water and space needs and in which CO_2 would be captured either from the gas phase directly or from the liquid phase after bubbling and with automatic and continuous harvesting. Scale-up up from small pilot to large demos.
- **Infrastructure required**: Flue gas with CO_2, water supply and, for ponds, space
- **Environmental impact**: Open ponds have high risk of contamination. Using lakes or ocean areas may be controversial. Open ponds require large amounts of water and land. To be investigated more for bioreactors. Ethical, esthetical, legal and societal aspects must be analysed.
- **Applications**: Power industry, industry

4.8 Supersonic Post-combustion Inertial CO_2 Extraction System

This process, Inertial CO_2 Extraction System (ICES), is based on the principle that aerodynamic expansion to high velocity converts potential energy contained in the form of pressure and temperature into kinetic energy. The conversion results in condensation of undesirable constituents of flue gas including the desublimation of CO_2. The high density of the solid phase constituents of the flow allows for inertial separation by centrifugal forces induced by flow path curvature.

ICES does not require external media or chemical processes and, due to high flow velocity, will have a very small system volume compared to membrane systems. It also has the ability to achieve steady capture conditions very rapidly after start up. The ICES has a footprint approximately 25 percent the size of an equivalent amine system, is readily scalable, reduces parasitic plant load from capture and compression, and includes steps for capture, purification, and highly efficient pressurization.

- **Maturity**: 3rd generation; TRL 1 – 2 (Concept stage for CCS but commercialized in another application)
- **Key challenges**: To generate CO_2 particles greater than approximately 2.5 μm in effective diameter to ensure efficient inertial migration; verify CO_2 particle growth to a size that permits them to migrate to a compact layer adjacent to one wall where they can be readily removed by a boundary layer capture duct. Confirm the feasibility of the inertial CO_2 separation in a compact device without any moving parts or consumables.
- **Some players**: Alliant Techsystems Operations, ACENT Laboratories, the Electric Power Research Institute and The Ohio State University
- **Pathway to technology qualification**: A detailed laboratory-scale investigation and analysis of the mechanisms underlying CO_2 condensation, nucleation, and particle growth. A bench-scale testing of the complete ICES incorporating the selected particle growth method with the optimized capture duct and diffuser systems to enable the integrated testing of CO_2 condensation, migration, removal, and flow diffusion.
- **Infrastructure required**: Flue gas with CO_2
- **Environmental impact**: Needs to be investigated.
- **Applications**: Power industry

4.9 Pressurised post combustion capture

It may be possible to use a coal fired pressurised fluidised bed boiler in post combustion applications to take advantage of much higher partial pressures of CO_2. Energy would be expended in compressing air into the boiler and would be recovered by re-expanding the flue gas after CO_2 capture. Efficiencies increase with increasing starting temperature for this expansion.

A similar process could work for a gas turbine based power plant whereby the capture of CO_2 would occur at high pressure prior to expansion. The proposal is to use hot potassium carbonate as the absorption medium. The hot flue gas has first to be cooled to about 100^{o}C before entering the capture plant but is reheated using heat exchange so that most of the heat is recovered. The pressurised gas, scrubbed of CO_2, is then expanded to generate power.

- **Maturity**: 2nd to 3rd generation; TRL 2 - 5
- **Key challenges**: Further work is needed to demonstrate it as a commercially competitive technology to conventional pulverised coal combustion. Also further work needs to be done to establish the overall energy efficiency of the systems with CO_2 capture.
- **Some players**: Sargas and GE
- **Pathway to technology qualification**: testing in pilot scale
- **Infrastructure required**: Access to a power station
- **Environmental impact**: Needs to be investigated.
- **Applications**: Power industry (new built, not retrofit)

5 Summary of Identified Technologies - Pre-combustion

In pre-combustion CO_2 capture the carbon and hydrogen in the fuel are separated before combustion. In the case of coal or biomass a gasification process followed by gas clean-up is necessary, in the case of gas, the fuel is reformed. In both cases the product is a syngas consisting mainly of hydrogen, carbon monoxide (CO) and minor amounts of other gases. A water gas shift (WGS) reaction, where steam is added to the syngas, produces a mixture mainly of hydrogen and CO_2 and the two are separated in a separation process. The process is shown schematically in Figure 2.

One advantage of the pre-combustion process over post-combustion, is that the CO_2 is released at significantly higher pressure and the CO_2 concentration is higher, thus potentially reducing the energy demand. However, energy is required for the air separation and the gasification or reforming processes, so the lowered energy demand is counteracted. The hydrogen-rich is fed to a gas turbine for power production. Pre-combustion is well suited for combined production of power, liquid fuel and hydrogen.

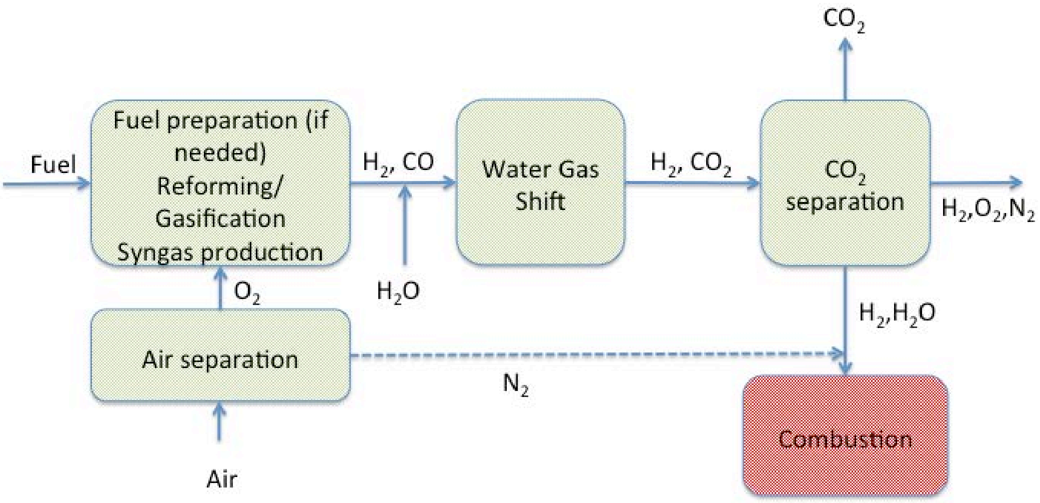

Figure 2. Schematic illustration of the pre-combustion process

The CO_2 capture becomes an integrated part of the combustion process, which adds to the complexity of the system. The system integration itself is a challenge. Thus, existing power or industrial plants are not easily retrofitted with pre- combustion CO_2 capture. Due to the complex system integration pre-combustion CO_2 capture is only an option for new built plants.

Research and development in pre-combustion involves better sorbents and membranes for the water gas shift and separation processes; combined processes of sorbents and membranes, including the combination of the WGS and separation processes into one stage; a more energy efficient air separation process; and turbines that can also be used for hydrogen-rich fuel without de-rating or fuel dilution.

Improvement in pre-combustion technologies will also benefit industrial applications where hydrogen production is an important element, e.g. fertilizer plants and refineries.

5.1 Pre-combustion solvents

Solvents are commercially used to remove CO_2 (and other acid gases) from syngas (e.g. Selexol^{TM}, based on Dimethyl Ether of Polyethylene Glycol (DEPG); Coastal AGR$^{®}$, based on DEPG; Purisol$^{®}$, based on N-Methyl-2-pyrrolidone (NMP); Rectisol$^{®}$, based on methanol; and Flour Solvent^{TM}, based on Propylene Carbonate) and solvents for pre-combustion applications can be considered mature technology used in e.g. hydrogen production for refineries and the fertilizer industry. However, these applications are often complex and may involve separation in more than one stage if H_2S is present. Adequate separation of CO_2 and H_2S in the regeneration is still a challenge, as is reduction of operation costs.

Thus, there is continuous to improve existing the pre-combustion CO_2 capture solvents. Identified players include CO2CRC in cooperation with the University of Melbourne, SRI International (an aqueous ammoniated solution containing ammonium carbonate, tested in pilot-scale on actual syngas) and a Japanese group from Kawasaki Heavy Industries and Research Institute of Innovative

Technology for the Earth (RITE), who cooperate on the developments of a chemical solvent called RH-x for high-pressure conditions.

5.2 Pre-combustion sorbents

5.2.1 Sorption- Enhanced Water Gas Shift (SEWGS)

The process is a multi-column process in which the columns are filled with a mixture of high temperature WGS catalyst and CO_2 adsorbent. Syngas (containing H_2, CO_2, CO, H_2O, CH_4, and inerts) is fed at high pressure and temperature and CO_2 is removed by the sorbent. The process almost completely converts the CO and maximises the production of H_2. CO and CO_2 are effectively removed from the feed gas, producing a high pressure, hydrogen rich product stream. When the adsorbent is saturated and CO_2 begins to show up in the product stream (breakthrough), the bed is taken off-line and regenerated. Regeneration is based on pressure swing (PSA) and produces a low-pressure by-product stream rich in CO_2. By using multiple beds and properly staggering the process cycle, the inherently dynamic process can mimic a continuous one, with essentially constant feed and product/by-product streams.

- **Maturity**: 2nd generation; TRL 4 - 5 (Pilot-scale 50 - 100 kg CO_2/hr)
- **Key challenges**: Prove or long term stability of sorbents with high volumetric cycling capacity, develop alterntive sorbenntssystem operation, providing steady stream of H2 for use
- **Some players**: ECN (Netherlands), TDA Research, URS Group, Air Products,
- **Pathway to technology qualification**: Scale-up to demo.
- **Infrastructure required**: SEWGS is a pre-combustion technology working at elevated pressures (30-40 bar). A (synthetic) syngas containing CO is needed, as well as steam
- **Environmental impact**: Probably very low, as SEWGS utilizes solid adsorbents that are non-volatile and stable materials without known negative environmental consequences. Deposition of used materials should also be non-problematic (i.e. better than for cracking catalysts that contain traces of metals).
- **Applications**: Power industry, refineries, hydrogen production

5.2.2 Sorption- Enhanced Steam-Methane Reforming (SE-SMR)

This technology is also called Sorption Enhanced Reforming (SER) or Chemical Looping autothermal Reforming (CLR). Its purpose is to enhance the well-known steam-methane reforming process used industrially for natural gas-based H_2 production, and to simultaneously capture CO_2. The principle has much in common with calcium looping systems, where a solid sorbent, typically CaO, continuously adsorbs the CO_2 that is generated in the steam-methane reforming process, thus shifting the equilibrium of the process towards a higher hydrogen yield, while $CaCO_3$ is formed. CO_2 can be captured when $CaCO_3$ is converted back to CaO in a calciner. As the calciner process is highly endothermic, heat must be supplied, typically through direct combustion of oxygen and natural gas in the calciner. Although the CO_2 adsorption is exothermic, the resulting reaction is slightly endothermic, meaning that heat must also be supplied to the reformer/carbonator. SE- SMR could enable the steam-methane reforming reaction to be carried out at lower temperatures than with conventional technology, which could lower investments and operational costs.

Studies indicate varying degree of potential for cost reductions.

- **Maturity**: 3rd generation; TRL 1 – 2 (Bench-scale)
- **Key challenges**: Further development of sorbents. Avoidance of contamination of NI-based catalyst by sorbent and development of separation method of NI-catalyst and deactivated sorbent. Assess where the technology can be a viable option
- **Some players**: IFE (ZEG Project) , SINTEF, NTNU, Chalmers, Vienna University of Technology, Instituto de Carboquímica (CSIC), Spain
- **Pathway to technology qualification**: Scale-up to small pilot.
- **Infrastructure required**: For stand-alone testing of the SE-SMR process on a pilot scale, steam is required, as well as methane or natural gas + pre-reformer. In addition, supplies of sorbent and catalyst, and disposal possibilities for deactivated sorbent is required.
- **Environmental impact**: Ni-catalyst that is required for steam-methane reforming is poisonous, and must be handled carefully.
- **Applications**: Power industry, refineries, hydrogen production

5.3 Pre-combustion membranes

Gas separation membranes use differences in physical or chemical interactions between gases and a membrane material, allowing one component to pass through the membrane faster than another. Two types of pre-combustion capture membranes are: 1) Hydrogen membranes, in which H_2 selectively passes through the membrane; and 2) carbon dioxide membranes, in which CO_2 selectively passes through the membrane. Membranes are used commercially for CO_2 removal from natural gas at high pressure. However, for CO_2 capture further development is required.

Membranes currently available for pre-combustion capture include porous inorganic membranes, metallic membranes, polymeric membranes, zeolites and carbon membranes acting as molecular sieves. The membranes can be used in a range of configurations, e.g. related to where they are placed regarding the shift process.

Only metallic and ceramic membranes are described below. Membranes made of other materials will in general be at the same stage of development as metallic and ceramic membranes.

5.3.1 Metal and composite membranes

Metal-based membranes are usually based on palladium or palladium alloys that are uniquely selective to hydrogen, and they can therefore be integrated in pre-combustion capture processes to separate hydrogen from shifted syngas. The hydrogen-selective membranes have been studied for integration in membrane reactors for water-gas shift membrane reforming (WGS-MR) or steam reforming (SR-MR) reactions, allowing simultaneous high CO or methane conversion and production of pure H_2. Advantage include the production of a high pressure CO_2 stream, reducing the need for compression energy, and high-purity H_2 for power generation. This can greatly facilitate the economics of power generation with carbon sequestration.

- **Maturity**: 2nd - 3rd generation; TRL 3 – 5 (Tested using slip-streams, CO_2 capture > 100 kg/hour)
- **Key challenges**: Long-term performance and stability of membrane in real gas streams, in particular when applied in coal-derived sulphur-containing syngas. Reduce sensitivity to impurities. Production methods for reduced Pd thickness (giving lower cost and higher permeability). Membrane and membrane reactor manufacturing equipment is required on a sufficient scale.

- **Some players**: Shell, BP, Chevron, Linde Gas, Plansee, Tecnimont KT, Reinertsen AS, Pall Corporation, HEF, GKN, NGK Japan, MTR USA, Mitsubishi Heavy Industries Japan, ECN, SINTEF, ENEA, Worchester Polytechnical Institute, Dalian Institute, SINTEF
- **Pathway to technology qualification**: A test infrastructure on 1/100 scale of full-scale (membrane area 10 – 50 m^2, 1-5 MW_{th}, or 1000- 5000 t/year of CO_2 captured) could be the next step. An industrial site with realistic operating conditions is needed for validation.
- **Infrastructure required**: Syngas, steam and nitrogen for sweep gas are required on site. Furthermore, systems for handling the CO_2-rich retentate and the H_2/N_2 stream are probably required.
- **Environmental impact**: No known emissions issues related to membrane technology,
- **Applications**: Power industry, refineries, hydrogen production

5.3.2 Ceramic based hydrogen transport membranes

These membranes have the same applications as metallic membranes but they are made of ceramics. Important criteria for ceramic and porous inorganic membranes are selectivity, diffusion rate and tolerance to impurities. They typically operates at higher temperature than Pd membranes.

- **Maturity**: 2nd - 3rd generation; TRL 2 - 4 (Lab scale to vey small pilot testing)
- **Key Challenges**: High flux vs. long term stability in operation. Sealing technology and robust and low cost fabrication routes. Membrane manufacturing and assembly at large scale: ceramic processing with extrusion; coating techniques (dip-coating, spray-coating)
- **Some Players**: Saint Gobain, Praxair, AirLiquide; Technip, CNRS in France, Fraunhofer IKTS and Eifer in Germany; DTU-Risoe in Denmark, SINTEF; University of Oslo and NTNU.
- **Pathway to technology qualification**: Verify stability of membranes in contact with sealing materials and, depending on integration under real operating conditions, including exposure to various gases and contaminants (e.g. sulfur, CO_2) and sufficiently high temperatures (around 850 °C). Up-scaling of the membranes toward commercial scales is also needed.
- **Infrastructure required**: On short to medium time-scale mainly lab- and very small pilot-scale:
    - Furnace facilities for low temperature de-binding and high temperature sintering of ceramics
    - Module testing: high pressure gas infrastructures to produce and supply a hydrogen rich gas at suitable temperatures (700-900 °C); gas chromatography for analysis; furnace for module testing at high temperature.
- **Environmental impact**: No known emissions issues related to membrane technology,
- **Applications**: Power industry, refineries, hydrogen production

5.4 Low temperature CO_2 separation from syngas

In low temperature syngas separation CO_2 is separated from the syngas as a gas-liquid separation by cooling pressurised and dehydrated syngas to temperatures around – 50°C. The CO_2-rich fluid and the H_2-rich gas are then separated by gravitational or rotational gas-liquid separators.

The advantages of this process include that it is simple, there are no chemicals involved and it produces a liquid that can be pumped to high pressures, thereby avoiding the high energy consumption and high cost of compression. A disadvantage is that the percentage capture of CO_2 is limited by phase equilibria.

Variations of the process involve combination with CO_2 recirculation (Timmins process) and combination with an upstream hydrogen membrane, the latter being better suited for pre-combustion of natural gas power systems.

Low temperature separation is different from cryogenic separation for post-combustion, which occurs at around -150°C and gives CO_2 as solid particles.

- **Maturity**: 3rd generation; TRL 1 - 3 (Lab scale as a CO_2 capture process, but most required components are commercially available, except for multistage expanders for H_2-rich gas which have been designed and tested)
- **Key Challenges**: Capture ratio depends on partial pressure of feed to low temperature process, CO_2 freeze-out. Some H_2 will potentially dissolve in the CO_2 stream due to high pressures. High cost.
- **Some Players**: British Petroleum and Mitsubishi Heavy Industries, SINTEF and Eindhoven University of Technology
- **Pathway to technology qualification**: Lab and pilot scale tests of parts and complete process.
- **Infrastructure required:** Natural gas reformer and shift reactor. Possibilities for gas dehydration, auxiliary refrigeration (propane, ethane, CO_2 or other); insulated coldbox; power; optionally generator or turbine brake.
- **Environmental impact.** Potentially significant advantages with respect to the environment. Since no chemicals are involved, issues and unknowns regarding emissions of chemical by-products can be completely avoided.
- **Applications**: Power industry, refineries, hydrogen production

5.7 Concepts for pre-combustion using fuel cells

Use of fuel cells has the potential for higher efficiency power generation. Fuel cell technologies are being improved by many companies and countries but units for large scale power generation are not yet available. Certain types of solid oxide fuel cells (SOFC) have high energy efficiencies and they are also able to inherently capture CO_2, which means that the incremental cost of including CCS could be low.

Some other fuel cells are designed to use hydrogen, which could be produced in plants with pre-combustion capture. Hydrogen fuel cells could be attractive particularly for distributed combined heat and power production, which would make hydrogen production with pre- combustion CCS a more favoured technology if their cost and efficiency were better than those of combined cycle plants.

- **Maturity:** 2nd to 3rd generation; TRL 3 – 6 (Concept study, small-scale sub-system validation in relevant environments)
- **Key Challenges**: Integration of SOFC with gasifier. Reduce degradation of SOFC with respect to voltage.
- **Some Players:** NETL
- **Recommended pathway for technology qualification:** Validate all sub-systems, test SOFC with a gasifier
- **Infrastructure required:** Gasification facilities
- **Environmental impact:** None identified so far
- **Applications:** Coal and biomass based power

Another solution to feed hydrogen from a reforming process of natural gas (or syngas) to a solid oxide fuel cell (SOFC). One such solution is the ZEG (Zero Emission Gas,http://www.zegpower.no),where hydrogen is produced by sorption-enhanced steam-methane reforming (SE-SMR) using a $CaO/CaCO_3$

process with inherent CO_2 capture. The SOFC provides the heat required for steam-methane reforming. Both electricity and hydrogen can be provided to users. Estimates show this could be a high potential process, with more than 70% energy efficiency, if successful.

- **Maturity:** 2nd -3rd generation (Pilot testing)
- **Key Challenges**: As for SE-SMR described above plus SOFC plus high-temperature heat transfer from the SOFC to the SE-SMR process. Scale-up of SOFC subject to appropriate material development.
- **Some Players:** IFE and Prototech (ZEG Power AS)
- **Recommended pathway for technology qualification:** Must be verified at a pilot scale before considering any further up-scaling. Also the high-temperature heat transfer between the SOFC and the SE-SMR needs to be demonstrated.
- **Infrastructure required:** Probably natural gas supply, handling systems for fresh sorbent and produced mixture of sorbent and Ni-catalyst, make-up water of power plant quality, and receivers of the produced electricity (and hydrogen).
- **Environmental impact:** If Ni-catalyst is employed for the SE-SMR, the handling of the mixture of deactivated sorbent and Ni must be given attention, due to the poisonous character of Ni.
- **Applications:** Power industry, hydrogen production

5.8 Improved pre-combustion technologies that do not require CO_2 capture test facilities

Several improvements can be made to elements of pre-combustion CO2 capture that do not particularly require access to capture test facilities. These include:

- **Hydrogen turbines**. The most modern high-class turbines developed for natural gas (up towards the H-class) needs to be modified so they can operate on the hydrogen-rich fuel gases produced in the pre-combustion capture technologies. The aim is to use as high hydrogen-content as possible without dilution with nitrogen or steam.
- **Gasification**. The gasification process, which produces syngas from solid fuels (coal, lignite, biomass) can be improved but this is outside the scope of this report
- **Oxygen production for pre-combustion applications**. Use of oxygen rather than air in gasification and reforming have potential for improving efficiency and cost of the processes. Air separation is expensive and energy consuming, cryogenic separation being most commonly used. Using oxygen transporting membranes has potential to improve the process. This is described in the chapter on oxy-combustion.

6 Summary of Identified Technologies - Oxy-combustion

In oxy-combustion processes the fuel is burnt in pure or almost pure oxygen rather than air. This avoids handling all the nitrogen and the exhaust is mainly CO_2 and water, which provides for a relatively simple separation by dehydration. The combustion process takes place with recycled flue gas (CO2) or a CO2/steam mixture to avoid very high temperatures of oxy-combustion. The process is shown schematically in Figure 3. Depending on the fuel and its contaminants, an additional step may be needed to purify the CO_2 before compression.

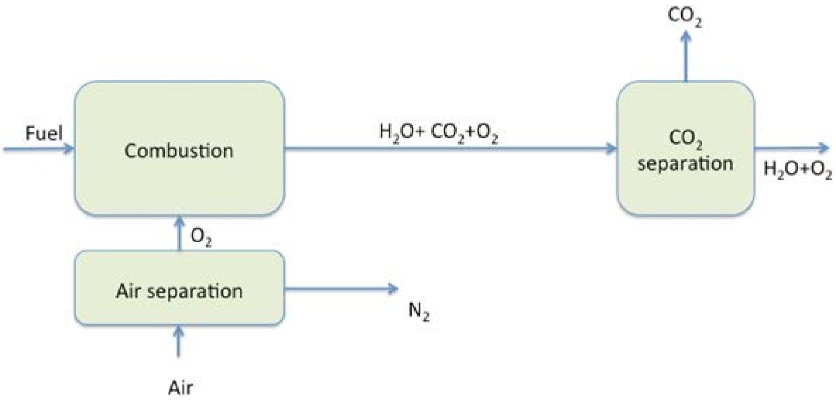

Figure 3. Schematic illustration of the oxy-combustion process

The CO_2 separation in the oxy-fuel process is straight forward, and the challenges lies within air separation and combustion. In this case the development may be along at least these paths:

1. Improve efficiency of oxygen production
2. Improve boiler for oxy-combustion
3. Improve gas turbine for oxy-combustion
4. CO_2 processing and clean-up are also areas where improvements can be made.

These paths will not necessarily involve CO_2 capture facilities, although in some cases that will be advantageous, and are only briefly summarized at the end of this chapter. It should be noted, however, that improved efficiency of oxygen production is relevant also to pre-combustion

Here we focus on a path to oxy-combustion that involves solid looping process.

An interesting potential of oxy-combustion technologies is that it allows for CO_2 recovery of nearly 100%.

6.1 Chemical Looping Combustion (CLC)

Chemical Looping Combustion (CLC) is a technology that relies on combustion or gasification in an N_2-free atmosphere. In principle this is an oxy-combustion technology with an unconventional way of producing oxygen for the combustion process.

CLC involves two-reactors where oxygen is removed from the air in one reactor, the air reactor, using metal or other solid O_2 carriers that will quickly oxidize at high temperature. The oxidized metal is then transported together with fuel to the other reactor, the fuel reactor. Here the oxygen reacts with the fuel, producing energy and a flue gas of mainly CO_2 and water vapour.

- **Maturity:** 3rd generation; TRL 2 -3 (Pilot scale testing up to 3 MW but still significant challenges).
- **Key Challenges**: oxygen carriers able to withstand the long-term chemical cycling, improved fuel conversion, obtain complete combustion, development and optimization of reactor and overall system and process designs
- **Some Players**: Alstom, Total, Shell, Chalmers, TU Vienna, CSIC, TU Darmstadt, SINTEF, Vito,

Ohio State University, University of Utah

- **Recommended pathway for technology qualification.** Development of oxygen carriers able to withstand the long-term chemical cycling, improved fuel conversion and combustion, development and optimization of reactor designs, ash separation, and technology scale-up. For coal CLC oxygen carriers based on low value or natural materials (e.g. steel rolling mill residues, ilmenite, limestone) are required. Need to develop a low-cost CLC with oxygen decoupling carrier (CLOU, in which the carrier and temperatures are selected to cause molecular oxygen release before reaction with the fuel).
  Further work on CLC for coal needs to confirm optimal reactor designs and process configurations, adequate carrier lifetime and good carrier/ash separation. The next stage is for scale-up to about 10 times the current, and, although natural gas-fuelled CLC will probably be first to get there, coal CLC is catching up.
- **Infrastructure required**
  - Steam facility
  - Air supply
  - Fuel supply
  - Oxygen carrier supply chain
- **Environmental impact:** In present state CLC fuel burn-out is not complete. Handling of particles that may contain un-healthy compounds such as metal dust is another issue. Some experience from test facilities using flue gas from FCC cracker may be relevant (In fact, the FCC cracker is a large two-reactor fluidized system with many similarities with CLC).
- **Applications:** Power industry

6.2 Oxygen Transport Membranes (OTM) Power Cycle

OTM technology integrates O_2 separation and combustion in one device. The membranes are ceramic tubes. OTM uses the chemical potential instead of pressure as the oxygen separation driving force. In conceptual designs, the OTM is integrated directly with the boiler. The combustion reaction on the fuel side of the membrane creates a very low oxygen partial pressure compared to the air side of the membrane. This difference in chemical potential drives oxygen through the membrane without the need for additional air compression. OTM can be used also as process heater and for syngas production.

- **Maturity:** 3rd generation; TRL 2 - 3 (Lab-scale, membrane materials and stack tested, rest conceptual stage)
- **Key Challenges**: Design, optimize, and test first generation OTM modules; design the unit operation process equipment, including the reactors housing the OTM modules, for both the syngas and oxy-combustion units
- **Some Players**: Praxair
- **Recommended pathway for technology qualification.** Pilot scale testing and validation of process
- **Infrastructure required**
  - Air supply
  - Fuel supply
  - Membrane production facilities
- **Environmental impact:** None expected
- **Applications:** Power industry
-

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6.3 Other elements for improving oxy-combustion

Below follow summaries of some technologies that cannot be directly classified as capture technologies but that have potential to reduce costs of CO_2 capture. The descriptions are taken from the references given in the headlines. Maturity in terms of generation or TRL has not been included.

Air separation and oxygen production is the major cost of CO_2 capture by oxy-combustion. Most Air Separation Units (ASU) use cryogenic air separation and the traditional technology is considered mature. Improvements can be achieved by at least two advanced technologies: 1) Use of membranes; and 2) novel cryogenic systems.

6.3.1 O_2 separation membranes for oxygen production (IEAGHG,2014; DOE/NETL, 2013)

In the Ion transport membrane (ITM) the O_2 separation is based on ionic transport in dense mixed ion and electron conducting membrane. This occurs at high temperatures (> 700 °C) in the presence of an oxygen partial pressure difference across the membrane. The membranes should preferably be very thin and will generally be fabricated as thin layers on porous structures. They are assembled in stacks of wafers. They have a potential for significant energy and cost reductions of air separation.

- **Maturity:** Lab to pilot scale, pilot in USA by Air Products
- **Key Challenges**: To obtain high flux vs. long term stability in operation. Sealing technology and robust and low cost fabrication routes.
- **Some Players**: Saint Gobain, AirProducts, Praxair, AirLiquide; Teknip, CNRS in France, Fraunhofer, IKTS and Eifer in Germany; DTU-Risoe in Denmark, SINTEF, University of Oslo and NTNU in Norway
- **Recommended pathway for technology qualification**: Testing of ITM multi-tube module (long tube –1 m long) with appropriate sealing technology in real conditions is needed. Also further development of stability of membranes in contact with sealing materials and, depending on integration, as well as exposure to various gases and contaminants (e.g. sulfur). Up-scaling of to commercial scales and commercial developing commercial scale manufacturing methods.
- **Infrastructure required**: Excluding elements connected to manufacturing: Module testing in high pressure gas infrastructures; gas chromatography for analysis; furnace for module testing at high temperature.
- **Environmental impact**: No direct environmental impact is foreseen through the use of OTM.
- **Applications**: Power industry, oxygen production

6.3.2 Cryogenic Air Separation (from IEAGHG 2014)

The standard industry method for cryogenic air separation is a double column distillation cycle with a high pressure column and a low pressure column. The columns have aluminium structured packing optimised for the purpose. This technology is mature and extensively used for oxygen production.

An improved version has been proposed, in which a third column is introduced, operating at an intermediate pressure (IEAGHG 2005[9]; Higginbotham et al, 2011[10]). This is expected to have

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[9] IEAGHG (2005) Oxy Combustion Processes for CO_2 Capture from Power Plant. Report number 2005/9

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significant impact on the energy efficiency of oxygen production (see IEAGHG 2014 for more). However, the trade-off is oxygen purity.

6.3.3 Other air separation methods (from DOE/NETL, 2013)

O_2 separation using a perovskite ceramic oxide adsorbent (composed of lanthanum, strontium, cobalt, and iron) at high temperature (800 to 900°C), the Ceramic Auto-thermal Recovery System (CARS) by Linde represents another approach that been assessed and pilot tested at 0.7t/day.

6.3.4 High-pressure oxy-combustion (from SINTEF, 2013)

Cycle analyses of pressurized oxy-combustion in coal fired boilers have shown efficiency improvements compared to atmospheric operation (which has so far been the usual approach to oxy-coal power production). The main advantages are higher heat recovery due to higher flue gas dew point temperature and reduced CO_2 compression work.

- **Maturity**: One 5 MW pilot plant built in Italy by ENEL)
- **Key Challenges**: Pressurization, Materials/Corrosion
- **Some Players:** ENEL, Mass. Inst. Of Tech.
- **Recommended pathway for technology qualification:**
    - Fundamental research on oxy-combustion at pressure
    - System integration and optimization studies
    - Pilot testing
    - Demonstration of infrastructure required
    - Oxygen production facility
    - Steam facility
- **Environmental impact**: Limited environmental effect is expected for this technology. The exhaust goes into the transport and sequestration systems and those stages will set the limit for allowable emission levels.
- **Applications:** Power industry

6.3.5 Oxy-combustion gas turbine (IEAGHG 2014)

Oxy-combustion gas turbines are mostly associated with the semi-closed oxy-combined-cycle (SCOCC). Component-wise the SCOCC cycle is rather similar to conventional combined cycles, but the gas turbine operates on pure oxygen from an ASU instead of air, and the working fluid is recycled $CO_2$from the exhaust.

- **Maturity:** Concept stage plus laboratory scale combustion development. The variant of Clean Energy Systems (CES) is at demo stage of several MW but is more like a steam/oxy cycle. Net Power and partners to test Allam cycle at 50 MW
- **Key Challenges**: Combustor design, turbomachinery heat transfer and corrosion
- **Some Players***:* Siemens, SINTEF, Lund University, CES, NET Power in collaboration with Toshiba, CB&I and Exelon.
- **Recommended pathway for technology qualification:** An oxy-combustion demonstration plant

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[10] Higginbotham, P., 2011. Oxygen supply for oxyfuel coal CO_2 capture. 2nd Oxyfuel Combustion Conference, Yeppoon, Australia, September 2011.

of the size 10 – 50 MWel with a single gas turbine for a power generation plant could be an adequate size in the time frame 2014-2016. Demonstrate new oxy-combustion dedicated turbomachinery and retrofitting capability of the technology. Test burner/combustor or turbomachinery. Test host material and cooling programs in relevant environments, necessary for the development of HP turbine.

- **Infrastructure required:** For full scale testing of the technology (i.e. a complete gas turbine with condenser and recirculation of CO_2) a feed of oxygen must be supplied by an ASU of a capacity of ca. 300 kg O_2/hr per MW of thermal power. If components like combustor/burner or turbomachinery are to be tested, large supply of CO_2 is necessary and other test facilities could supply it from the other capture plants.
- **Environmental impact:** In Emission levels of non-climate pollutants such as NO_x and SO_x are the low mostly. The oxygen separation unit is a thermodynamic process and the CO_2 is separated from the exhaust gases by condensation, therefore no chemicals are involved.
- **Applixations:** Power industry

6.3.6 Oxy-combustion boilers (from IEAGHG 2014)

Currently, technologies for oxyfuel combustion for PF (Pulverized Fuel) or CFB (Circular Fluidized Bed) coal fired power plants have reached the necessary maturity ready for large scale demonstration (i.e. 100 – 400 MW_e). This is a crucial step to bring this technology forward and achieve the goal of commercialisation by a 2020-2030 horizon. The large scale demonstration is an important step to sustain the current R&D investment and activities necessary to develop technologies and key components that would lead to cost reduction and improve efficiencies.
Some key areas could be the main focus of future development for oxy-combustion:

- Materials development contributing to the understanding of the impact on the boiler materials, welding, etc. when operating under oxyfuel combustion condition.
- Enabling the use of warm recycled flue gas to increase efficiency (i.e. materials development along the flue gas recycle path).
- Development of low flue gas recycle rate and high oxygen content in the furnace – for CFB only.

6.3.5 CO_2 processing and clean-up (IEAGHG 2014)

The CO_2 Processing Unit (CPU) is the purification step of the CO_2 rich flue gas before its delivery to the storage site. The CPU and its development could be sub-divided into the three key areas namely:

- Pre-treatment of the CO_2 rich flue gas from the oxyfuel boiler (i.e. removal of SOx, NOx, particulates, Hg and water)
- Inert removal via a cryogenic process and the use of an auto-refrigeration cycle using impure CO_2 as refrigerant
- Development of the process for additional recovery of CO_2 from the CPU vent.

Several major vendor, e.g. Linde, Praxair and Air Liquide, are working to improve all or some of the key areas, see e.g. IEAGHG (2014).

7 Other new emerging concepts

Several new concepts that are not yet described in details in open literature have recently received funding . Below follows brief descriptions organized by country.

US (ARPA??)

UK

Canada

Japan

EU

Korea

Norway

- The CARBOMAG-project by SINTEF and NTNU combines nano technology with magnetic separation to remove CO_2. Use of magnetism to capture CO_2 has the potential to reduce costs by more than 50% compared to technologies that are in use today. The capture plants can be significantly more compact
- Combining other promising technologies may lead to step changes. The two technologies Chemical Looping Oxygen Production CLOP and Chemical Looping Combustion (CLC) each have potential for high efficiency in power production with CCS. SINTEF is looking at the possibility to produce oxygen by use of metal oxides for gasification and further for combustion of produced syngas
- Combination of 3rd generation solvents and membrane contactors may lead to savings in energy consumptions for CO_2 capture. The solution by NTNU may also lead to a capture solution with low environmental impact that can be scaled up in a relatively short time
- Liquid crystals that may function both as capture, transport and storage medium have been proposed by NTNU and the University of Bergen. The proposed method may lead to an integrated solution for the CCS chain.

8 Test facilities and their capabilities

8.1 International CCS Test Centre Network (TCN)

TCN is a network of five large test facilities that all have the ability to test some kind or another of capture technologies at a scale of more than 100 tonnes CO_2 per day. Members and capacities are shown in Table XX. They are all back-to-back of producing plants and operate on real flue gases. More details for each test facility is given below.

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Table XX. TCN member facilities and capacities.

Facility	Owner(s)	Country	Technology approach (post-, pre- or oxy-combustion) that may be tested	Flue gas	Capacity		Available infrastructure	Comment
				Type, amount	Carbon dioxide, t CO_2/y	Power (real or equivalent)		
National Carbon Capture Center	DOE, operated by Southern Company	USA	Post and pre	Coal power:14 %; Post: Slip stream ~ 17 000 kg/hr. Possibiity to dilute with air to 3% Pre: Syngas 750 kg/hr		Post: 0.5 – 1.2 MW Pre:	Real flue gas, water, electricity	
CO2 Test Center Mongstad	Gassnova, Statoil, Shell and Sasol	Norway	Post	Refinery FCC: 12 – 14%, 22 – 50 000 Sm^3/hr CHP gas turbines: 3.5-9%; 28 – 56 000 Sm^3/hr	FCC : 80 000 CHP: 25 000	Coal: 10 - 12 MW Gas: ~ 7.5 MW	Real flue gas, water, electricity	
Shand	SaskPower	Canada	Post, may evalove into other tyupes after 1 – 2 years	Coal power	45 000	5 – 6 MW	Real flue gas, water, electricity	Presently operated by Mitsubishi, may be open to others from 2017
PACT	UKCCSRC	UK	Post, pre and oxy				Flue gas from stand-alone burner or turbine; water, electricity	
Wilhelmshaven	E.ON	Germany		Coal power: 13%;	25 000	~ 5 MW	Real flue gas,	Presently

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				16 000 Nm^3/hr			water, electricity	operated by Fluor, may be open to others from 2016

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8.2 ECCSEL (European Carbon dioxide Capture and StoragE Laboratory Infrastructure)

The ECCSEL consortium consists of selected Centres of Excellence on Carbon Capture and Storage research (CCS) from 10 countries across Europe. The aim is to establish and operate a new world class CCS distributed research infrastructure (RI) in Europe. ECCSEL will be in operation from 2015 and is foreseen to contribute significantly to the development of European research and innovation capacities.

ECCSEL laboratories are basically research facilities. Many have already been used to bring identified 2nd and 3rd generation capture technologies to where they are today and only a limited number have the size, capacity and location to demonstrate technologies at larger scales.

8.3 Other (Canada, China, Japan, Korea, UK, US, etc)

9 Acknowledgements

Abbreviations and Acronyms

APGTF	Advanced Power Generation Technology Forum (UK)
ASU	air separation unit
BECCS	bio-energy with carbon capture and storage
CCS	carbon capture and storage
CPU	CO_2 purification unit
CSLF	Carbon Sequestration Leadership Forum
DECC	Department of Energy and Climate Change (United Kingdom)
DOE	Department of Energy (USA)
EC	European Commission
ECCSEL	European Carbon Dioxide Capture and Storage Laboratory Infrastructure
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
IFE	Institute for Energy Research, Norway
IGCC	integrated gasification combined cycle
LSIP	large-scale integrated project
NETL	National Energy Technology Laboratory (USA)
O&M	operation and maintenance
OECD	Organization for Economic Co-operation and Development
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)
WGS	Water Gas Shift
UK	United Kingdom
ULCOS	Ultra-low CO_2 Steelmaking consortium
USA	United States of America
ZEG	Zero Emissions Gas Power Project, an IFE project
ZEP	European Technology Platform for Zero Emission Fossil Fuel Power Plants

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APPENDIX A - CO2 Capture from Industrial sources

Cement

CO_2 emissions from cement production stem from calcination of the raw material, the limestone, and from (fossil) fuel combustion to provide process heat. The former is responsible for more than 50% of the CO_2 emissions from a cement plant. Great efforts have been made by the cement industry to reduce the CO_2 emissions through efficiency improvements, use of substitute clinker and fuels, including biomass and waste (for more information, see IEAGHG 2013a).

Post-combustion technologies are well suited to capture CO_2 from cement production. They may be retrofitted to existing plants without fundamental changes in the clinker-burning process. Commercially available solvent-based technologies can be applied, as can emerging processes described above based on improved solvents, on sorbents or on membranes. The composition of the cement plant's flue gas and its impurities is an issue that needs consideration and will require tests at pilot scale. As surplus heat is usually heavily exploited in cement plants, heat for re-generation of solvent/sorbent may require a separate heat supply.

Application of calcium looping in a cement plant would create some synergies because the purge stream of de-activated calcium sorbent could be reused as raw material in the cement clinker production process.

Post-combustion capture technologies for cement production is being tested at a few locations:

- Norcem, Brevik, Norway: Several small scale or pilot trials of post combustion capture using cement plant flue gas (2013- 2017). Companies involved in this project include Aker Solutions (amine scrubbing), RTI (dry adsorption with specialized polymers), KEMA, Yodfat and NTNU (membranes) and Alstom (calcium looing).
- ITRI/Taiwan Cement Corp.: Pilot plant capturing 1 tonne CO_2/h from a cement plant and a power plant using a calcium looping process, commissioned June 2013.
- Skyonic Corp. has developed the SkyMine" process. In this process salt and water are electrolyzed to produce hydrogen and chlorine gases and sodium hydroxide solution, which is reacted with CO_2 in flue gas to produce sodium bicarbonate, which can be sold on the market. Other combinations of chemicals can also be produced. The first SkyMine® facility opened October 2014 in San Antonio, Texas at Capitol Aggregates cement plant. To date, the plant equipped with SkyMine® technology has reduced its carbon-emissions by 15 percent – 83,000 tons of CO_2 annually.

Oxy-combustion can also be used to remove CO_2 from cement production. In this process, the fuel combustion and calcination both take place in a high-purity oxygen atmosphere and captured CO_2 is condensed out of the combustion gas. Oxy-combustion requires modification of the cement clinker process and energy to separate O_2 from air. R&D and lab testing is still required. A pilot plant trial of oxy-combustion in a cement plant calciner with a capacity of 2-3t/h of feedstock has been undertaken by FLSmidth, Air Liquide and Lafarge at Dania, Denmark.

Pre-combustion technologies can be used to capture CO_2 from combustion of fuel but CO_2 generated by the calcination of calcium carbonate is released to the atmosphere without being captured. This technology is therefore at a disadvantage for cement production.

Iron and steel

Steel mills need power plant and air separation units to support the iron and steel production processes and these are generally included as parts of an integrated steel mill. Surplus off-gases from the steel mill are typically used by the power or cogeneration plant as fuel to produce electricity or steam. The main purpose of the air separation unit is to deliver large amount of oxygen needed by both iron making and steelmaking processes. Other industrial gases such as nitrogen and argon are also used as utility gases for these processes. Thus, CO_2 emissions in an integrated mill come from multiple point sources. However, the distribution of the direct CO_2 emissions among the different units within the integrated mill is very site specific and is dependent on the manner how the off-gases are used.

For a blast furnace – basic oxygen furnace steel mill in a coastal location in Western Europe producing 4 million tonnes of hot roll coil without CO_2 capture, the top five sources of CO_2 emissions are from the flue gases of the hot stoves, power plant, sinter plant, coke ovens' under-fired heaters and lime kilns. This consists of ~90% of the total direct CO_2 emissions of the steel mill (IEAGHG 2013b).

The steel and iron industry has incorporated several best practices in their operations which should improve the energy intensity and CO_2 emissions per tonne of crude steel produced. The best practices include:

- Use of better grade raw materials input to the blast furnaces
- Higher level of scrap recycling at the BOF steelmaking process
- Increased utilization of the different off-gases available on-site
- Various energy efficiency improvements and upgrades to the different iron and steelmaking processes, including the finishing mill.

However, to achieve reductions of CO_2 emissions by more than 50% CO_2 capture will be necessary. Recognizing the challenges associated with decarbonising the industry, the steel community has initiated several programmes to study the possibilities of CCS.

- In Japan, the COURSE50 Programme, funded by NEDO and a consortium of Japanese steel and allied industries, evaluates removal of CO_2 from the blast furnace gas (BFG) by chemical absorption with a solvent and physical adsorption using solid sorbent
- In South Korea, the Ministry of Knowledge supports the programme POSCO/RIST, with some contributions from the private sector. The programme develops capture technology to remove CO_2 from the BFG using aqueous ammonia solution.
- In Europe, ULCOS, a consortium consisting of all major EU steel companies, of energy and engineering partners, research institutes and universities and is supported by the European commission, has the aim to reduce the Carbon dioxide(CO_2) emissions of today's best routes by at least 50 percent. ULCOS has pursued four options, of which three will require CCS and the fourth is base on carbon free electricity. The three options requiring CCS are:
    - ULCOS BF or Oxygen-Blown Blast Furnace with Top Gas Recycle, in which CO_2 removal from the BF top gas has been considering using either Pressure Swing Adsortion (PSA), Vacuum Pressure Swing Adsorption (VPSA), PSA or VPSA in combination with cryogenic separation, or chemical absorption
    - The Hisarna process, developed by ULCOS, which involves a series of gas cleaning, incinerator and heat recovery steps that eventually leads to a CO_2-rich (90-95%) gas, from which the CO2 is removed via cryogenic separation
    - ULCORED is a direct reduction iron (DRI) production method in which a H_2-rich syngas is used as reduction agent. In the gas based version of ULCORED, a partial oxidation

reactor and a shift reactor produce H_2 and CO_2. The latter is removed using PSA or VPSA. In coal based ULCORED gasification will have to proceed a water shift reactor. CO_2 can be removed using PSA, VPSA or physical absorption.

Air Products and Danieli Corus have developed a decarbonization scheme in which the CO_2 is removed from the top gas from the BF by a pre-combustion like process, using a water gas shift reactor to produce a gas rich in H_2 and CO_2 and separating the two using a physical solvent, CO is compressed and stored, H2 is used in a turbine to produce power (http://www.ieaghg.org/docs/General_Docs/Iron%20and%20Steel%20Presentations/08%20Lanyi%20BF%20Plus%20for%20CCS%20Workshop.pdf).

Post-combustion like processes can be used in the DRI methods ENERGIRO and MIDREX. The former can use PSA, VPSA or amine or potassium carbonate separation technologies to remove CO_2 from the shaft reactor, the latter can use PSA or amine base separation to remove CO_2 from the top gas.

In summary, CO2 capture technologies based on post- and pre-combustion principles are applicable to the steel and iron industry.

Refineries

CO_2 emissions from refineries come from a range of sources and are very site specific. The sources can broadly be divided in three categories:

1. Hydrogen production
2. Fluid catalytic cracking
3. Process heaters and boilers and utilities (e.g. combined hate and power, power plant etc)

Hydrogen production is usually base on steam methane reforming or partial oxidation and petcoke gasification, i.e. well established technologies. CO_2 removal and storage from hydrogen production is a low hanging fruit and is presently taking place at Port Arthur, USA and planned to take place at Tomakomai, Japan and Quest in Canada (oil sand upgrader).

The largest single CO_2 emitter in a refinery is often the Fluid Catalytic Cracker (FCC). The emissions are asscociated with regeneration of the catalyst and thus process rather than combustion related. The CO_2 concentration is usually in the range 10 – 20%. The off-gas from the FCC can be removed by post-combustion technologies, as demonstrate at the CO2 Technology Centre Mongstad (TCM), where both amine and chilled ammonia have been shown to work well. Oxyfiring has also been considered.

The third category has much in common with general power production and has the same opportunities for CO_2 removal.

High purity sources

Several industrial processes result in high-purity and high-concentration CO_2-streams, which can be readily prepared for compression, transport and storage.

<u>Ammonia</u> is primarily used for production of fertilizers. The building blocks of ammonia are hydrogen and nitrogen. The former is normally produced from natural gas that is team reformed and CO-shifted. CO_2 is removed from the process by varies methods like membranes, chemical absorption using amines, PSA and physical sorbents. As in refineries, CO_2 capture from ammonia production is a low hanging fruit.

Natural gas processing is done on a large scale globally to remove unwanted quantities of CO_2 from sales gas or Liquified Natural Gas (LNG). However, the removed CO_2 is transported and stored underground in a limited number of cases. Chemical absorption is the most commonly used method to remove CO_2 but other post-combustion methods may also be applied.

Ethylene oxide has a range of uses in the chemical industry. It is produced by oxidation of ethylene using metallic silver as catalyst. By-products of the process are H_2O and CO_2. After removal of the ethylene oxide CO_2 can easily be separated out.

Biomass conversion

Global demand for biofuels is expected to increase significantly over the next 20 – 30 years. Both main routes for conversion of raw biomass feedstock to biofuels, gasification and biological processing (fermentation), result in CO_2 emissions. If these emissions are captured negative a net removal of CO_2 from the atmosphere may be achieved, given that the biomass production is sustainable.

The gasification process creates a gas rich in H_2 and CO_2, after the synthesis gas has been subjected to a water gas shift reaction. This process is similar to the pre-combustion process for power plants.

The fermentation process is used to produce bio-ethanol, commonly from sugar and starches. A by-product is a relatively pure stream of CO_2.

The paper and pulp industry emits CO_2 from biomass combustion, with 13 – 14% CO2 concentration. This can be removed by post-combustion technologies, although this is expensive using 1st generation technology.

Black liquor is a toxic by-product of pulp and paper production. It is primarily a liquid mixture of pulping residues (like lignin and hemicellulose) and inorganic chemicals from the process (sodium hydroxide and sodium sulfide, for example). Rather than discharging the black liquor, it can be gasified to produce synthetic gas, to which pre-combustion technologies can be applied to remove the CO_2.

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Carbon Sequestration Leadership Forum

www.cslforum.org

CSLF-P-2015-04
04 June 2015

POLICY GROUP

Key Messages for the 6th CSLF Ministerial Conference

Background

The upcoming 6th CSLF Ministerial Conference will have the overall theme “CCS: A Critical and Viable Solution to Combat Climate Change”. To that end, the Policy Group’s Communications Task Force, led by Saudi Arabia with support from the International Energy Agency (IEA) and the Global CCS Institute, developed a draft “Key Messages” document which will serve as input to the Ministerial Communiqué. The CSLF Ministerial Steering Committee then worked to revise this document into its current state.

This paper is a draft-in-progress of the “Key Messages” document, and was included in the books presented to the Ministers at the sixth Clean Energy Ministerial (CEM6) in Mexico from May 27-28, 2015.

Action Requested

The Policy Group is requested to review this draft document, and be prepared to discuss and offer comments at the Policy Group meeting.

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Carbon Sequestration Leadership Forum (CSLF) Key Messages
Carbon Capture and Storage: A Critical and Viable Solution to Combat Climate Change

Given the following:

- Carbon capture and storage (CCS) is one of the critical low-carbon technology options that deliver global emissions reductions at the required scale from both coal and gas-fired power plants, and the only option for decarbonizing high emission process industries such as refineries, the chemical sector, and cement and steel production. As noted by the International Energy Agency (IEA), in a scenario in which global CO_2 emissions are constrained to levels consistent with a less than 2°C rise in global temperatures at the lowest cost, CCS should contribute about one-sixth of needed CO_2 emission reductions in 2050, and 14 percent of the cumulative emissions reductions between 2015 and 2050 compared to a business-as-usual approach.

- CCS plays a vital role as part of an economically sustainable route to meet climate mitigation goals within the 2050 timeframe while ensuring global and regional energy security. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Synthesis Report (AR5) concluded that without CCS the costs of climate change mitigation would increase by 138 percent, and without CCS, 2°C may not be possible.

- Global momentum is building to combat climate change, with the possibility of an ambitious deal at the 2015 United Nations Climate Change Conference of the Parties (COP21) in Paris in December 2015. The global challenge is daunting, and in that context, countries and industries will need to consider and implement a range of low-carbon energy options. Given the continued predominant global reliance on fossil resources for energy, CCS has a strong role to play, and its advantages for various sectors should be fully taken into account in national and regional settings, along with individual countries' Intended Nationally Determined Contributions (INDCs) that reflect national circumstances, yet represent a progression towards the collective ambition to limit global warming to below 2°C relative to pre-industrial levels. CCS, including utilization options (CCUS) such as enhanced recovery of hydrocarbons, has also been recommended by the United Nations Economic Commission for Europe (UNECE), along with other organizations, as a necessary technology to support implementation of the UNFCCC objectives, including enhanced actions post 2015.

- CCS is no longer science-fiction. In 2014, the world's first large-scale CCS project in the power sector commenced operation at the Boundary Dam power station in Saskatchewan, Canada. Boundary Dam is an example of how carbon dioxide (CO_2) utilization for enhanced oil recovery (EOR) is improving financial returns and providing additional resource recovery needed to incentivize CCUS demonstrations in regions such as North America and the Middle East. In addition, CCS is being demonstrated at a bio-ethanol plant in Decatur, Illinois, resulting in negative emissions. These projects reflect how CCS has been implemented where supporting regulatory, commercial and technical factors have converged (including government funding support) to support a viable business case. Globally, 22 large-scale CCS projects are now in operation or under construction, with several others in final design awaiting financial investment decision. Now is the time for governments to take policy action needed to help advance projects and realize the global potential of CCS.

- Early projects and investments from both the public and private sector are critical to ensuring that CCS is available where it is needed over the coming decades. These projects are driving innovation by providing opportunities for testing, demonstrating and refining advanced technologies, and developing critical infrastructure which will facilitate and de-risk future projects.

- The importance of early CCS projects and investments was noted in the 2013 Carbon Sequestration Leadership Forum (CSLF) Ministerial Communiqué, which identified key actions needed for CCS deployment and cited our common goal to increase the number of CCS demonstrations by 2020 and expand commercial deployment in the 2020's.

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In pursuit of our common global climate mitigation goals, we must:

1. **Create and harness "sweet spots" for CCS.** Around the world, CCS has been implemented in selected "sweet spots" where regulatory, commercial and technical factors converge with timely government support to realize a business case that attracts private investments. Governments must capitalize on these existing opportunities by taking policy action to create and sustain conditions that support investment and broaden CCS deployment. Governments and industry must work together to identify the most cost-effective early opportunities. Early CCS deployment opportunities may require development of or access to existing key infrastructure, such as pipelines, geophysical surveys, and wells, which should be part of early assessment and planning.

2. **Work toward comprehensive CCS policy frameworks**. CCS can provide different opportunities and solutions for different countries. Hence the appropriate design of a CCS policy framework, including development of financing policy and incentives, will vary among countries and across industries. Comprehensive policy frameworks should be created across the CCS chain to help improve technology performance, reduce cost and create favorable conditions for CCS deployment. Financial incentives, such as tax credits, contract for differences, and feed-in tariffs should be considered as part of a policy framework that enables deployment and provides greater parity to CCS as a clean technology option.

3. **Foster international collaboration aimed at advancing CCS deployment.** Development and deployment of CCS can be accelerated by encouraging the development of open networks to share lessons learned and help stakeholders, especially in non-OECD countries, to deal with difficult and time-consuming challenges including financing hurdles.

4. **Pursue industrial CCS applications.** Typically, CCS is viewed mainly as a solution for decarbonizing electricity. However, CCS is also the only option for decarbonizing high emission process industries such as refineries, and the chemical, cement and steel sectors. By 2050, half of the captured CO_2 could come from industrial sources outside the power sector. Furthermore, industrial processes will offer opportunities for early projects, as many processes produce relatively pure streams of CO_2, and thus will have significantly lower capture costs. It is therefore critical to increase efforts to ensure that substantial scalable CCS pilot projects are implemented on industrial sectors.

5. **De-risk storage through early stage exploration, hubs and clusters.** Early stage exploration and common user storage and transport infrastructure can significantly de-risk many potential CCS projects. Finding and characterizing a suitable storage site for a CO_2 capture project can be a time-consuming and expensive process. In some cases, it may prove advantageous to transport captured CO_2 to the same storage sites characterized and used by early projects, as long as the appropriate infrastructure is available for doing so. Governments can facilitate and significantly de-risk future projects by incentivizing early projects to oversize their storage and transport infrastructure, and by undertaking pre-commercial characterization of potential storage sites.

6. **Ensure that the role of CCS is recognized under the UNFCCC process and mechanisms**. Global momentum is building toward an agreement on ambitious climate change mitigation goals. CCS can and should play an important part of the solution. Governments should work together to ensure that CCS is recognized under the UNFCCC process and included in mechanisms to support clean energy technology development.

7. **Accelerate CCS adoption through greater RD&D (Research, Development, and Demonstration) and commercial trials.** Capturing CO_2 is the most expensive part of the CCS chain. Many emerging (2nd and 3rd generation) technologies with potential to reduce the cost of CO_2 capture are in the process of being developed, tested, and scaled up, with timeframes for commercialization and deployment generally beyond 2020. The technologies need to be brought out of the laboratory scale and testing environments to pilots and demonstrations at commercial facilities to accelerate market adoption. National and regional policies and approaches exist, as well as larger test facilities, but there is also a need for on-site evaluation at commercial facilities. Governments, technology vendors, test centers, and commercial facilities, must work together to intensify RD&D efforts and share best practices to bring capture costs down and to ensure the successful deployment of the most suitable technologies. Greater emphasis on CO_2 utilization RD&D can not only help to bring down the cost of CCS but also generate value for CO_2, thereby bringing the cost-value equation more into alignment.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2014-09
Draft: 19 May 2015
Prepared by CSLF Secretariat

DRAFT

Minutes of the Technical Group Meeting

Warsaw, Poland
Tuesday, 28 October 2014

LIST OF ATTENDEES

Chair	Trygve Riis (Norway)

Technical Group Delegates

Australia:	Clinton Foster (*Vice Chair*), Zoe Naden
Canada:	Eddy Chui (*Acting Vice Chair*), Kathryn Gagnon
China:	Sizhen Peng, Xian Zhang, Chenyong Sun
European Commission:	Estathios Peteves
France:	Didier Bonijoly, David Savary
Italy:	Giuseppe Girardi
Japan:	Ryozo Tanaka, Takashi Kawabata
Korea:	Chang Keun Yi, Seung Phill Choi
Mexico:	Giselle Pérez
Netherlands:	Paul Ramsak
Norway:	William Christensen, Lars Ingolf Eide
Poland:	Elżbieta Wróblewska, Piotr Kisiel
Russia:	Oleg Tailakov, Valery Zakharov
Saudi Arabia:	Ahmed Aleidan
South Africa:	Tony Surridge (*Vice Chair*), Landi Themba
United Kingdom:	Philip Sharman, Suk Yee Lam
United States:	John Litynski

Representatives of Allied Organizations

IEA GHG:	Tim Dixon

CSLF Secretariat

Richard Lynch, Adam Wong

Invited Speakers

Małgorzata Mika-Bryska, Deputy Director, Energy Department, Ministry of Economy, Poland

Elżbieta Wróblewska, Coordinator, Unit of New Technologies and Environmental Protection, Energy Department, Ministry of Economy, Poland

Liv Bjerge, Project Manager, Norcem CO_2 Capture Project, Norway

Observers

IEA:	Tristan Stanley
Poland:	Alexander Koteras, Adam Wócicki
South Africa:	Gina Downes
United Kingdom:	Luke Warren
United States:	Jim Wood

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 Warsaw.

Mr. Riis provided context for the meeting by mentioning that during this meeting the Technical Group would be updating its Action Plan, especially for two proposed actions where decisions on whether or not to move forward had been postponed at the March 2014 Technical Group meeting in Seoul, Korea. Appraisals on these proposed actions, by delegates from the United Kingdom and South Africa, are agenda items for the current meeting. Mr. Riis also noted that two currently active task forces will be providing updates, as will the Projects Interaction and Review Team which has researched and developed a progress report on the CSLF Technology Roadmap.

In closing, Mr. Riis also mentioned that the current meeting includes an informative presentation about the current status of CCS in Poland and a presentation about the Norcem CO_2 Capture Project which has been nominated for CSLF recognition.

2. Host Country Welcome

Małgorzata Mika-Bryska

Małgorzata Mika-Bryska, Deputy Director of the Energy Department at Poland's Ministry of Economy, welcomed the CSLF Technical Group to Warsaw and provided a keynote message for the meeting. On October 24th, the European Council agreed on the 2030 climate and energy policy framework for the European Union, and this included a binding EU target of a 40% reduction in greenhouse gas emissions by 2030 as compared to 1990. Ms. Mika-Bryska stated that this decision sets a benchmark for the rest of the world and it is hoped that all economies, not just the major economies, would agree to make emissions reductions of this magnitude next year in Paris at the 2015 United Nations Climate Change Conference.

Ms. Mika-Bryska closed her brief remarks by stating that the CSLF is an example of the kind of forum that is very important part of the global dialog on climate change. A common effort toward finding ways to propagate technologies like CCS for addressing climate change is the right path not only for Europe but also the rest of the world.

3. Introduction of Delegates

Technical Group delegates present for the meeting introduced themselves. Seventeen of the twenty-three CSLF Members were present, including representatives from Australia, Canada, China, the European Commission, France, Italy, Japan, Korea, Mexico, the Netherlands, Norway, Poland, Russia, Saudi Arabia, South Africa, the United Kingdom, and the United States. Observers representing the International Energy Agency, Poland, South Africa, the United Kingdom, and the United States were also present.

4. Adoption of Agenda

The Agenda was adopted without change.

5. Approval of Minutes from Seoul Meeting

The Minutes from the March 2014 Technical Group Meeting were approved with one minor alteration: in Item 9, change the description of the GHGT-12 conference to show that it was organized by the IEA GHG and not sponsored by that organization.

6. Report from CSLF Secretariat

Richard Lynch

Richard Lynch provided a two-part report from the Secretariat which covered the status of action items from the March 2014 meeting in Korea and some of the highlights from that meeting.

Mr. Lynch stated that there were eight Action Items from the March 2014 meeting, seven of which are now complete. For the remaining Action Item, the Secretariat will not be creating a new page at the CSLF website for compilation of Best Practice Manuals and other related results from the recently-concluded task force in that area. Instead, the Global CCS Institute has recently brought this information online at its "**decarboni.se**" website and the Secretariat will create a link to that page from the CSLF website.

Concerning the March 2014 meeting, Mr. Lynch mentioned that it was a four-day event, including a technology workshop and visits to CO_2 capture pilot plants at Hadong and Boryeong. The Technical Group created a new Task Force on Offshore CO_2 Storage (led by the United States), and concluded activities for the Review of Best Practices and Standards Task Force (which had been led by Norway). The overall meeting also included a Roundtable on CCS Technologies and Projects for Emerging Economies which depicted how CCS would work best in emerging economy countries.

Elżbieta Wróblewska

7. CCS in Poland

Elżbieta Wróblewska, Coordinator of New Technologies and Environmental Protection in the Energy Department at Poland's Ministry of Economy, gave a presentation that described the status of CCS in Poland. Poland's energy mix for electricity generation is extremely dependent on hard coal and lignite, which combined account for nearly 85% of power generation. Therefore, clean coal technologies, including development of CCS and CO_2 utilization technologies, have become a priority. Poland's involvement with CCS dates back to 2008 when the Ministry of Environment initiated a four-year research program to locate and characterize geological formations where safe and secure sequestration of CO_2 could be done. In 2009, the Ministry of Economy issued the "Energy Policy of Poland until 2030" and included CCS as a part of the overall energy strategy.

Ms. Wróblewska stated that Poland began a R&D program on "New Technologies for Energy Generation" in 2009, with three of the four main tasks concerning research on clean coal technologies including CCS options. In particular, Poland's Institute for Chemical Processing of Coal (IChPW) has tested, at small pilot-scale, two promising technologies: high-pressure coal oxycombustion and fluidized-bed coal gasification utilizing CO_2 as a feedstock in the gasification process. This latter method was shown to improve the efficiency of production of end-products such as fuels and chemicals.

Concerning CO_2 capture, Ms. Wróblewska stated that two pilot-scale facilities have been built, at the Łagisza and Jaworzno coal-fueled power plants, for testing vacuum-pressure swing adsorption and amine-based CO_2 capture technologies. Information gained will help optimize such systems for subsequent use in larger-scale pilots. As for CO_2 storage and utilization, Ms. Wróblewska mentioned that there have been a number of studies and assessments in those areas, and that the Ministry of Environment and the National Centre of Research and Development have funded a program which includes case studies, injection simulations, laboratory experiments, and other related activities. These had been intended to support the now-cancelled Bełchatów CCS Project, but the outcomes could be used in conjunction with any other projected future demonstration project.

Ms. Wróblewska ended her presentation by describing Poland's laboratory infrastructure for support of CCS and related topics. The IChPW, located in Zabrze, has been working on pressurized oxycombustion of solid fuels and chemical looping combustion. The Central Mining Institute, located in Katowice, has been supporting interdisciplinary research, including process engineering analyses. There is also a technology centre, located at an experimental mine in Mikołów, which is involved in coal gasification research. These are all part of The Clean Coal Centre, a €41 million project co-financed with European Union funds. A new Energy Centre at the AGH University of Science and Technology in Kraków is also part of the overall project and will open in late 2014.

During the ensuing discussion, William Christensen inquired about Poland's short-term plans for CCS development, including the status of the Bełchatów CCS Project where a full-scale CCS project had been planned at the power plant's new 858 megawatt lignite-fueled unit. Małgorzata Mika-Bryska responded, stating that the Bełchatów Project was not moving forward largely because of cost. The agreement with the European Union to become one of its flagship projects meant that if the project had proceeded, it would have had an obligation to be in operation for ten years. Given the current high operational cost (and plant efficiency loss) for CO_2 capture, this would have resulted in a cumulative extra cost of approximately one billion zlotys which would have raised the price of energy from the power plant to an unacceptable level. Ms. Mika-Bryska stated that Poland had instead opted, in the near term, to work on CCS at a smaller scale and the laboratory infrastructure described by Ms. Wróblewska is an example of that.

8. Update from the IEA Greenhouse Gas R&D Programme (IEA GHG)


Tim Dixon

Tim Dixon gave a presentation about the IEA GHG and its continuing collaboration with the CSLF's Technical Group. The IEA GHG was founded in 1991 with the mission to provide information about the role of technology in reducing greenhouse gas emissions from use of fossil fuels. The focus is on CCS, and the goal of the organization is to produce information that is objective, trustworthy, and independent, while also being policy relevant but not policy prescriptive. The "flagship" activities of the IEA GHG are the technical studies and reports it publishes on all aspects of CCS, the nine international research networks about various topics related to CCS, and the biennial GHGT conferences, the most recent of which was held earlier in October in Austin, Texas, USA.

Mr. Dixon mentioned that since 2008 the IEA GHG and CSLF Technical Group have enjoyed a mutually beneficial relationship which allows each organization to cooperatively participate in the other's activities. This has included the opportunity for the Technical Group 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" (November 2013). The most recent proposal from the Technical Group was for a benchmarking lifecycle assessment of carbon capture, utilization, and storage (CCUS). Mr. Dixon stated that this was approved at the 46th IEA GHG ExCo Meeting, in October, with the anticipated outcome being a workshop and an accompanying report. Mr. Dixon also stated that the next deadline for receiving outlines for proposed IEA GHG studies is 22 January 2015.

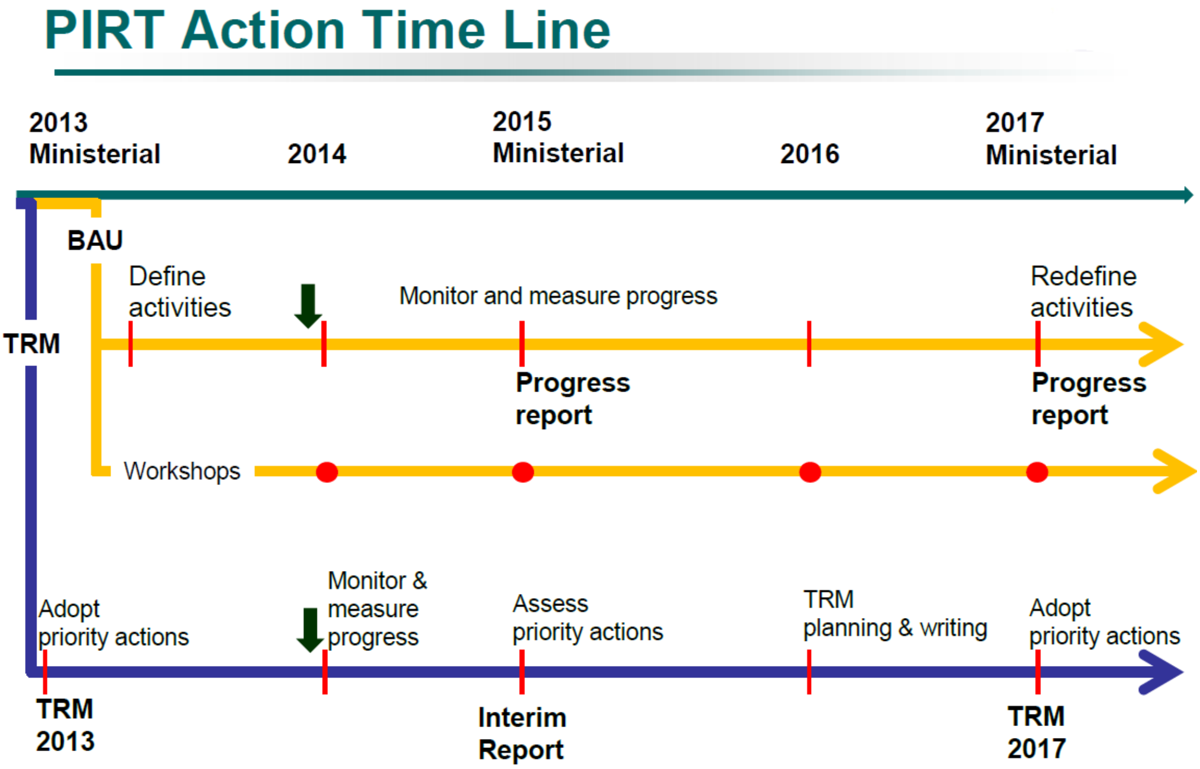
During ensuing discussion, John Litynski and Sizhen Peng both mentioned that work going on in their countries could perhaps be inputs to the benchmarking lifecycle assessment, and agreed to provide relevant information as it becomes available. Dr. Peng noted that a Chinese report covering 25 different CO_2 utilization technologies had been completed and that an English language version of the report would be available at about the end of 2014. The Secretariat was requested to post a link to the Chinese report, once it is available, at the CSLF website.

9. Report from the CSLF Projects Interaction and Review Team (PIRT) and Update on the CSLF Technology Roadmap (TRM)

The PIRT Chair, Clinton Foster, gave a short presentation that summarized the previous day's PIRT meeting, including a brief update on the CSLF-recognized Gorgon Project. The PIRT currently has two main types of responsibilities. "Business As Usual" (BAU) activities include monitoring and measuring progress of the portfolio of CSLF-recognized projects, investigation of any new projects proposed for CSLF recognition, and organizing CSLF Technology Workshops. In parallel to this, the PIRT also has primary responsibility for updating the TRM.

Dr. Foster stated that the PIRT is on track in both of these areas of responsibility. During its previous day meeting, the PIRT had evaluated the Norcem CO_2 Capture Project as a first step in the CSLF recognition process and had been updated on the status and progress of the CSLF-recognized Gorgon CO_2 Injection Project (both of these BAU activities). In addition, the PIRT had developed a plan for producing a TRM Interim Report in time for the next CSLF Ministerial Meeting.

Clinton Foster



Specific outcomes from the meeting were:

- The PIRT recommends approval by the Technical Group for the Norcem CO_2 Capture Project.
- The PIRT will continue to gather information, from organizations which are actively working on various aspects of CCS, about “Identified Technology Needs” that were described in the 2013 TRM.
- The Secretariat will organize information received and working groups formed within the PIRT will examine this information as it pertains to the ten needs areas:

  Area #1: CO_2 Capture Technologies in Power Generation (*Norway*)
  Area #2: CO_2 Capture in Industrial Sector (*South Africa* and *United Kingdom*)
  Area #3: CO_2 Transport (*Australia*)

Area #4: Large-Scale CO_2 Storage (*Japan* and *France*)

Area #5a: Monitoring (*United States* and *France*)

Area #5b: Mitigation / Remediation (*European Commission*)

Area #6: Understanding the Storage Reservoirs (*United Kingdom* – to be confirmed)

Area #7: Infrastructure (*United Kingdom*)

Area #8a: CO_2 Utilization, non-Enhanced Oil Recovery [EOR] (*France*) [also see below]

Area #8b: CO_2 Utilization, EOR (*Saudi Arabia* and *Canada*)

- The ten working groups will write short progress reports for these areas that will be combined into a TRM Interim Report for the next CSLF Ministerial Meeting.

Dr. Foster stated that the Secretariat had prepared a short TRM Progress Report for the current meeting, which was based on information-gathering activities subsequent to the March 2014 meeting. A template, developed by the Secretariat, was used to solicit the opinions of organizations in CSLF member countries about perceived progress in the ten needs areas. As of September 29th, a total of twelve completed templates had been returned and these were used as inputs to the TRM Progress Report. There was judged not to be enough information yet to definitely describe the global status of CCS, but some trends were evident:

- For 1st generation technologies, none of the 10 technology needs areas were perceived as "fast moving" in terms of progress. Progress in most areas was perceived as a mixed opinion of "very slow" and "moderate".
- Results for 2nd and 3rd generation technologies were similar, but many more "no opinion" responses were received.
- There appeared to be a geographical bias in responses so far received. North American responders were, in general, more pessimistic on the amount of progress being made.
- All types of barriers and/or drivers (economic, policy, and technology) were perceived to exist for most technology needs areas.
- Individual country results provided a wide range of responses, showing that issues surrounding CCS are viewed by different countries in different ways.

One of the conclusions from this exercise was that the 2013 TRM is still reasonably accurate in its depiction and portrayal of the status and barriers/drivers for development and deployment of CCS technologies. There is still a need for progress in all of the technology needs areas, some more than others. Also, results confirm that worldwide, CCS is not a "one size fits all" collection of technologies and there appears to be a great need for individualized country-specific technology roadmaps.

Dr. Foster closed his presentation by noting that at the previous day's PIRT meeting, Canada had volunteered to be part of the Area #8b working group on EOR. Sizhen Peng then requested that China be part of the Area #8a working group on non-EOR CO_2 utilization, and this was welcomed and accepted by Dr. Foster on behalf of the PIRT.

10. Report from Review of CO_2 Storage Efficiency in Deep Saline Aquifers Task Force

Richard Lynch provided a brief update on the task force and its timeline on behalf of the Task Force Chair, Stefan Bachu, who could not attend the meeting. The task force was established at the November 2013 meeting in Washington, with the mandate to critically review, compile and report on relevant literature published since the 2007 final report by the CSLF Task Force for Review and Identification of Standards for CO_2 Storage Capacity Estimation. Storage capacity estimates can be "static" (i.e., based on pore volume) or "dynamic" (i.e., based on injectivity and pressure build-up). The mandate of the task force was to review, compile, and report on published literature since the 2007 final report of the previous task force, and also to review and evaluate the applicability of various published values for the storage efficiency coefficient 'E', which is the amount of CO_2 that can be stored in a unit of aquifer pore volume.

Mr. Lynch mentioned that Dr. Bachu intends to report on the task force's findings in a special issue of *The International Journal of Greenhouse Gas Control*, which will be published mid-year 2015, and this paper would also serve as the task force's final report. The title of Dr. Bachu's paper will be "CO_2 Storage Efficiency in Deep Saline Aquifers". Dr. Bachu also provided his intention to disband the task force, and there was consensus that upon publication of the paper the task force will have concluded its activities.

11. Report on Barriers and Technical Needs for Sub-Seabed Storage of CO_2


John Litynski

John Litynski gave a brief update on the task force and its timeline on behalf of the Task Force Chair, Mark Ackiewicz, who could not attend the meeting. The task force was established at the March 2014 meeting with the mandate to identify technical barriers and R&D needs/opportunities for sub-seabed storage of CO_2. Mr. Litynski stated that the task force had so far established its membership and developed a draft outline of what its final report would be. A first draft of the report is expected by about the end of 2014. At the 2015 CSLF Mid-Year Meeting, the task force will report its findings and conclusions, and submit its final report to the Technical Group. Sections of the report will be written by the United States, Japan, Norway, and the IEA GHG. Mr. Litynski also stated that the task force will hold a teleconference soon to finalize the report's outline.


Tony Surridge

During the ensuing discussion, Tim Dixon stated that the IEA GHG would like to contribute to the chapter of the report on "Monitoring, Verification and Assessment Tools for Offshore Storage" that Norway will be drafting. Suk Yee Lam stated that the United Kingdom was volunteering to join the task force. Both of these offers were welcomed and accepted by Mr. Litynski on behalf of the task force.

12. Appraisal of the Proposed Technical Group Action concerning CCS with Industrial Emissions Sources

Tony Surridge provided an assessment of the proposed Technical Group Action Plan item on "CCS with Industrial Emissions Sources". At the March

2014 meeting, a decision had been postponed on whether or not to form a task force in this area pending review of results from a Norwegian workshop and a United Kingdom report related to this topic. Dr. Surridge stated that additionally, a "framework" report had been completed by South Africa on this topic. Based on the findings of the two reports and workshop, Dr. Surridge concluded that there was no need for a new task force. The delegations from Norway and the United Kingdom added their support for this recommendation and after brief discussion there was consensus not to form such a task force.

13. Appraisal of the Proposed Technical Group Action concerning Energy Penalty Reduction

Philip Sharman

Philip Sharman provided an assessment of the proposed Technical Group Action Plan items on "Energy Penalty Reduction". At the March 2014 meeting, a decision had been postponed on whether or not to form a task force in this area. Mr. Sharman stated that results from the United Kingdom's CCS Cost Reduction Task Force had provided a good basis for further work in this area, as it had identified several prime targets for cost reduction, including designing CCS projects (including transport) at an optimal scale and de-risking the CCS chain by encouraging the right funding mechanisms and stronger/better regulatory frameworks. However, further work in this area would be premature, until results from ongoing front-end engineering design (FEED) studies are available for some of the large-scale projects that are now in planning stages. Mr. Sharman concluded that there was not yet a need form a new task force in this area and instead continue to collaborate with the Policy Group on its action for "Supporting Development of 2nd and 3rd Generation CCS Technologies". There was consensus to accept this recommendation.

14. Review of Technical Group Action Plan

Trygve Riis stated that the Secretariat had prepared an Action Plan Status Report, which was included in the meeting's documents book. Mr. Riis inquired if there were ideas for other possible additions to the Technical Group's Action Plan, but there were no proposals for new task forces.

15. Review and Approval of Project Proposed for CSLF-Recognition: Norcem CO_2 Capture Project

Liv Bjerge

Liv Bjerge, Project Manager for the Norcem CO_2 Capture Project, gave a presentation about the Norcem project. This project, located in southern Norway at a commercial cement production facility, is testing four different post-combustion CO_2 capture technologies at scales ranging from very small pilot to small pilot. Technologies being tested are a 1st generation amine-based solvent, a 3rd generation solid sorbent, 3rd generation gas separation membranes, and a 2nd generation regenerative calcium cycle, all using flue gas from the cement production facility. Objectives of the project are to determine the long-term attributes and performance of these technologies in a real-world industrial setting and to learn the suitability of such technologies for implementation in modern cement kiln systems. Important focus areas include CO_2 capture rates, energy consumption, impact of flue gas impurities, space requirements, and projected CO_2 capture costs. Project partners include Norcem, HeldelbergCement, and the European Cement Research Academy, and the project has also received funding from Norway's CLIMIT program. The project began in 2013 and is expected to continue into 2017.

After a brief discussion, there was consensus to recommend to the Policy Group that the Norcem CO_2 Capture Project receive CSLF recognition.

16. Collaboration with the CSLF Policy Group

Trygve Riis informed the Technical Group about outcomes from the June 2014 Policy Group Meeting in London. One of the actions from that meeting was formation of a joint Policy-Technical task force on "Supporting Development of 2nd and 3rd Generation CCS Technologies", with Norway assuming the lead for the Technical Group. The technical mandate of the task force includes:

- Mapping/identifying 2nd and 3rd generation technologies under consideration in CSLF member countries, especially those that may mature in the 2020-2030 timeframe;
- Identifying major challenges facing development of these next generation technologies; and
- Using existing networks such as the International CCS Test Centre Network to map potential for testing these next generation technologies at existing test facilities.

Mr. Riis stated that he would be reporting on this topic at the Policy Group meeting on October 30th, but previewed his presentation at this current meeting in order to get comments and suggestions from the Technical Group delegates. Kathryn Gagnon remarked that this task force builds on the good work done by Lars Ingolf Eide in setting up the International Test Centre Network and creates a hub structure that facilitates information gathering. Suk Yee Lam noted that the United Kingdom had commissioned an in-house report from the IEA GHG assessing new CO_2 capture technologies that would provide valuable information for the task force, and Tim Dixon commented that the report should be released by about the end of 2014. Philip Sharman inquired about the scope of the task force and if it should be limited to utility applications related to cost of electricity, and Mr. Eide responded that the task force would be limited in scope to only CO_2 capture technologies, but that this could include industrial applications.

Mr. Riis noted that for this task force to be successful, other CSLF member countries would need to volunteer to participate. In response, delegations from the European Commission, Japan, Korea, the United Kingdom, and the United States all expressed their interest in contributing, as did the IEA GHG. Mr. Riis stated that he would recommend to the Policy Group that Norway and Canada be co-chairs, with Canada being mainly responsible for Policy-related aspects and Norway taking the lead for all Technical-related components.

17. Update on Future CSLF Meetings

Richard Lynch announced that the next CSLF meeting will be in June 2015 in Regina, Saskatchewan, Canada. This will be a five day meeting, organized as follows:

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- Day 1: PIRT meeting (in afternoon)
- Day 2: Technical Group meeting
- Day 3: Technology Workshop
- Day 4: Visit to CSLF-recognized Boundary Dam Project
- Day 5: Policy Group meeting

Mr. Lynch stated that further details concerning the Regina meeting would be forthcoming soon. Ahmed Aleidan then stated that Saudi Arabia will be hosting the 6th CSLF Ministerial and that a more formal announcement would be made during the October 30th Policy Group meeting.

18. Open Discussion and New Business

Clinton Foster proposed that the Technical Group consider a new activity that would examine how gas stream compositions affect the performances of CO_2 capture solvents. Such an investigation might be relevant to the new Policy-Technical task force on "Supporting Development of 2nd and 3rd Generation CCS Technologies". Dr. Foster stated that he would prepare a paper on this topic for the next Technical Group meeting.

Tony Surridge reported that South Africa has published a framework report with support from the CSLF Capacity Building Fund, on impacts of CCS on South African national priorities beyond climate change. This report, titled "CCS Impact on South African National Priorities", is now linked at the CSLF website (from the "Publications and Links" page). Dr. Surridge also stated that South Africa will be conducting a pilot-scale surface CO_2 monitoring project that will develop baselines and methodologies for utilization by the planned pilot-scale CO_2 storage project scheduled for 2017. Dr. Surridge mentioned that there have already been two workshops held in support of this project, one in South Africa and one at the recent GHGT-12 Conference, and that CSLF members were welcome to participate.

19. Review of Consensuses Reached and Action Items

Consensus was reached on the following items:

- The Norcem CO_2 Capture Project is recommended by the Technical Group to the Policy Group for CSLF recognition.
- The Review of CO_2 Storage Efficiency in Deep Saline Aquifers Task Force has concluded its work and will disband following publication of its journal paper.
- The Technical Group will not form a task force to address the Action Plan item on "CCS with the Industrial Emissions Sources".
- The Technical Group will not yet form a task force to address the Action Plan item on "Energy Penalty Reduction".
- The Technical Group will continue its collaboration with the Policy Group on "Supporting Development of 2nd and 3rd Generation CCS Technologies" with Norway the lead for all technical-related components. Other task force members will include Japan, Korea, the United Kingdom, the United States, and the IEA GHG.

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 Norcem CO_2 Capture Project be recognized by the CSLF. (*Note: this was done at the October 30th Policy Group meeting.*)
2	CSLF Secretariat	Finalize the minutes from the March 2014 meeting, incorporating one minor change.
3	CSLF Secretariat	Provide a link at the CSLF website to the English-language version of China's report on CO_2 utilization technologies.
4	CSLF Secretariat	Produce a new Action Plan Status Report for the next Technical Group Meeting.
5	Technical Group Chair	Provide the Technical Group's recommendation to the Policy Group that Norway and Canada be co-chairs for the joint Policy-Technical task force on "Supporting Development of 2nd and 3rd Generation CCS Technologies". (*Note: this was done at the October 30th Policy Group meeting.*)
6	Australia	Prepare a paper for the next Technical Group meeting on a possible new activity for examining how gas stream compositions affect the performances of CO_2 capture solvents.

20. Closing Remarks / Adjourn

In adjourning the meeting, Trygve Riis expressed his appreciation to the host country Poland, the CSLF Secretariat, and all the meeting attendees. Mr. Riis mentioned that the meeting was very interactive and participatory, and that much had been accomplished in this the beginning of the run-up to next year's Ministerial meeting.

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Addendum to Minutes: Affiliations of CSLF Technical Group Delegates

Ahmed Aleidan, Petroleum Engineer, EXPEC Advanced Research Center, Saudi Aramco, Saudi Arabia

Didier Bonijoly, Deputy Director for Geosciences, BRGM, France

Seung Phill Choi, Senior Advisor, KCCSA, Korea

William Christensen, Deputy Director General, Ministry of Petroleum and Energy, Norway

Eddy Chui, Director, Clean Electric Power Generation, CanmetENERGY, Natural Resources Canada

Lars Ingolf Eide, Consultant, CLIMIT Programme, Research Council of Norway

Clinton Foster, Chief Scientist, Geoscience Australia

Kathryn Gagnon, Policy Advisor, Innovation and Energy Technology, Natural Resources Canada

Giuseppe Girardi, Manager, Sustainable Fossil Fuels and CCS, ENEA, Italy

Takashi Kawabata, Deputy Director, Environmentally Sustainable Industries and Technologies Office, Ministry of Economy, Trade and Industry, Japan

Piotr Kisiel, Senior Expert, Energy Department, Ministry of Economy, Poland

Suk Yee Lam, Office of Carbon Capture and Storage, Department of Energy and Climate Change, United Kingdom

John Litynski, Division of Carbon Capture and Storage R&D, Office of Fossil Energy, United States Department of Energy

Zoe Naden, International CCS Policy, Clean Energy and Environment Division, Department of Industry, Australia

Sizhen Peng, Deputy Director General, ACCA21, Ministry of Science and Technology, China

Giselle Pérez, SENER, Mexico

Estathios Peteves, Head of Unit – Energy Systems Evaluation, Institute for Energy and Transport, European Commission

Paul Ramsak, Energy and Climate Agency, Netherlands

Trygve Riis, Special Adviser, Division for Energy, Resource's and the Environment, Research Council of Norway

David Savary, Senior R&D Engineer, Solvay, France

Philip Sharman, Director, Evenlode Associates Ltd., United Kingdom

Chenyong Sun, Deputy Director General, Department of Social Development, Ministry of Science and Technology, China

Tony Surridge, Senior Manager: Advanced Fossil Fuel Use, SANEDI, South Africa

Oleg Tailakov, Vice-Rector of T.F. Gorbachev Kuzbass State Technical University, Russia

Ryozo Tanaka, Senior Researcher, CO_2 Storage Research Group, RITE, Japan

Landi Themba, Director, Coal and Gas Policy, Department of Energy, South Africa

Elżbieta Wróblewska, Coordinator of the Team for Environmental Protection and New Technologies, Energy Department, Ministry of Economy, Poland

Chang Keun Yi, Director, Climate Change Technology Research Division, KIER, Korea

Valery Zakharov, Director of the Institute of Comprehensive Exploitation of Mineral Resources, Russian Academy of Sciences

Xian Zhang, ACCA21, Ministry of Science and Technology, China

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Carbon Sequestration Leadership Forum
www.cslforum.org
CSLF-T-2015-02
14 May 2015

TECHNICAL GROUP

CSLF Technology Roadmap Interim Report

Background

The 2013 CSLF Technology Roadmap (TRM) was launched at the 5th CSLF Ministerial Meeting in November 2013 as the latest in a series of TRM documents that date back to 2004. Commencing in 2015, the CSLF Technical Group agreed to monitor progress in ten distinct 'technology needs areas' at regular intervals and publish its findings. Progress in these ten areas is considered vital for successful commercial implementation of large-scale CCS projects.

To that end, this document, prepared by the CSLF Secretariat, is a **draft interim progress report** on the 2013 TRM, based on information received via a survey questionnaire from organizations in CSLF member countries that are working to develop, improve, demonstrate, or implement technologies relevant to CCS. A final version of this report will be a deliverable at the upcoming 6th CSLF Ministerial Meeting in November 2015.

Action Requested

The Technical Group is requested to review the draft interim TRM Progress Report and provide comments.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2015-02
14 May 2015

CSLF Technology Roadmap Interim Report

Introduction

The 2013 CSLF Technology Roadmap (TRM) was launched at the 5th CSLF Ministerial Meeting in November 2013 as the latest in a series of TRM documents that date back to 2004. The main objective of the 2013 TRM was to recommend to governments the technology priorities for successful implementation of carbon capture and storage (CCS) in the power and industrial sectors. In particular, the 2013 TRM was intended to answer three questions:

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

The 2013 TRM contained several key recommendations for advancing carbon capture and storage (CCS) technologies toward the year 2020 and beyond:

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.
- 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.

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- 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-enhanced oil recovery (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 1st generation technologies costs.

The 2013 TRM also identified ten distinct ‘technology needs areas’ that are vital for successful commercial implementation of large-scale CCS projects:

a) CO_2 capture in power generation
b) CO_2 capture in the industrial sector
c) CO_2 transport
d) Large-scale CO_2 storage
e) Monitoring stored CO_2
f) Mitigation / remediation procedures
g) Understanding storage reservoirs
h) Infrastructure and the integrated CCS chain (capture to storage)
i) CO_2 utilization, non-EOR
j) CO_2 utilization, EOR

Commencing in 2015, the CSLF Technical Group agreed to monitor progress in these areas at regular intervals and publish its findings. To that end, information was obtained (via a survey) from organizations in CSLF member countries that are working to develop, improve, demonstrate, or implement technologies relevant to CCS. Representatives of these organizations were requested to provide their evidence-based opinions, for each of the ten technology needs areas, on whether progress in these areas was occurring either ‘very slowly’, or at ‘moderate pace’, or ‘fast moving’. They were also asked to indicate if there were economic, policy, and/or technological drivers that are affecting the relative amount of progress.

Information gathered in the survey has been used to chart progress in both application and adaption of 1st generation technologies that are now being used in commercial or demonstration-scale CCS projects; and also 2nd and 3rd generation technologies that are being tested in pilot-scale CCS projects (i.e., >1 MW and/or >1,000 tonnes of CO_2 injected per year). Although the 2013 TRM covers decadal timeframes towards the years 2020, 2030, and 2050, this survey was only concerned with progress towards the year 2020. The results of the survey are summarized below.

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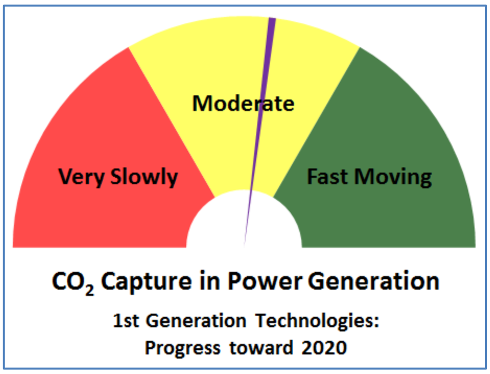
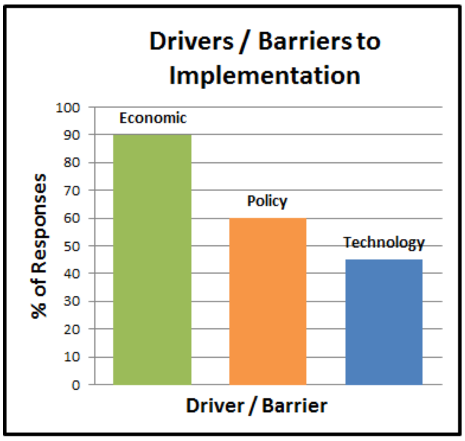
Global Trends in CO_2 Capture Technology from Power Industry

Evidence for the findings below is supported by responses from the survey and the Global CCS Institute (GCCSI) "Global Status CCS 2014" document.

Finding 1: First generation capture implementation is showing moderate progress.

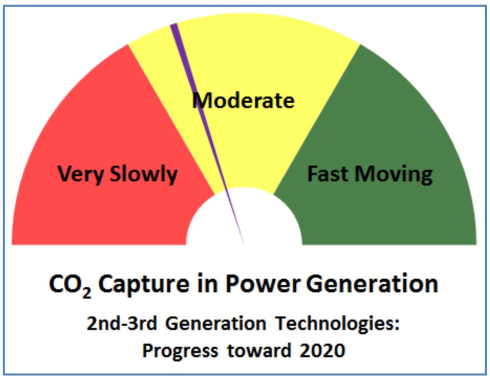


Respondents regard 1st generation capture technology as ready for large scale demonstration from a technology point of view. First generation for gas and coal are built and under qualification in pilots (Technology Centre Mongstad in Norway, etc.) but only one power station, Boundary Dam in Canada, is among the 13 CCS operating projects on the GCCSI list, and two others (Kemper County and Petra Nova, both in the USA) are on the Execute list. Since 2013, more power production CCS projects have been cancelled than have been added to the GCCSI list. It is hoped that as a first-of-a-kind (FOAK) plant, Boundary Dam will contribute to proving the feasibility of CO_2 capture from power plants.



Most commonly cited barriers are economics and policy. High cost, moderate public funding and limited regulations and incentives were mentioned by respondents. Two potential technical challenges that were mentioned are: 1) Emissions from amine plants and that amine based absorption processes can lead to aerosol formation; and 2) Integration of the capture technology with the power plant. Both are being addressed by the international CCS community.

Finding 2: Emerging (2nd and 3rd generation) capture implementation is showing moderate to slow progress.



Respondents found that although 2nd -3rd generation capture technologies are being advanced at the R&D scale and to some extent being commercialized, they need to be scaled up and field tested in pilot plants. Within the next few years, several breakthrough processes are ready for field tests. Overall progress was found to be slow to moderate.

Development of technologies is largely a function of economics and policy regarding adoption of CCS as a low emissions technology. There is still R&D funding despite the limited progress of implementation of 1st generation technologies. However, two barriers were mentioned: 1) New generation capture technologies have not yet been shown to provide significant cost savings that are needed to make CCS competitive; and 2) Costs are not fully understood and, to date, have been grossly underestimated.

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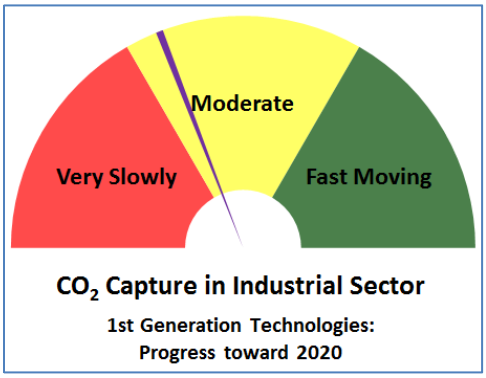
Global Trends in CO_2 Capture from Industrial Sector

Evidence for the findings below is supported by responses from the survey and reports from the GCCSI addressing the cement, liqufied natural gas (LNG), and iron and steel sectors.

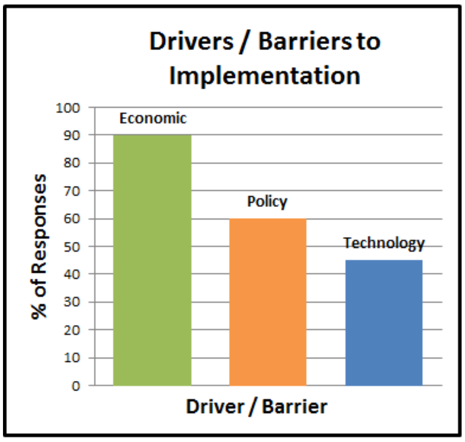
Finding 1: First generation capture implementation is showing slow to moderate progress depending on the industrial sector



CO_2 Capture in Industrial Sector

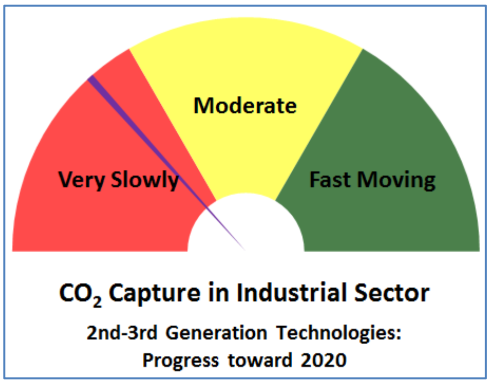
1st Generation Technologies: Progress toward 2020

Respondents rated the readiness of 1st generation capture technology in different dependencies. For LNG processing, ethanol production and hydrogen production from reforming natural gas, CO_2 capture is an inherent part of the process and 1st generation technologies for doing so have progressed relatively rapidly. For the steel and cement industry, progress is moderate. For other industries, progress is slow. The need for more pilot projects is seen as important by most respondents.



Most commonly cited barriers were the cost of the technology and the lack of policy in most countries for directing companies to pursue large-scale implementation of CCS. Some specific technical barriers were also cited – operational challenges (e.g. contamination and intermittency) and integration issues – although the general view was that the technology for industrial applications is at a similar level of maturity as for application to power generation.

Finding 2: Emerging (2nd and 3rd generation) capture implementation is showing very slow progress.



CO_2 Capture in Industrial Sector

2nd-3rd Generation Technologies: Progress toward 2020

Nearly all respondents are of the opinion that progress for 2nd -3rd generation capture technologies is very slow, although some applied R&D is taking place, in particular in BECCS (bio-energy with CCS) and in the cement industry (e.g., Norcem/Heidelberg Cement in Norway and Germany). In some cases further R&D is required before pilot-scale projects can happen.

Development of technologies is largely a function of economics and policy regarding adoption of CCS as a low emissions technology. This is in particular the case for 2nd -3rd generation technologies, as the development of these technologies is still in the early stages and is focused on cost reduction and operational performance. The costs of these technologies are not yet established, but most respondents are of the opinion that the costs are likely to be high. Further policy development is also required to enhance progress. The lack of regulatory or policy drivers for implementing CCS in industrial sectors has meant that this area has been a lower priority than CO_2 capture in the power sector to date.

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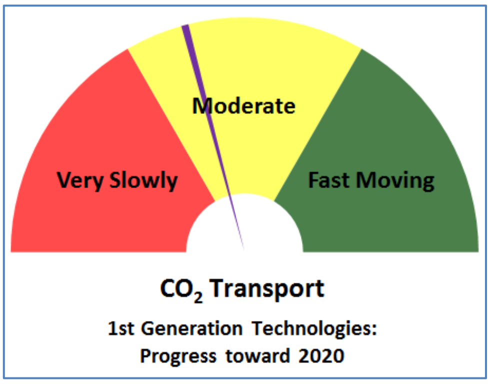
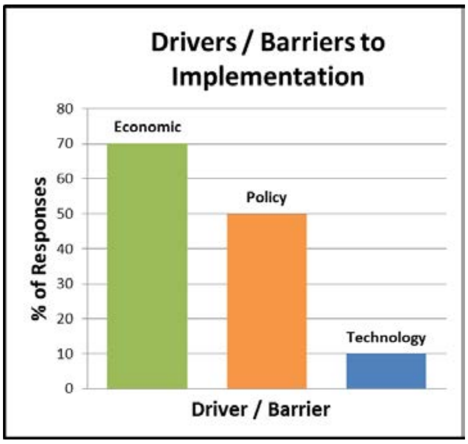
Global Trends in CO_2 Transport

Evidence for the findings below is supported by responses from this survey and the GCCSI "Global Status CCS 2014" document.

Finding 1: First generation transport is showing only moderate progress.

Countries that transport CO_2 either using pipelines, for enhanced oil recovery (EOR), or by road/rail transport for food/chemical processing considered that progress towards 2020 transport ranged from very slow to fast moving. However, considering the volumes needed to be transported to reach the 2030 target (1 gigatonne), progress is only moderate. CO_2 for EOR is successfully transported in the USA, but the volumes are relatively small (approx. 60 million tonnes annually), and this is an essentially bespoke operation.



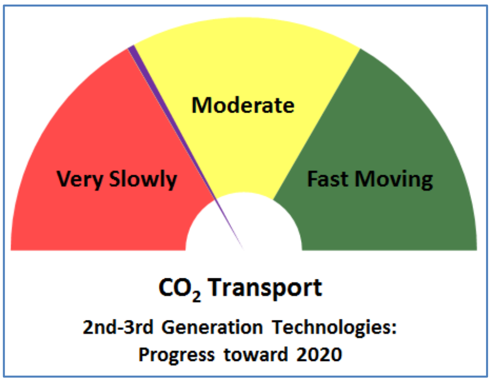


Physical properties considerations for CO_2 (e.g. hydrate formation, Joule-Thompson cooling, etc.) and the purity of the capture stream can complicate operational procedures (e.g. customized solutions for pipeline re-pressurization and emergency shutdown) and need to be considered; but there appears to be no insurmountable technical issues for onshore transport.

Most commonly cited barriers are economics and policy. With the exception of current EOR operations, societal approval and completing land access requirements for onshore CO_2 pipelines is challenging: it was one of the factors in stopping the Bełchatów CCS project in Poland.

Finding 2: Second and third generation technology for CO_2 transport is showing slow progress.

Respondents noted that 2nd and 3rd generation transport technologies are being being researched and developed for onshore and offshore pipelines; and hybrid transportation is under evaluation – this involves pipeline transport and shipping of CO_2. Amongst others, Japan, South Korea, and Norway, are investigating shipping CO_2 from onshore sources and injecting from transport ships into sub-sea geologic reservoirs. Ships with capacity to transport over relatively short distances and inject 1 million tonnes annually; and larger vessels with a capacity for transport over 500 kilometers are being evaluated.



Brazil is already injecting 700,000 tonnes of CO_2 annually from a FPSO in the offshore Lula oil field. Developments in shipping platforms, collection hubs, and injection technologies will form the bulk of the 2nd and 3rd generation technologies.

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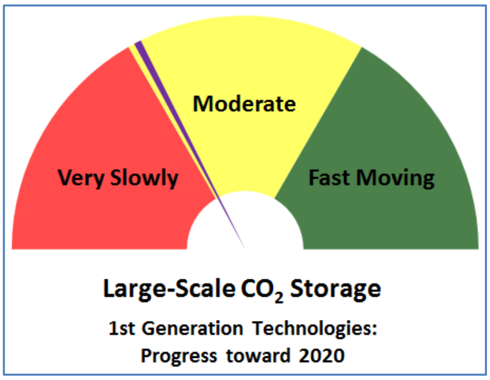
Global Trends in Large-Scale CO_2 Storage

Evidence for the findings below is supported mainly by responses from the survey, the GCCSI "Global Status CCS 2014" document, and the US DOE/NETL web site.

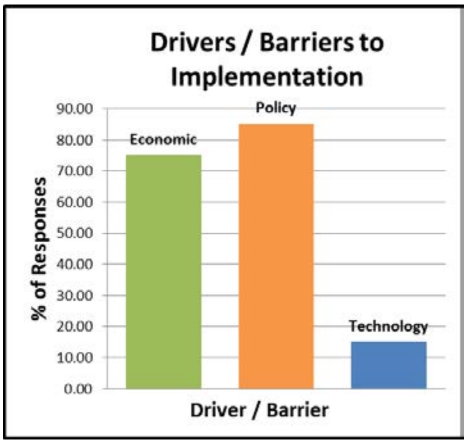
Finding 1: First generation large-scale CO_2 storage implementation is showing very slow to moderate progress.



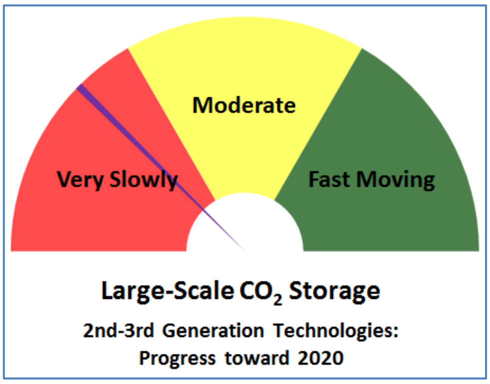
Respondents mostly consider that there are sufficient technologies to conduct large-scale CO_2 storage but that more such projects are needed to demonstrate these technologies at various geological settings. Whereas IEA, for example, set a goal of 200Mt-CO_2 storage by 2020 in their CCS roadmap 2013, the total capture capacity of the 13 operational large-scale CCS projects on the GCCSI list is limited to 28 Mt-CO_2.

Among the 13 CCS projects, nine projects are taking place with onshore EOR operations in North America. The remaining four are two offshore and one onshore aquifer storage projects, and one offshore EOR project. Six out of the nine projects under construction are again located in North America, but once the remaining three become operational, all continents will have experience in large-scale storage. In addition, there are a number of operational or under-construction medium-scale projects to store CO_2 of hundreds of thousands to millions tonnes in total. These are mostly located in North America but some are seen in other places such as Japan.

Most commonly cited barriers are policy and economics. The political barriers include uncertainty in long-term liability, i.e. handover of storage site to the competent authorities. Economics that most respondents regard as a barrier sounds overall costs of a project rather than costs of storage. To compensate the high project costs, some respondents consider that investigations of strategies for combining storage and enhanced hydrocarbon recovery and near-depleted gas field are needed more. A barrier that was not captured by the CSLF survey but can be critical is public acceptance.



Finding 2: Emerging (2nd and 3rd generation) large-scale CO_2 storage implementation is showing very slow progress.



The number of respondents for the emerging large-scale CO_2 storage is two thirds of that for the 1st generation and there are no comments on the emerging storage technologies. This may be because there is no well-accepted definition of 2nd and 3rd generation storage even in the CSLF Technology Roadmap 2013.

The emerging storage technologies could include basalt storage and storage associated with EGR. There are not yet any large-scale storage projects of these kinds.

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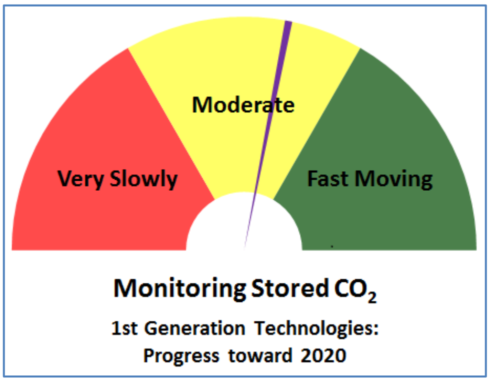
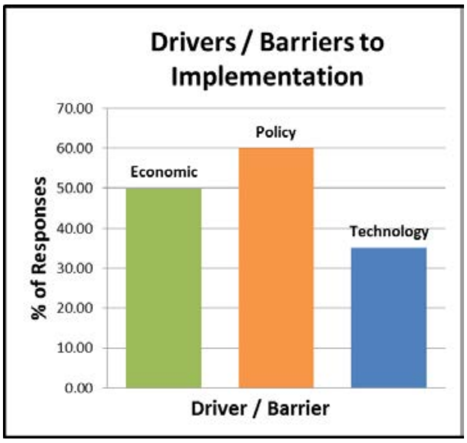
Global Trends in Monitoring Technologies for CO_2 Storage

Evidence for the findings below is supported by responses from the survey and the GCCSI "Global Status CCS 2014" document. Additionally, efforts at projects such as Nagaoka in Japan, Ketzin in Germany, and the Regional Carbon Sequestration Partnerships (RCSPs) in the USA are also recognized.

Finding 1: First generation monitoring technologies for CO_2 storage are showing moderate progress.

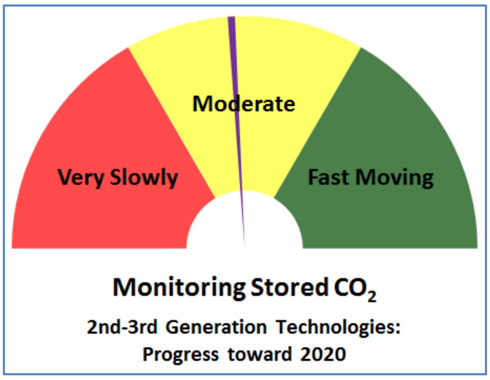


Respondents generally consider 1st generation monitoring technologies for CO_2 as improving and progressing. Technologies previously developed for the oil and gas industry are proving to be good techniques for monitoring storage of CO_2. However, current monitoring technologies are limited or have too much uncertainty regarding the exact plume size and understanding complex geology and fluid flow.



Most commonly cited barriers are economics and policy. The lack of large-scale test sites and the fact that most technology development and field tests are government-funded were commonly cited issues.Monitoring technology itself was not necessarily considered a barrier and that projects will use what technologies and tools are available. However, opportunities exist to improve current state of the art, because some of these technologies, such as seismic, are considered too costly or of low precision.

Finding 2: Emerging (2nd and 3rd generation) monitoring technologies for CO_2 storage are showing moderate progress



Respondents generally considered monitoring technologies to be making moderate progress, but the challenge has been gaining enough experience at large-scale field sites to prove reliability. EOR sites, the Sleipner project, and small-scale field tests such as Nagaoka and Ketzin, have provided opportunities to broaden the knowledge base and contribute scientific understanding. The contribution of government funding to progressing 2nd and 3rd generation technologies was recognized as a key contributor to advancing monitoring technologies, but large-scale sites are needed for technology validation.

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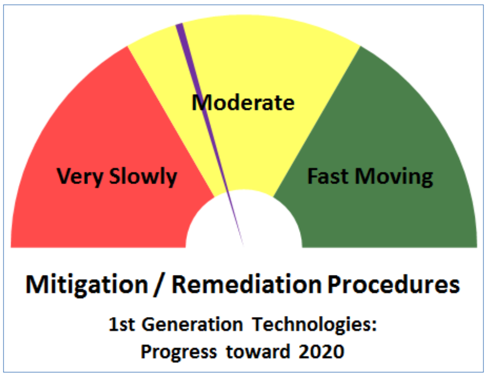
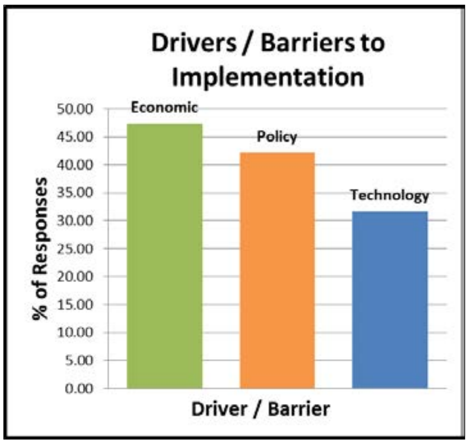
Global Trends in Mitigation and Remediation Procedures

Evidence for the findings below is supported by responses from the survey.

Finding 1: Mitigation and remediation procedures are showing slow to moderate progress.

Respondents regard the progress in mitigation and remediation procedures as slow to moderate. The commercial and environmental potential of these technologies is recognised, and it is acknowledged that these technologies should be in place before CCS can be deployed. However, the technologies and procedures are in a very early stage, and their development should be accelerated.

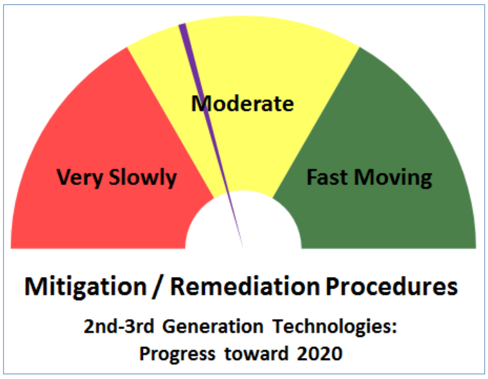




Most commonly cited barriers are economics and policy. For example, there is no obvious consensus as to what constitutes a leakage and hence when a regulator might require remediation.

Finding 2: Research and demonstration are needed to bring this technology to fruition

Technical barriers are also very significant. Mitigation and remediation, as 'end of chain' technologies, have as yet received much less attention than capture, transport and storage. Universities and research institutes carry out most of the research and desk studies, and this is expected to progress the technologies. As a follow-up, real-life field testing using controlled release, and involving industry, needs to be carried out for a variety of scenarios. However, an important regulatory barrier is the difficulty to obtain a permit for such experiments.



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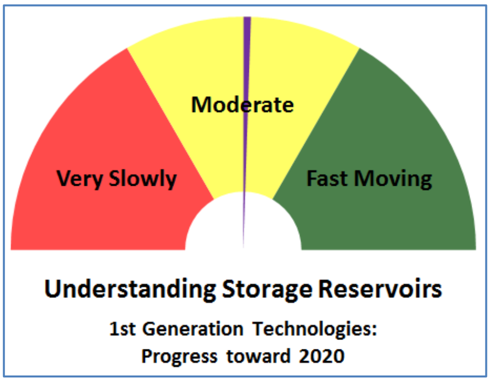
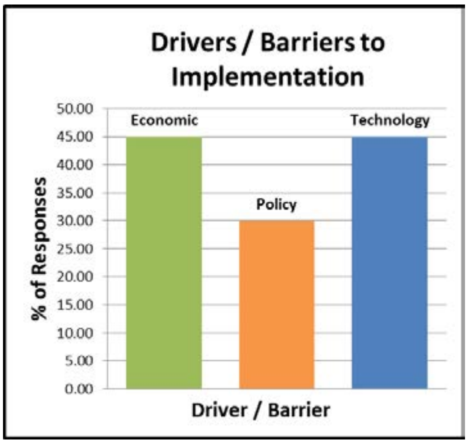
Global Trends in Understanding Storage Reservoirs

Evidence for the findings below is supported by responses from the survey, various reports published by the GCCSI, and other reports and journal papers.

Finding 1: Reservoir understanding in early projects is progressing at a moderate rate.

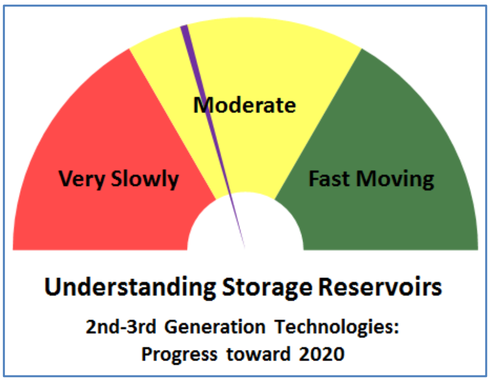


Respondents regard the understanding of storage reservoirs in early CCS projects to be progressing at a moderate rate. Commercial CO_2 storage operations (e.g. the Sleipner and Snøhvit CCS projects in Norway, the Weyburn-Midale CO_2-EOR operations in Canada, the In-Salah CCS project in Algeria and the Lula in Brazil) are providing an expanding source of experience and are of great value to future CCS projects. These projects have generally adopted oil & gas industry best practices (e.g. well logging and seismic techniques) and the development of these for onshore CO_2-EOR and storage in deep saline formations has led to rapid advancement. Offshore CO_2-EOR is being evaluated.



Survey respondents cited economic, technology and policy barriers: Deploying conventional geological, geochemical and geophysical techniques at commercial scale and in a variety of scenarios is very expensive and, although such approaches have provided detailed characterisation of potential storage reservoirs, barriers to large-scale deployment have prevented the evaluation of many reservoirs under actual injection conditions. Allocation of perceived risks and raising finance are both difficult. The prediction of CO_2 plume behaviour using modelling techniques is not as straightforward as some had expected due to factors including heterogeneity and the wide range of length and timescales in geological formations. Pressure management in reservoirs is a critical factor. Other cost barriers exist, generally linked to the high cost of using O&G techniques in CCS applications.

Finding 2: Progress of emerging (2^{nd}/3^{rd} generation) understanding moderate to slow.



Understanding storage reservoirs for large-scale, commercial CCS operations (i.e. greenfield, migration-assisted storage, unconventional and heterogeneous reservoirs) has proved more difficult than first predicted. In order to provide a better and more cost-effective understanding of such storage reservoirs, RD&D into advanced technologies and techniques that can further reduce residual subsurface uncertainties following site characterisation using costly conventional approaches is needed: Cost-effectively reducing this uncertainty during site characterisation will significantly

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reduce characterisation time, development cost, operational risks and closure liability. Characterisation and site selection link with regulatory requirements for site monitoring, and cost reduction in site monitoring is a key requirment.

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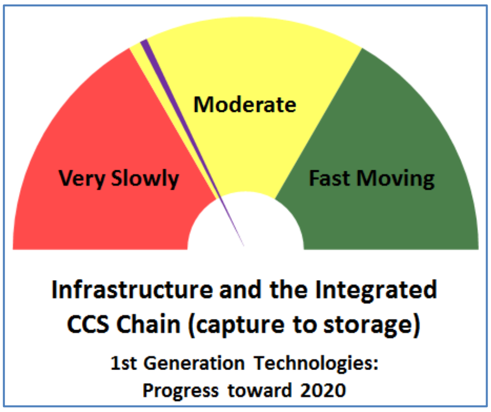
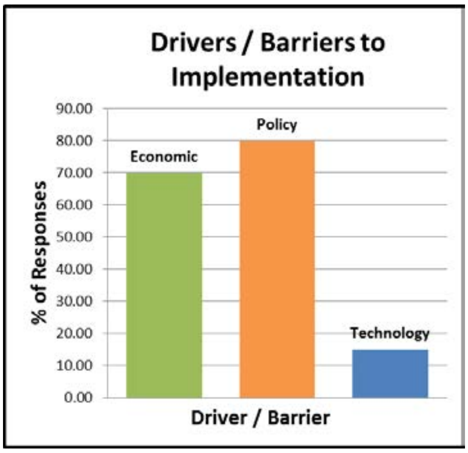
Global Trends in Infrastructure and the Integrated CCS Chain (Capture to Storage)

Evidence for the findings below is supported by responses from the survey, various reports from the GCCSI, and a number of European reports (e.g. mainly from the UK and the Netherlands).

Finding 1: Progress with first generation infrastructure and integration implementation is showing moderate to slow progress.

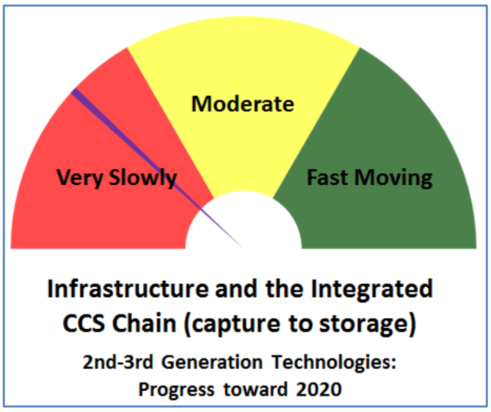


With the notable exception of the UK, where progress is considered to be fast moving, survey respondents generally regard progress of implementing 1st generation infrastructure and integrated CCS chain technologies to be at a moderate to slow rate, with only a few large-scale, fully integrated projects in the 'operate' or 'execute' phase (e.g. in USA, Canada, and Australia), and few studies/activities being undertaken to consider necessary infrastructure and integration issues associated with widespread CCS roll-out (e.g. in the UK and the Netherlands). These projects/activities provide the only source of experience with large-scale infrastructure and integrated CCS chains (e.g. the ROAD project has helped develop an understanding of integration issues at the design phase, but significant additional experience will only be gained from the contruction and commissioning phases. Such infrastructure and integration activity is expensive and requires government support.



The most commonly cited barriers are lack of policy and economics, including finance, ownership, business cases, risk allocation, etc. 'Future proofing' – particularly regarding 3rd party access, accounting for CCUS and the high cost for early-stage projects were specifically mentioned by respondents. While technical issues are not generally considered to be barriers, CO_2 purity could be a major issue, and plant and grid flexibility will also need careful management.

Finding 2: Progress with emerging (2nd and 3rd generation) infrastructure and integration implementation is very slow.



Respondents generally thought that progress with 2nd and 3rd generation technologies was very slow, with implementation requiring adaption to industrial processes with CCS (e.g. chemicals plants, iron and steel, cement, etc.). Furthermore, at the scale likely to be material with regard to global emissions, multiple sources linked via 'hubs' to basins or even reservoirs, will pose challenges that are not currently being addressed through R&D activities.

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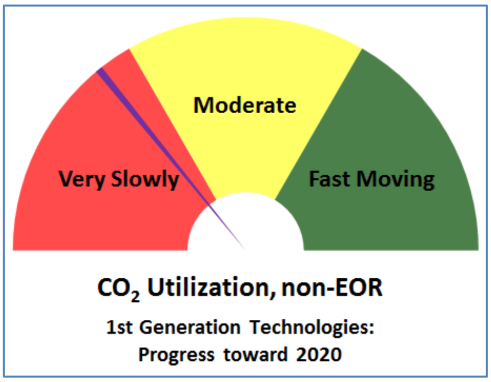
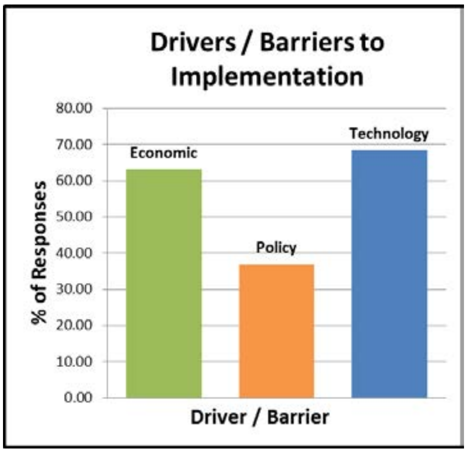
Global Trends in CO_2 Utilization, non-EOR

Finding 1: First generation technology for non-EOR CO_2 utilization is moving very slowly.

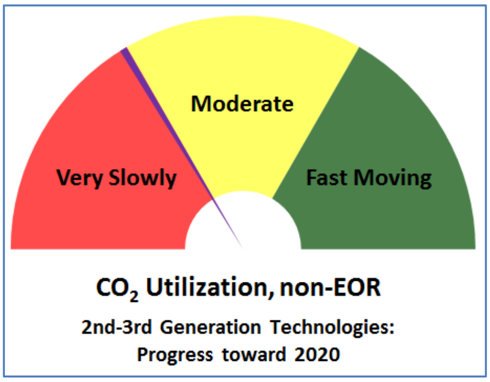


Feedback from the respondents indicate that the 1st generation technology for non-EOR CO_2 utilization is moving very slowly, there may be some technologies which are ready for some niche applications, however for most options, good business cases are very few owing to high-cost and energy-intensive features for non-EOR CO_2 utilization.

Most commonly cited barriers are economics and technology. Improvement of technology, small volume of used CO_2, and the necessity for commercial demonstration of 1st generation technology for non-EOR CO_2 utilization were mentioned by respondents.



Finding 2: Second generation technology for non-EOR CO_2 utilization is moving very slowly.



Respondents found the 2nd generation technology for non-EOR CO_2 utilization is moving very slowly, however it is better than the 1st generation technology owing to the commercial interests in developing related technologies in carbonation, BECCS, steel and cement etc. At the same time, special attention from governments (especially in China) promotes the development CO_2 utilization technologies.

Similar to the 1st generation technology, concerns are rised from the respondents for the 2nd generation technology for non-EOR CO_2 utilization such as low economic competence and process efficiencies. Consequently, extensive researches and further develoments are needed for the 2nd generation technology to enhance its potential for CO_2 mitigation.

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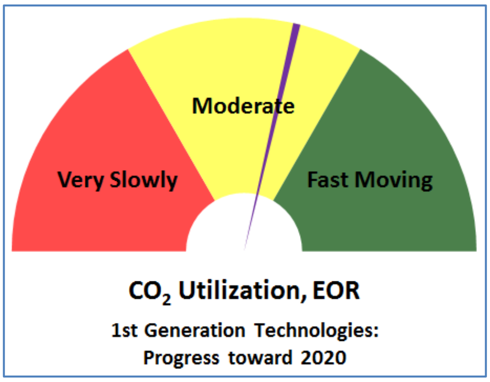
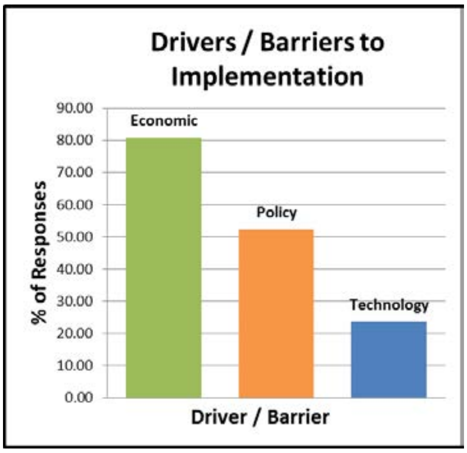
Global Trends in CO_2 Utilization, Enhanced Oil Recovery (EOR)

Finding 1: First generation CO_2-EOR implementation is showing moderate to fast moving progress.

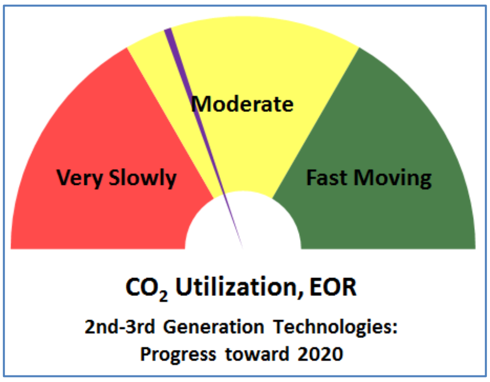


Respondents consider CO_2-EOR as a deployed technology but its widespread implementation around the world is limited because of applicability, economics, or policy barriers. In the USA, CO_2-EOR has been commercially used for more than 40 years. The first patent on the use of CO_2 to recover oil was granted in 1952 and CO_2-EOR was first tested on a large scale in the Permian Basin of west Texas and south-eastern New Mexico. CO_2-EOR is therefore a mature technology in terms of operation, but not yet from the verification and monitoring point of view. Outside of North America, however, this technology has not yet gained serious consideration. This is because of the abundant conventional resources that can be extracted naturally as is the case in the Middle East, the high cost of CO_2 from anthropogenic sources, and the lack of EOR prospects in places like Australia, Japan, and Korea.



The most cited barrier was economic, as EOR will signficantly increase the cost of extracting oil compared to waterflooding or tertiary recovery using natural gas and solvents, even though EOR is still conidered economical (at current oil prices). The other cited barrier was policy where goverment support is lacking to fund RD&D or deployment through subsidy incentives.

Finding 2: Emerging (2nd and 3rd generation) CO_2-EOR implementation is showing moderate to slow progress.



Respondents believed that 2nd and 3rd generation CO_2-EOR is slow moving, like its application in unconventional reservoirs and enhanced coal-bed methane (ECBM), and extending its application to include storage. Extending CO_2-EOR to CO_2 storage requires new monitoring techniques to cover areas beyond the conventional monitored areas in EOR, to include wider parameters, and to be extended for longer periods of time beyond the operational time of the oil field.

The main barriers include: 1) Economics because of the additional monitoring requirements that change project costs; 2) Policy where jurisdictional responsibility and long term liability are not yet defined; and 3) Technology that is still evolvoing to define reliable monitoring techniques that will provide high resolution tracking of the CO_2 movement and storage underground.

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Conclusions

Overall, except for a very few niche industrial sector applications, for 1st generation technologies, *none* of the ten technology needs areas were generally perceived as progress being 'fast moving'. To the contrary, 'slow-to-moderate' progress was perceived as the norm for almost all of the ten areas. As might be expected, the progress for 2nd and 3rd generation technologies was perceived as proceeding at an even slower rate.

At the 5th CSLF Ministerial Conference, convened in 2013, Ministers stressed that the next seven years were critically important for creating the conditions for CCS to be ready for large-scale deployment by the end of the decade. The 2013 TRM established that the year 2020 was an achievable timeframe for demonstration of the 1st generation of CCS technologies and that by the year 2030, 2nd generation technologies should be moved through demonstration and into commercialization. However, now, two years later, barriers are still in place that inhibit the accomplishment of these goals.

CCS is considered a key contributor in strategies for decreasing the impacts of climate change and global warming. The main takeaway from this interim report is that the next several years are a critical time period when technologies, regulatory policies and approaches toward project financing all must become mature. In this context, the following recommendations are made to accelerate progress:

- Concerning economic barriers, governments should urgently consider methods to assist stakeholders to significantly drive down the cost of CCS deployment, since it is the stakeholders who will be making the majority of the financial investments.
- Concerning policy barriers, governments should review institutional regulatory policies to identify how these barriers to CCS deployment may be reduced.
- Concerning technology barriers, stakeholders should increase their mechanisms for sharing best practices, particularly regarding communications, regulation and cost reduction, and pledge to engage in public-private partnerships to encourage the development of additional demonstration projects and facilitate the development of CCS projects internationally.

Finally, Ministers should be champions of CCS, and should ensure that they understand how critical CCS is to reaching target goals for CO_2 emissions, and that CCS deployment will create and preserve jobs. Ministers should also recognize the contribution that CCS can provide in terms of energy security. These will all form part of the narrative that will help shape the future progress of CCS.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2015-03
22 April 2015

TECHNICAL GROUP

Action Plan Status Report

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. This Action Plan was updated at the Washington meeting in November 2013, the Seoul meeting in March 2014, and the Warsaw meeting in October 2014.

This paper is an update, prepared by the CSLF Secretariat, on the status of the Technical Group's Action Plan.

Action Requested

The Technical Group is requested to review the Action Plan status report.

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Carbon Sequestration Leadership Forum
www.cslforum.org

CSLF-T-2015-03
22 April 2015

CSLF Technical Group Action Plan Status

(as of April 2015)

COMPLETED ACTIONS

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: Final Report has been issued. Key findings are:

- At a high level there are no major technology gaps. CCS technologies are ready and available, and are being deployed today.
- There are many contending capture technologies, in both current technologies and 2nd & 3rd generation technologies.
- Next generation technologies are vital for substantial cost reduction.
- However, there is no strong market pull for new technologies at the moment.
- There is a need to continue work towards low cost, high resolution MMV, particularly in the offshore environment.
- The lack of exploration for CO_2 storage sites is a significant barrier to rapid deployment of CCS and, thus, learning by doing.

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: Final Report has been issued. Task force key findings are:

- 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.

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- 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, and generally monitoring requirements for CCS which are broader and more encompassing than for CO_2-EOR.

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: Final report has been issued. Task force key findings are:

- A number of CO_2 utilization options are available which can serve as a mechanism for deployment and commercialization of CCS.
- EOR is the most near-term CO_2 utilization option. Non-EOR CO_2 utilization options are at varying degrees of commercial readiness and technical maturity.
- For mature non-EOR CO_2 utilization options, efforts should be on demonstration projects and on the use of non-traditional feedstocks or polygeneration concepts.
- Efforts that are focused on hydrocarbon recovery other than EOR should focus on field tests.
- Efforts that are in early R&D or pilot-scale stages should focus on addressing key techno-economic challenges, independent tests to verify the performance, and support of small and/or pilot-scale tests of first generation technologies and designs.
- More detailed technical, economic, and environmental analyses should be conducted on these options.

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.

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Status: Reports for Years 2012 and 2013 have been issued. Findings of the task force will be archived at the CSLF website. The task force was discontinued in part because other organizations such as the European Commission's CO_2 GeoNet Project and the ISO TC265 committee on CCS may be planning similar activities.

Review of CO_2 Storage Efficiency in Deep Saline Aquifers

Action: The Technical Group will recommend the proper storage efficiency coefficients to be used when estimating CO_2 storage capacity, based on the scale of the assessment, geological characteristics and other parameters of the storage operation.

Outcome: Identification of guidelines for use of appropriate CO_2 storage efficiency coefficients that can be used by governments and industry in the assessment of CO_2 storage resource and in site selection for CO_2 storage.

Status: The CSLF Task Force for Review and Identification of Standards for CO_2 Storage Capacity Estimation published reports in 2005, 2007, and 2008 before concluding its work. A task force (*led by Canada*) was formed in November 2013 to critically review, compile and report on relevant literature published since 2008, and is issuing its findings in a paper on "CO_2 Storage Efficiency in Deep Saline Aquifers" that is being published in a special issue of *The International Journal of Greenhouse Gas Control*. This paper will also serve as the task force's final report.

CURRENT ACTIONS

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 has been assigned to Projects Interaction and Review Team (*led by Australia*). A linkage has been established with Global CCS Institute's low emissions technology website, **decarboni.se**, which now includes CSLF projects and reports. Also, Technical Group is holding annual technology workshops featuring representatives of CSLF-recognized projects.

Offshore CO_2 Storage

Action: The Technical Group will provide a current assessment on the status of the global sub-seabed CO_2 storage potential, including potential for offshore EOR.

Outcome: Identification of technical barriers and challenges to sub-seabed CO_2 storage as well as RD&D opportunities. Also, identification of any potential opportunities for global collaboration. A previously-proposed Action on "CO_2 Compression and Transport" is being incorporated into this Action.

Status: A task force (*led by the United States*) has been active since March 2014 and expects to have a draft of its final report at the 2015 CSLF Mid-Year Meeting.

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Proposed actions in the following areas have been deferred and will be revisited at a later time:

- Energy Penalty Reduction
- CCS with Industrial Emissions Sources
- CO_2 Compression and Transport
- Competition of CCS with Other Resources
- Lifecycle Assessment and Environmental Footprint of CCS
- Carbon-neutral and Carbon-negative CCS

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Carbon Sequestration Leadership Forum
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DRAFT

MEETING SUMMARY

Projects Interaction and Review Team (PIRT) Meeting
Warsaw, Poland
27 October 2014

Prepared by the CSLF Secretariat

LIST OF ATTENDEES

PIRT Active Members

Australia: Clinton Foster (Chair)
Canada: Eddy Chui
China: Xian Zhang
France: Didier Bonijoly
Japan: Ryozo Tanaka
Mexico: Giselle Pérez
Netherlands: Paul Ramsak
Norway: Trygve Riis, Lars Ingolf Eide
Saudi Arabia: Ahmed Aleidan
South Africa: Tony Surridge
United Kingdom: Philip Sharman
United States: John Litynski
IEA GHG: Tim Dixon

Other CSLF Delegates

Australia: Zoe Naden
Korea: Seung-Phill Choi, Chang Keun Yi
Poland: Piotr Kisiel
Russia: Oleg Tailakov, Valerii Zakharov
South Africa: Landi Themba
United Kingdom: Suk Yee Lam

CSLF Secretariat

Richard Lynch, Adam Wong

Invited Speaker

Norway: Liv Bjerge, Project Manager, Norcem CO_2 Capture Project

Observers

France: David Savary
Poland: Adam Wójcichi

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1. Welcome and Summary of Previous PIRT Meeting

Clinton Foster

PIRT Chairman Clinton Foster welcomed participants to the 22nd meeting of the PIRT and provided a brief summary of the March 2014 PIRT meeting in Seoul, Korea. At that meeting the PIRT reached consensus on the following:

- The PIRT will produce a short progress report on the CSLF's Technology Roadmap (TRM) in time for the 2014 CSLF Annual Meeting. The PIRT will also work toward producing an interim report on the TRM for the 2015 CSLF Ministerial Meeting and a new edition of the TRM in time for an anticipated 2017 CSLF Ministerial Meeting.
- Three new members (China, Mexico, and the Netherlands) were added to the PIRT's Active Membership core group.
- PIRT meetings will include updates from the Global Carbon Capture and Storage Institute (GCCSI) about its "**decarboni.se**" knowledge hub website and other CCS-related knowledge-sharing activities.

Dr. Foster noted that this was the first meeting under the PIRT's revised Terms of Reference, and briefly summarized the new procedures for how the PIRT will examine projects nominated for CSLF recognition:

- Project proposals should be circulated to PIRT Active Members by the CSLF Secretariat.
- No later than ten days prior to PIRT meetings, Active Members are asked to submit a free-text comment, either supporting or identifying issues for discussion, on each project nominated for CSLF recognition.
- At PIRT meetings or via proxy through the PIRT Chair, individual country representatives will be required to comment on projects nominated for CSLF recognition.
- Recommendations of the PIRT should be reached by consensus with one vote per Active Member country only.

Dr. Foster noted that these new procedures have worked very well for analysis of the Norcem CO_2 Capture Project, being considered at the current meeting, and thanked the PIRT Active Members who provided comments on the project.

2. Adoption of Meeting Agenda

The meeting Agenda was adopted with the addition of a short update on the CSLF-recognized Gorgon Project after the report on PIRT activities concerning knowledge-sharing (i.e., after Item 6 on the PIRT Agenda).

3. Introduction of Meeting Attendees

PIRT meeting attendees introduced themselves. In all, fifteen CSLF delegations were represented at the meeting.

4. Approval of Meeting Summary from Seoul PIRT Meeting

The Meeting Summary from the March 2014 PIRT meeting in Seoul was approved as final with two minor adjustments to the draft document:

- For clarity, change the word "parsing" to "sorting" in the description of how information from the technology needs reporting template would be examined.
- Add Canada as a volunteer to examine information from technology needs reporting templates in the area of "CO_2 Utilization – Enhanced Oil Recovery (EOR)".

5. Report from CSLF Secretariat

Richard Lynch

Richard Lynch provided a four-part report from the Secretariat, which covered the status of PIRT Action Items from the March 2014 meeting in Seoul, the TRM Progress Report prepared by the Secretariat for the current meeting, outcomes from the March 2014 Technology Workshop that had been held in conjunction with the Seoul Technical Group Meeting, and an update on CSLF-recognized projects.

Mr. Lynch stated that there were six Action Items from the March 2014 meeting, all of which are now complete. A link to the GCCSI's "**decarboni.se**" website has been created on the "Publications/Links" page of the CSLF website. Four of other completed Actions were related to the TRM Progress Report.

Concerning the TRM Progress Report, Mr. Lynch stated that in the months following the Seoul meeting, the Secretariat developed a template (which was approved by the PIRT Chair) for gathering information about the technology needs areas identified in the 2013 TRM. The template was provided to Technical Group delegates, who then sent it to representatives of organizations within their countries which are working on CCS. As of September 29th, a total of 12 completed templates had been returned and these were used as inputs to the TRM Progress Report. There was judged not to be enough information yet to definitively describe the global status of CCS, but some trends were evident:

- For 1st generation technologies, none of the 10 technology needs areas were perceived as "fast moving" in terms of progress. Progress in most areas was perceived as a mixed opinion of "very slow" and "moderate".
- Results for 2nd and 3rd generation technologies were similar, but many more "no opinion" responses were received.
- There appeared to be a geographical bias in responses so far received. North American responders were, in general, more pessimistic on the amount of progress being made.
- All types of barriers and/or drivers (economic, policy, and technology) were perceived to exist for most technology needs areas.
- Individual country results provided a wide range of responses, showing that issues surrounding CCS are viewed by different countries in different ways.

Mr. Lynch stated that one of the conclusions from this exercise was that the 2013 TRM is still reasonably accurate in its depiction and portrayal of the status and barriers/drivers for development and deployment of CCS technologies. There is still a need for progress in all of the technology needs areas, some more than others. Further, results confirm that worldwide, CCS is not a "one size fits all" collection of technologies and there appears to be a great need for individualized country-specific technology roadmaps.

Concerning the March 2014 Technology Workshop, Mr. Lynch stated that the event consisted of two sessions: "Cost Reduction Strategies for CO_2 Capture" and "Examining Technology Pathways and Business Models for Scaling-up CCS". It was a very well-attended event and there were many takeaways:

- Advances and innovation in the area of CO_2 capture are important and critical to the commercial deployment of CCS. The wide range of technology options under development is appropriate at this time.
- Technology scale-up is a critical step to cost reductions and technology validation, especially for 2nd and 3rd generation technologies. Simulations and modeling are important, but there is no substitute for experience and knowledge from real-world projects.
- Technological development and innovation must be rooted in clearly-defined targets and metrics. These will help drive sound RD&D investments.
- Understanding the overall CCS value chain is essential, with "market pull" mechanisms (e.g., policy incentives and drivers) being just as important as "technology push" efforts (e.g., grants and government cost share).
- Issues for governments to address include matching potential CO_2 sinks to CO_2 sources, adding infrastructure such as pipelines, and stimulation of skills development (which is as important as maturity of technologies).
- Issues for industry and project sponsors to address include reducing the risk of integration (which is a big contributor to the high cost of first-of-a-kind large-scale CCS demonstrations) and expeditiously bringing 2nd and 3rd generation technologies to pilot-scale testing.
- Issues for financial organizations to address include finding ways to reduce financial risk to equity holders and developing effective financial mechanisms for CCS demonstration projects.
- Above all, collaboration is essential for success.

Finally, concerning the portfolio of CSLF-recognized projects, Mr. Lynch stated that as of mid-September there were 43 active and completed projects, spread out over five continents. However, at the end of September, Italy announced that the Zero Emission Porto Tolle Project had been cancelled. Mr. Lynch concluded his presentation by reiterating that the Norcem CO_2 Capture Project was up for CSLF recognition at the current meeting.

6. Review and Approval of Project Proposed for CSLF-Recognition: Norcem CO_2 Capture Project

Liv Bjerge, Project Manager for the Norcem CO_2 Capture Project, gave a presentation about the Norcem project. This project, located in southern

Liv Bjerge

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Norway at a commercial cement production facility, is testing four different post-combustion CO_2 capture technologies at scales ranging from very small pilot to small pilot. Technologies being tested are a 1st generation amine-based solvent, a 3rd generation solid sorbent, 3rd generation gas separation membranes, and a 2nd generation regenerative calcium cycle, all using flue gas from the cement production facility. Objectives of the project are to determine the long-term attributes and performance of these technologies in a real-world industrial setting and to learn the suitability of such technologies for implementation in modern cement kiln systems. Important focus areas include CO_2 capture rates, energy consumption, impact of flue gas impurities, space requirements, and projected CO_2 capture costs. Project partners include Norcem, HeldelbergCement, and the European Cement Research Academy, and the project has also received funding from Norway's CLIMIT program. The project began in 2013 and is expected to continue into 2017.

Outcome: After a comprehensive discussion, there was consensus by the PIRT to recommend approval of the Norcem CO_2 Capture Project by the Technical Group.

7. Report on PIRT Activities concerning Knowledge-Sharing

Dr. Foster stated that the GCCSI's "**decarboni.se**" website now has a page summarizing the work of the Technical Group's recently-concluded Task Force on Best Practices and Standards for Geologic Storage and Monitoring of CO_2. The task force's report, downloadable from that page, includes sections on standards, guidelines, and best practice manuals. Lars Ingolf Eide, the Chair of the task force, complemented the GCCSI on its work to get this information online. Dr. Foster also thanked the GCCSI on behalf of the PIRT. The Secretariat was asked to create a link from the CSLF website to this report.

8. Update on the CSLF-recognized Gorgon CO_2 Injection Project

Dr. Foster provided an update on the status of the Australia's Gorgon Project, which had received CSLF recognition at the 2010 Annual Meeting (also held in Warsaw). This project, when it comes online in 2016, will inject between 3.4 and 4.0 million tonnes of CO_2 per year into a water-bearing sandstone formation approximately two kilometers beneath Barrow Island, off the northwest coast of Australia. The CO_2 will be separated from natural gas being produced near that location. Over the life of the project, as much as 100 million tonnes of CO_2 could be injected. Dr. Foster mentioned that the project features an extensive monitoring plan, and using photographs provided by the project sponsors, showed the progress in site preparation and construction over the past four years including installation of the CO_2 compressor modules. The Gorgon Project will be the largest CO_2 capture and injection project globally and also the first project in Australia to inject CO_2.

9. Future PIRT Activities

Dr. Foster referred to the Secretariat's presentation on the TRM Progress Report from earlier in the meeting and reviewed the responsibilities of the PIRT Active Members for information analysis for each of ten needs areas. After ensuing discussion, the following breakdown was confirmed:

Area #1: CO_2 Capture Technologies in Power Generation (*Norway*)
Area #2: CO_2 Capture in Industrial Sector (*South Africa* and *United Kingdom*)
Area #3: CO_2 Transport (*Australia*)

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Area #4: Large-Scale CO_2 Storage (*Japan* and *France*)
Area #5a: Monitoring (*United States* and *France*)
Area #5b: Mitigation / Remediation (*European Commission*)
Area #6: Understanding the Storage Reservoirs (*United Kingdom* – to be confirmed)
Area #7: Infrastructure (*United Kingdom*)
Area #8a: CO_2 Utilization, non-EOR (*France*)
Area #8b: CO_2 Utilization, EOR (*Saudi Arabia* and *Canada*)

Ryozo Tanaka noted that some of the information being requested, such as progress on 2nd and 3rd generation CO_2 transportation systems, may not even be relevant and the template should perhaps be modified to black out areas in the template where no information would be forthcoming. Philip Sharman noted that it was not clear on how this information would be used to produce a TRM Interim Report in time for the 2015 Ministerial Meeting. After an extended discussion on how to move the process forward, Mr. Lynch proposed the following:

- The Secretariat will make adjustments to the technology needs reporting template, after consulting with PIRT Active Members. (This would be completed by early December.)
- As was done previously, the Secretariat would then send the template to Technical Group delegates, who would then sent it to representatives of organizations within their countries which are working on CCS. (Deadline TBD, but probably by early February.)
- The Secretariat would prepare a detailed and sortable spreadsheet containing all information received from the CCS experts, and would send the spreadsheet to the PIRT Active Members who are doing the data analysis, as shown above. (Deadline TBD, but probably by early March.)
- For each of the ten needs areas, the “owners” of those areas would examine the information in the spreadsheet (as pertaining to their areas) and would draft short progress reports that can be combined into a TRM Interim Report. (Deadline TBD, but probably by early May.)

There was agreement to use this approach.

10. Adjourn

Dr. Foster encouraged CSLF delegations to become PIRT Active Members, if they have not already done so. Dr. Foster then thanked the attendees for their participation, noting the high level of interaction during the meeting, and adjourned the meeting.

Summary of Consensuses

- The PIRT recommends approval by the Technical Group for the Norcem CO_2 Capture Project.

Summary of Action Items

- The Secretariat will finalize the Summary for the March 2014 PIRT meeting including the two minor changes described above.
- The Secretariat will add a link from the CSLF website to the report from the Task Force on Best Practices and Standards for Geologic Storage and Monitoring of CO_2 at the GCCSI’s “**decarboni.se”** website.

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- The Secretariat will make adjustments to the technology needs reporting template, after consulting with PIRT Active Members.
- The Secretariat will send the template to Technical Group delegates, who will facilitate the process in obtaining information from representatives of organizations in their countries which are actively working on various aspects of CCS.
- PIRT Active Members, as designated above, will take charge of information analysis for the technology needs areas, once information gathering is complete, and draft short progress reports for inclusion in a TRM Interim Report.

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Carbon Sequestration Leadership Forum

Revised: November 2013

www.cslforum.org

Terms of Reference

CSLF Projects Interaction and Review Team

Background

One of the main instruments to help the CSLF achieve its goals is through the recognition of CSLF projects. Learnings from CSLF projects are key elements to knowledge sharing which will ultimately assist in the acceleration of the deployment of carbon capture and storage (CCS) technologies. It is therefore of major importance to have appropriate mechanisms within the CSLF for the recognition, assessment and dissemination of projects and their results for the benefit of the CSLF and its Members. To meet this need the CSLF has created an advisory body, the PIRT, which reports to the CSLF Technical Group.

PIRT Functions

The PIRT has the following functions:

- Assess projects proposed for recognition by the CSLF in accordance the project selection criteria developed by the PIRT. Based on this assessment make recommendations to the Technical Group on whether a project should be accepted for recognition by the CSLF.
- Review the CSLF project portfolio and identify synergies, complementarities and gaps, providing feedback to the Technical Group
- Provide input for further revisions of the CSLF Technology Roadmap (TRM) and respond to the recommended priority actions identified in the TRM.
- Identify where it would be appropriate to have CSLF recognized projects.
- Foster enhanced international collaboration for CSLF projects.
- Ensure a framework for periodically reporting to the Technical Group on the progress within CSLF projects.
- Organize periodic events to facilitate the exchange of experience and views on issues of common interest among CSLF projects and provide feedback to the CSLF.
- Manage technical knowledge sharing activities with other organizations and with CSLF-recognized projects.
- Perform other tasks which may be assigned to it by the CSLF Technical Group.

Membership of the PIRT

The PIRT consists of:

- A core group of Active Members comprising Delegates to the Technical Group, or as nominated by a CSLF Member country. Active Members will be required to participate in the operation of the PIRT.

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- An *ad-hoc* group of Stakeholders comprising representatives from CSLF recognized projects. (*note: per Section 3.2 (e) of the CSLF Terms of Reference and Procedures, the Technical Group may designate resource persons*)

The PIRT chair will rotate on an *ad hoc* basis and be approved by the Technical Group.

Projects for CSLF Recognition

- CCS projects seeking CSLF recognition will be considered on their technical merit.
- Projects for consideration must contribute to the overall CSLF goal 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".
  - There is no restriction on project type to be recognized as long as the project meets the criteria listed below.
  - Learnings from similar projects through time will demonstrate progress in CCS.
- Proposals will meet at least one of the following criteria.
  - An integrated CCS project with a capture, storage, and verification component and a transport mechanism for CO_2.
  - Demonstration at pilot- or commercial-scale of new or new applications of technologies in at least one part of the CCUS chain.
  - Demonstration of safe geological storage of CO_2 at pilot- or commercial-scale.

Operation and Procedures of the PIRT

- The PIRT will establish its operational procedures. The PIRT will coordinate with the Technical Group on the agenda and timing of its meetings.
- The PIRT should meet as necessary, often before Technical Group meetings, and use electronic communications wherever possible.
- The TRM will provide guidance for the continuing work program of the PIRT.

Project Recognition

- Project proposals should be circulated to Active Members by the CSLF Secretariat.
- No later than ten days prior to PIRT meetings, Members are asked to submit a free-text comment, either supporting or identifying issues for discussion on each project nominated for CSLF recognition.
- At PIRT meetings or via proxy through the PIRT Chair, individual country representatives will be required to comment on projects nominated for CSLF recognition .
- Recommendations of the PIRT should be reached by consensus with one vote per member country only.

Information Update and Workshops

- Project updates will be requested by the Secretariat annually; the PIRT will assist in ensuring information is sent to the Secretariat.
- The PIRT will facilitate workshops based on technical themes as required.
- As required, the PIRT will draw on external relevant CCS expertise.

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Carbon Sequestration Leadership Forum
www.cslforum.org

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

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

1. Purpose of the CSLF

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

2. Function of the CSLF

The CSLF seeks to:

2.1 Identify key obstacles to achieving improved technological capacity;

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

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

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

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

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

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

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

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

2.10 Build the capacity of Members;

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

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

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

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

3. Organization of the CSLF

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

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

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

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

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

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

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

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

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

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

4 Membership

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

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

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

5 Funding

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

6 Open Research and Intellectual Property

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

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

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7. Commencement, Modification, Withdrawal, and Discontinuation

7.1 Commencement and Modification

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

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

7.2 Withdrawal and Discontinuation

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

8. Counterparts

This Charter may be signed in counterpart.

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Carbon Sequestration Leadership Forum

revision date: 07 October 2010

www.cslforum.org

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:

- Identify key technical, economic, environmental and other issues related to the achievement of improved technological capacity.

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- 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.

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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.

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:

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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.

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.

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

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

5. Interaction with Stakeholders

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

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Carbon Sequestration Leadership Forum
www.cslforum.org

Active and Completed CSLF Recognized Projects

(as of November 2014)

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 Carbon Trunk Line**
   Nominators: Canada (lead) and United States
   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.
   Recognized by the CSLF at its Washington meeting, November 2013

3. **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

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4. **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

5. **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 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

6. **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

7. **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

8. **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

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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

9. **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

10. **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

11. **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

12. **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

13. **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

14. **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

15. **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

16. **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

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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

17. 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

18. 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

19. 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

20. 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

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21. 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

22. 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 the eastern Texas region of the United States. 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

23. 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

24. 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.

Recognized by the CSLF at its Warsaw meeting, October 2010

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25. 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

26. 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

27. 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

28. 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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29. **Kemper County Energy Facility**
Nominators: United States (lead) and Canada
This commercial-scale CCS project, located in east-central Mississippi in the United States, will capture approximately 3 million tonnes of CO_2 per year from integrated gasification combined cycle (IGCC) power plant, and will include pipeline transportation of approximately 60 miles to an oil field where the CO_2 will sold for enhanced oil recovery (EOR). The commercial objectives of the project are large-scale demonstration of a next-generation gasifier technology for power production and utilization of a plentiful nearby lignite coal reserve. Approximately 65% of the CO_2 produced by the plant will be captured and utilized.
Recognized by the CSLF at its Washington meeting, November 2013

30. **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

31. **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

32. **MRCSP Development Phase Project**
Nominators: United States (lead) and Canada
This is a large-scale CO_2 storage project, located in Michigan and nearby states in the northern United States that will, over its four-year duration, inject a total of one million tonnes of CO_2 into different types of oil and gas fields in various lifecycle stages. The project will include collection of fluid chemistry data to better understand geochemical interactions, development of conceptual geologic models for this type of CO_2 storage, and a detailed accounting of the CO_2 injected and recycled. Project objectives are to assess storage capacities of these oil and gas fields, validate static and numerical models, identify cost-effective monitoring techniques, and develop system-wide information for further understanding of similar geologic formations. Results obtained during this project are expected to provide a foundation for validating that CCS technologies can be commercially deployed in the northern United States.
Recognized by the CSLF at its Washington meeting, November 2013

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33. Norcem CO_2 Capture Project

Nominators: Norway (lead) and Germany

This project, located in southern Norway at a commercial cement production facility, is testing four different post-combustion CO_2 capture technologies at scales ranging from very small pilot to small pilot. Technologies being tested are a 1st generation amine-based solvent, a 3rd generation solid sorbent, 3rd generation gas separation membranes, and a 2nd generation regenerative calcium cycle, all using flue gas from the cement production facility. Objectives of the project are to determine the long-term attributes and performance of these technologies in a real-world industrial setting and to learn the suitability of such technologies for implementation in modern cement kiln systems. Important focus areas include CO_2 capture rates, energy consumption, impact of flue gas impurities, space requirements, and projected CO_2 capture costs.

Recognized by the CSLF at its Warsaw meeting, October 2014

34. 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

35. 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

36. 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

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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

37. 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

38. 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.
Recognized by the CSLF at its Beijing meeting, September 2011

39. SECARB Early Test at Cranfield Project
Nominators: United States (lead) and Canada
This is a large-scale project, located in southwestern Mississippi in the United States, 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

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40. SECARB Phase III Anthropogenic Test and Plant Barry CCS Project

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

This large-scale fully-integrated CCS project, located in southeastern Alabama in the United States, brings together components of CO_2 capture, transport, and geologic storage, including monitoring, verification, and accounting of the stored CO_2. A flue gas slipstream from a power plant equivalent to approximately 25 megawatts of power production is being diverted to allow large-scale demonstration of a new amine-based process that can capture approximately 550 tons of CO_2 per day. A 19 kilometer pipeline has also been constructed, as part of the project, for transport of the CO_2 to a deep saline storage site. Objectives of the project are to gain knowledge and experience in operation of a fully integrated CCS large-scale process, to conduct reservoir modeling and test CO_2 storage mechanisms for the types of geologic storage formations that exist along the Gulf Coast of the United States, and to test experimental CO_2 monitoring technologies.

Recognized by the CSLF at its Washington meeting, November 2013

41. 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

42. Uthmaniyah CO_2-EOR Demonstration Project

Nominators: Saudi Arabia (lead) and United States

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.

Recognized by the CSLF at its Washington meeting, November 2013

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43. 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

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

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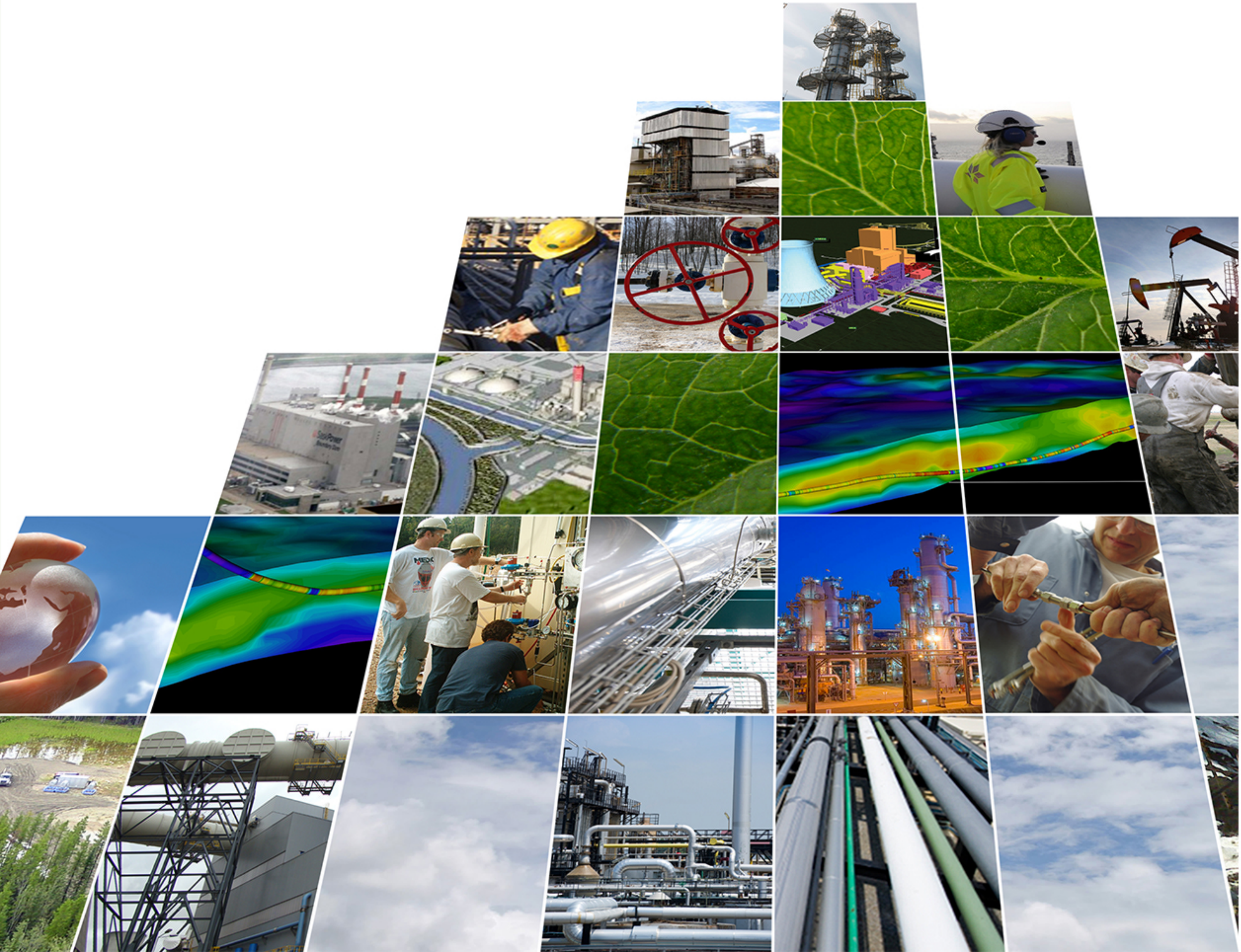

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Executive Summary

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*

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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

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[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.

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- 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.

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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).

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°C 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*

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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

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[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.

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[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 decarbonisation	• 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).

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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

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[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.

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

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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

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

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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 2nd 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 2nd and 3rd 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.

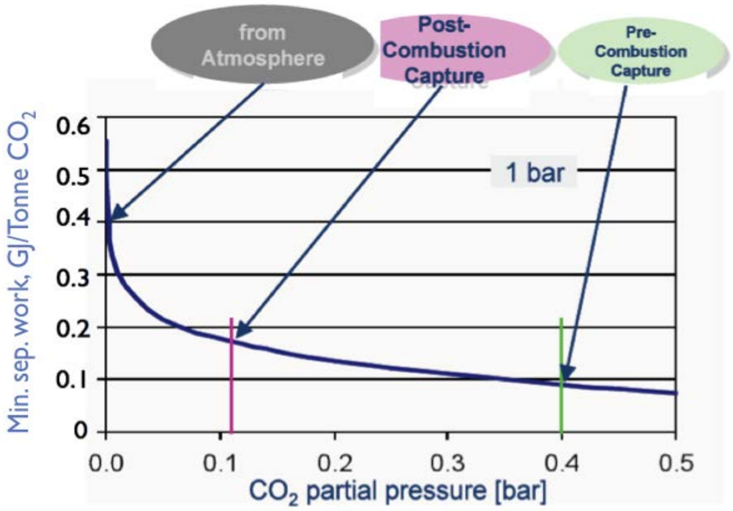

Figure 1: Theoretical minimum separation work of CO_2 from a flue gas depending on the partial pressure of CO_2 [modified from Bolland et al., 2006]

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.

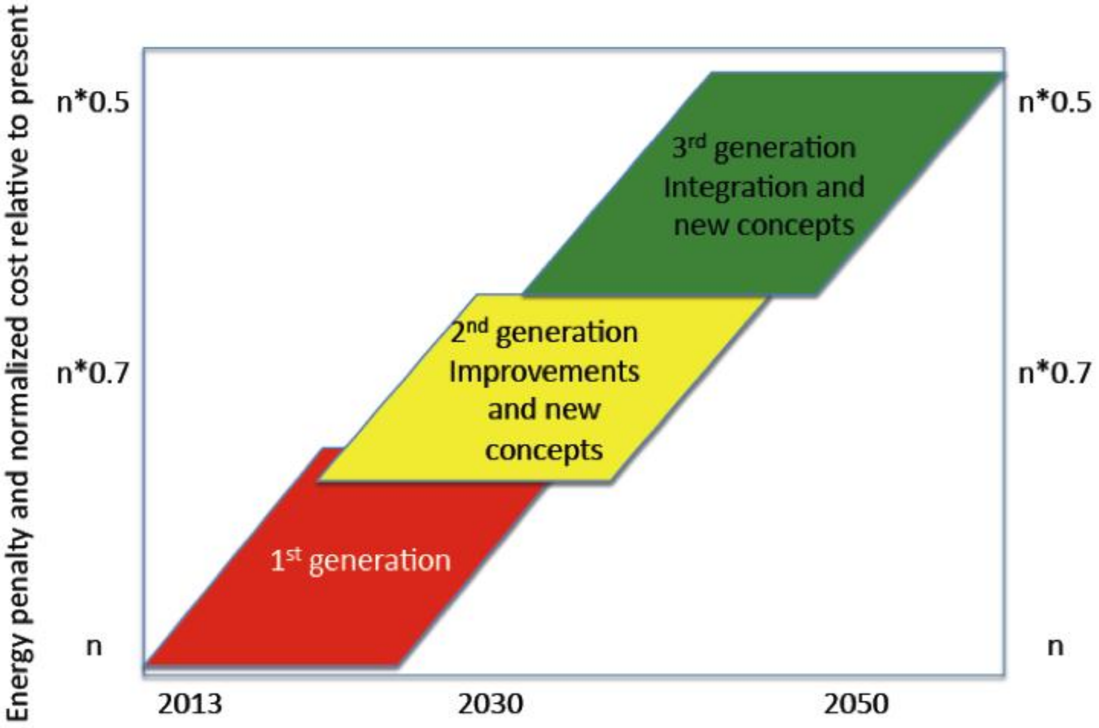

Figure 2: Priorities for CCS technology development. The energy penalty and normalized costs are shown in relation to the present level (n), i.e. equivalent to reduction by 30% in 2030 and 50% towards 2050.

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

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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.

- 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

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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°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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